Unfolding Higgs-top CP structure

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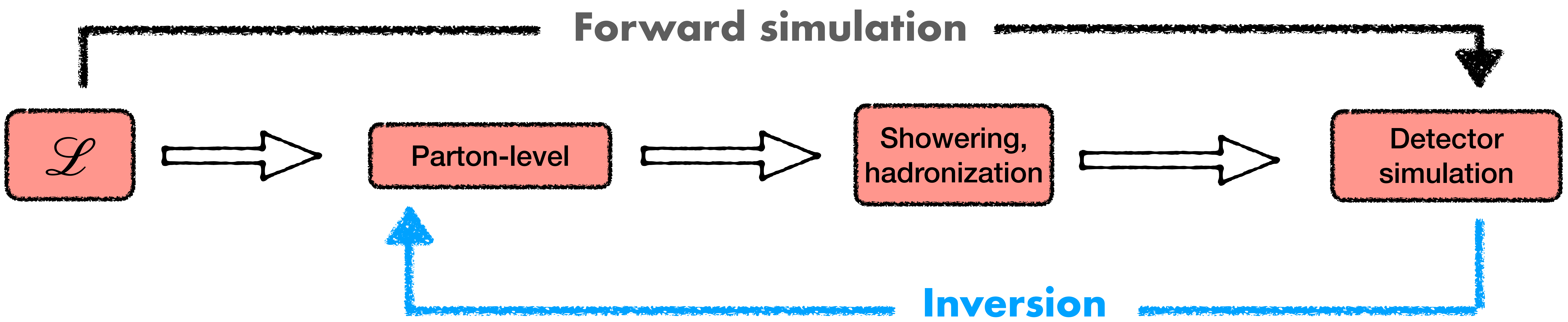
Unfolding

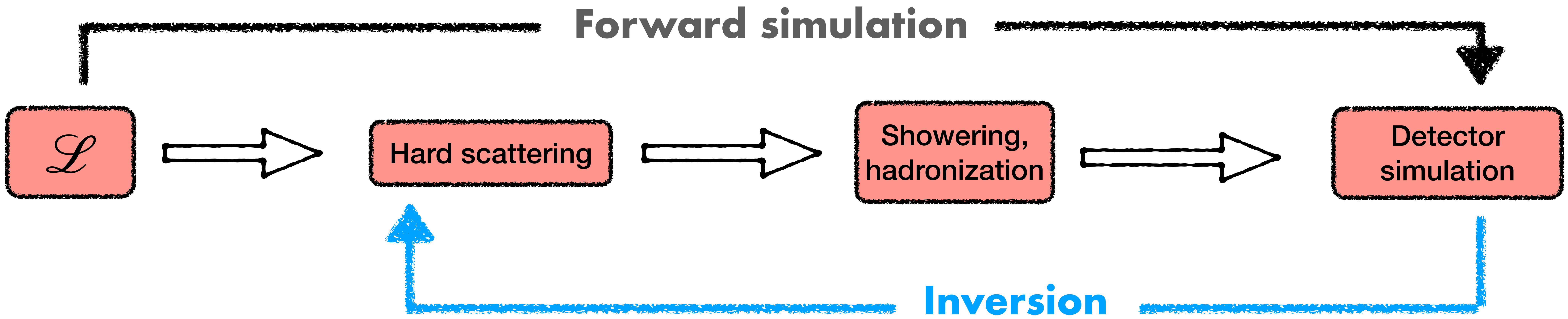


- Conventional LHC analysis involves comparing measured data with MC events simulated under NP hypothesis.
  - Reconstructed LHC events present a convoluted version of the `true' underlying physics.
  - Forward simulation chain can be highly resource intensive.

Invert simulation chain → apply on measured data → reconstruct phase space at the parton-level

→ compare new physics hypotheses at the parton-level.

Unfolding



The unfolding model is required to be:

✦Bin-independent ✦Able to invert multi-dimensional d.o.f.

Possible with machine learning based generative models.

[Talk by R. Winterhalder]

✱Generative Adversarial networks
✱Variational Autoencoders
✱**Normalising flows**

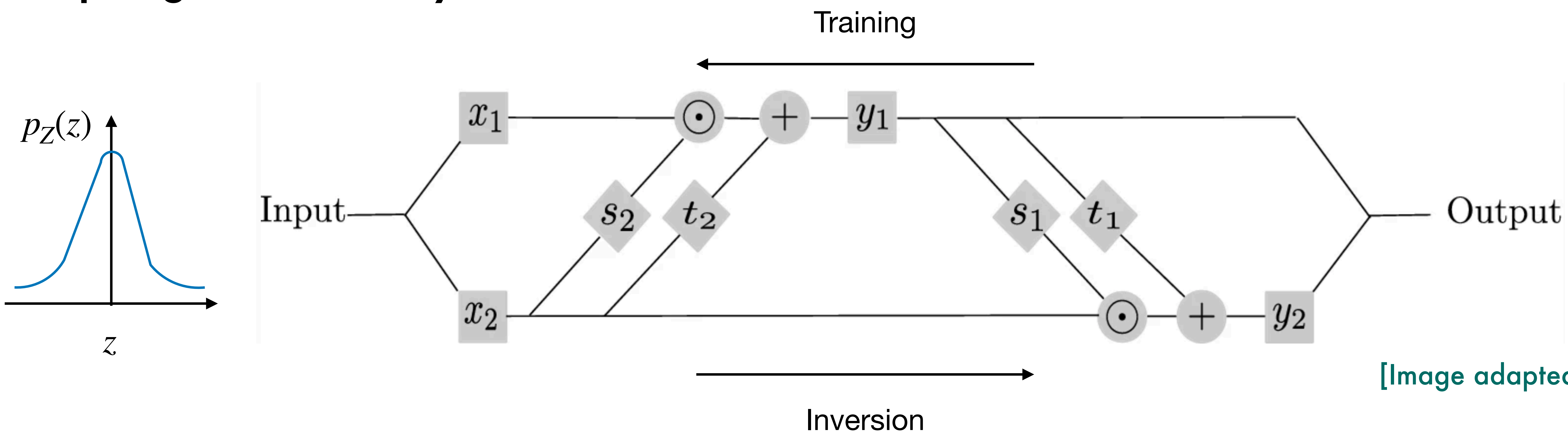
[Bellagente, Butter, Kasieczka, Plehn, Winterhalder (2020)]
[Bellagente, Butter, Kasieczka, Plehn, Rousselot, Winterhalder, Ardizzone, Kothe (2020)]
[Andreassen, Komiske, Metodiev, Nachman, Thaler (2020)]
[Komiske, McCormack, Nachman (2021)]

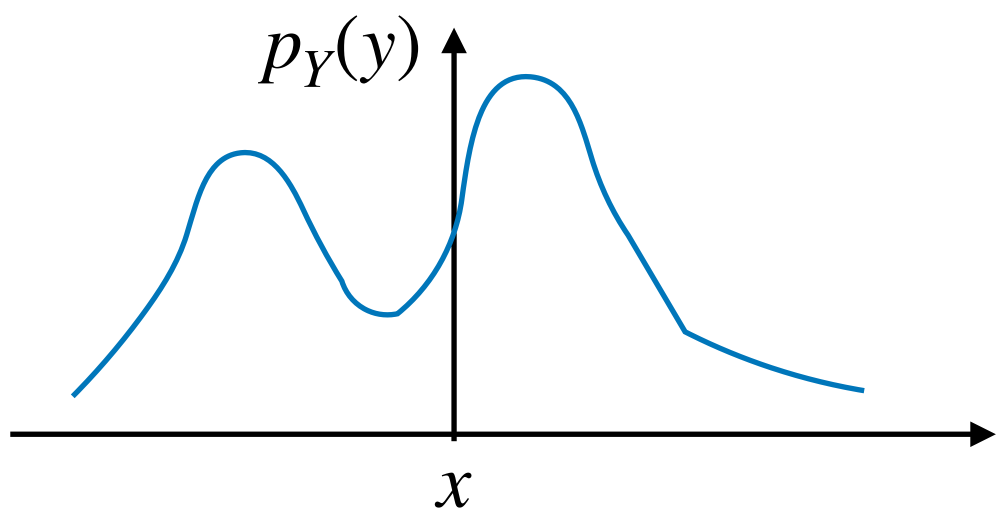
Normalising flows

- Series of invertible layers that transform complex (Y) to simple probability distributions (Z).
- Tractable Jacobian J : $p_Y(y) = p_Z(g(y))J$ | $Z = g(Y)$ — g: Invertible function

☑ Fast sampling and density estimation.

[Talk by T. Heimel]





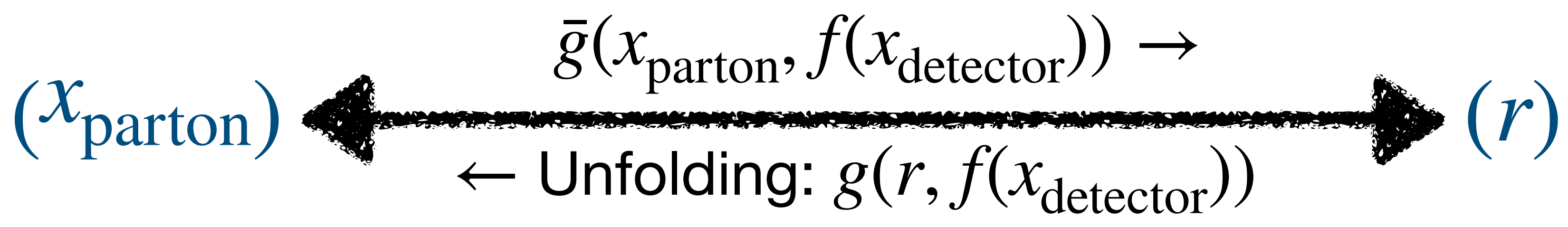
[Image adapted from Nguyen, Ardizzone, Kothe (2019) and talk by A. Butter at Pheno-2022]

- Bijective map between parton-level and detector-level phase space

$$\begin{pmatrix} x_{\text{parton}} \\ r_{\text{parton}} \end{pmatrix} \underset{\leftarrow \text{ Unfolding: } g}{\overset{\text{Forward simulation: } \bar{g} \rightarrow}{\longleftrightarrow}} \begin{pmatrix} x_{\text{detector}} \\ r_{\text{detector}} \end{pmatrix}$$

[Bellagente, Butter, Kasieczka, Plehn, Rousselot, Winterhalder, Ardizzone, Kothe (2020)]

Conditional INN



- Generate probability distributions at the parton-level, given detector-level events x_{detector}

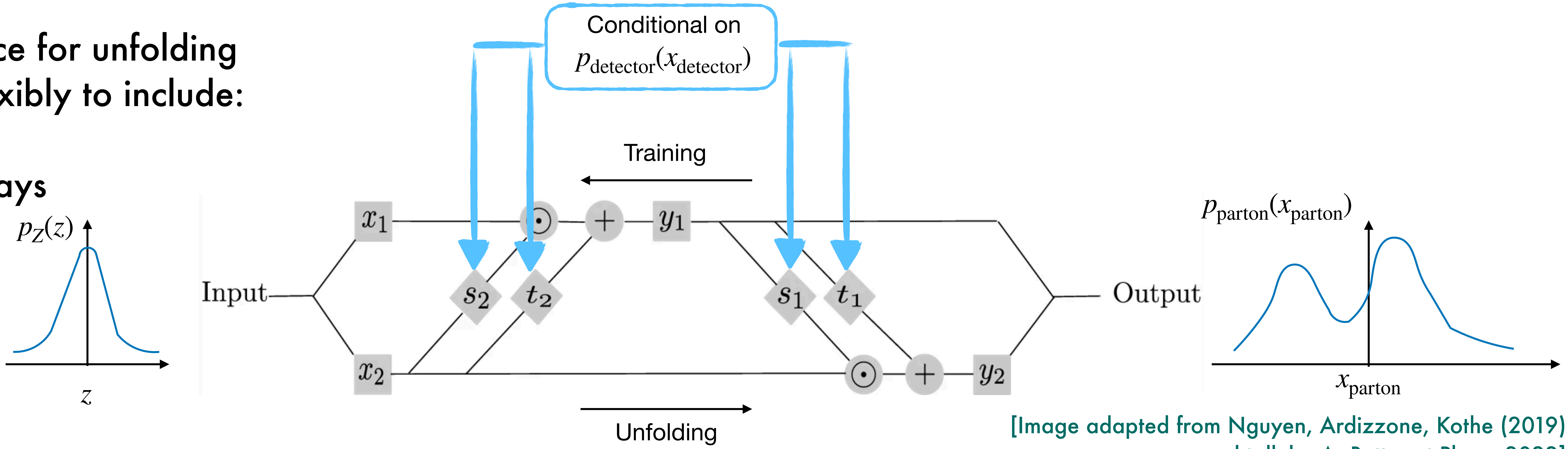
  $\longrightarrow$ Conditional on x_{detector}

  $\longrightarrow$ x_{parton} mapped with r

[Bellagente, Butter, Kasieczka, Plehn, Rousselot, Winterhalder, Ardizzone, Kothe (2020)]

Target phase space for unfolding can be chosen flexibly to include:

- jet radiation
- Particle decays



[Image adapted from Nguyen, Ardizzone, Kothe (2019) and talk by A. Butter at Pheno-2022]

- We use the Bayesian version of cINN
  - Stable network predictions
  - Allows the estimation of training-related uncertainties.

[Butter, Heimel, Hummerich, Krebs, Plehn, Rousselot, Vent (2021)]

Case study: CP measurement in Higgs-top interactions

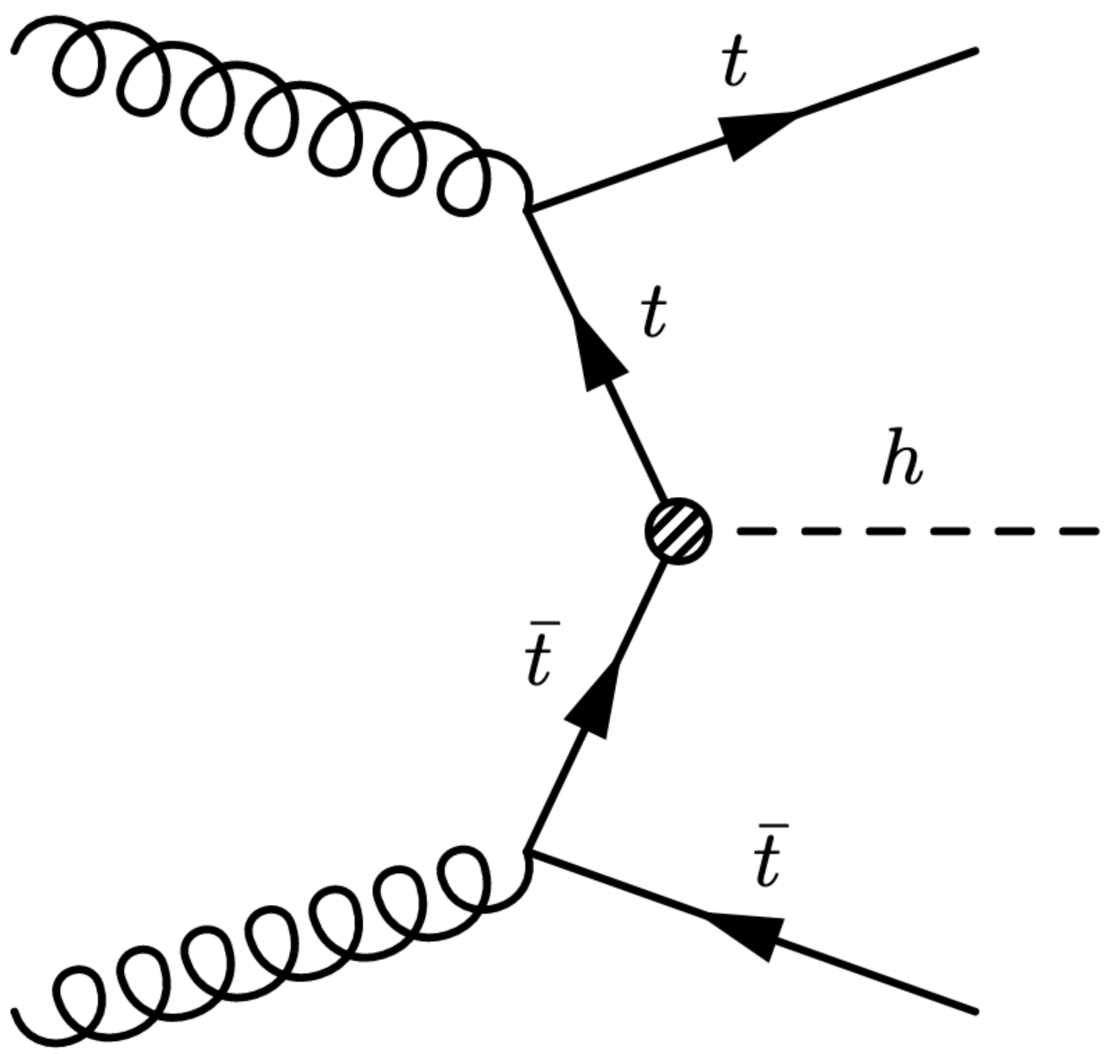
- New sources of CPV interactions can explain the baryon asymmetry in the universe.

- CPV in hVV interactions is extensively tested at the LHC

[Englert, Goncalves, Mawatari, Plehn (2012)]
[Djouadi, Godbole, Mellado, Mohan (2013)]
[Anderson, Bolognesi, Caola, Gao et al. (2013)]

- CPV in $hf\bar{f}$ couplings manifest at tree-level:
  → desirable choice: $ht\bar{t}$

$$\boxed{\mathscr{L} = -\frac{m_t}{v}\,\kappa_t\, h\, \bar{t}\,(\cos\alpha\ +\ i\,\gamma_5\ \sin\alpha)\, t}$$



- $pp \to h$ $(+\ \text{jets})$: indirect constraints.

[Brod, Haisch, Zupan (2013)]
[Dolan, Harris, Jankowiak, Spannowsky (2014)]

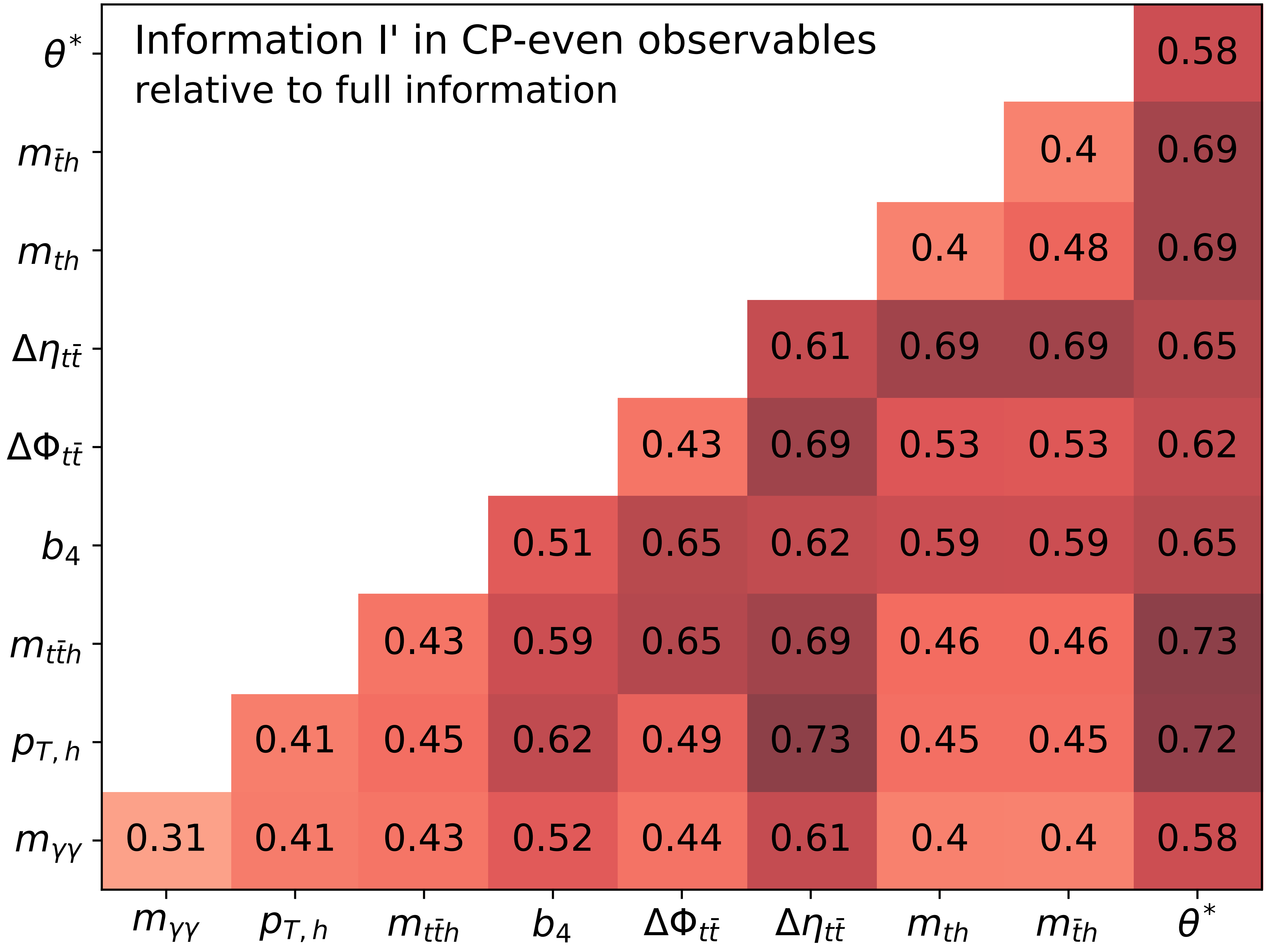
- $pp \to t\bar{t}h$: opportunity to directly probe α and κ_t

[Boudjema, Godbole, Guadagnoli, Mohan (2015)]
[Buckley, Goncalves (2016)]
[Azevedo, Onofre, Filthaut, Goncalo (2017)]

Current limit (ATLAS: 2004.04545):
$|\alpha| < 43^0$ at $95\ \%$ CL

Improved statistics @ HL-LHC paves the pathway for precision studies.

$t\bar{t}(h \to \gamma\gamma)$ @ HL-LHC



Importance matrix at the **non-linear level** computed using Fisher Information metric

[RKB, Goncalves, Kling (2021)]

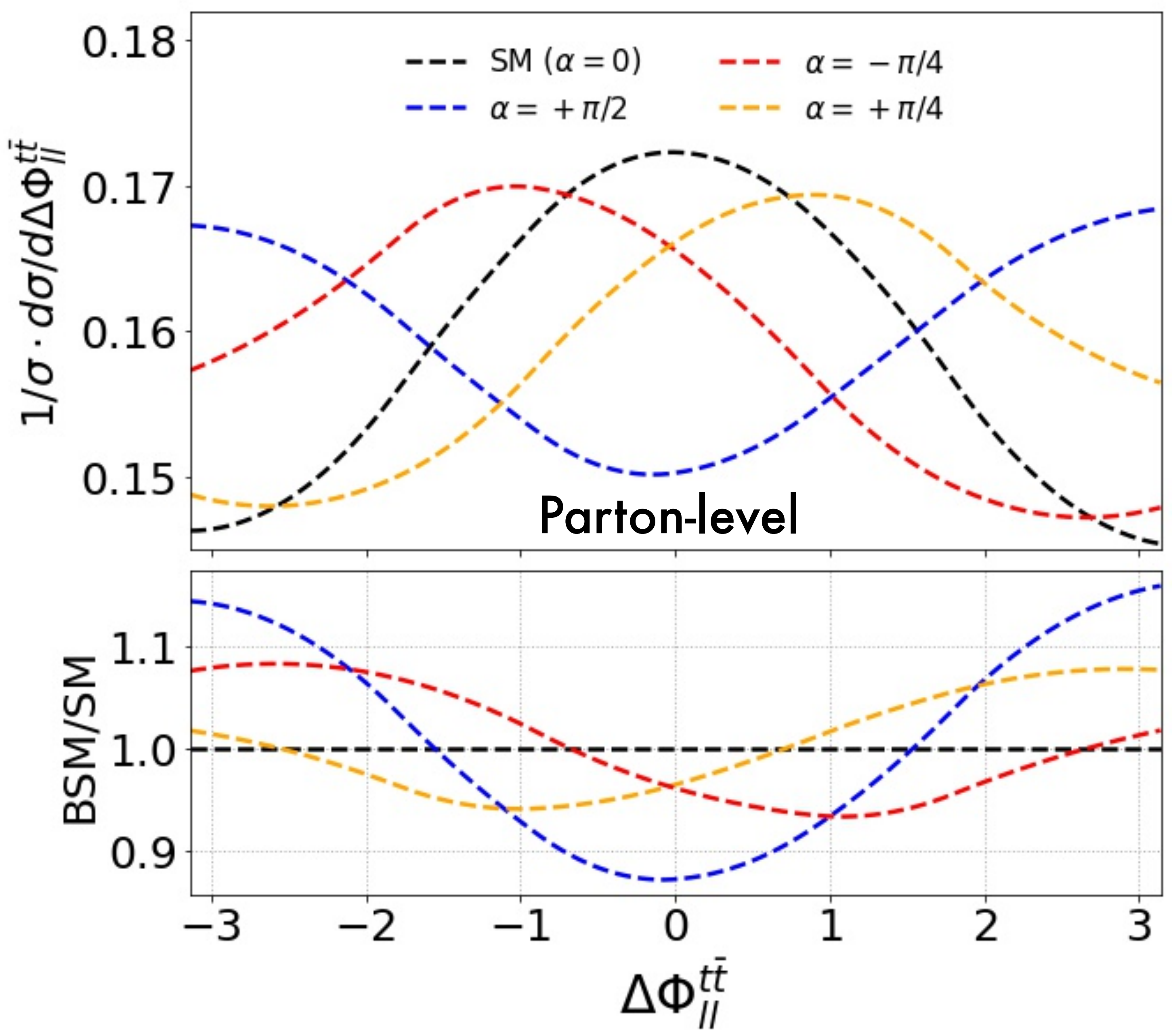
Sensitive only to non-linear new physics effects.

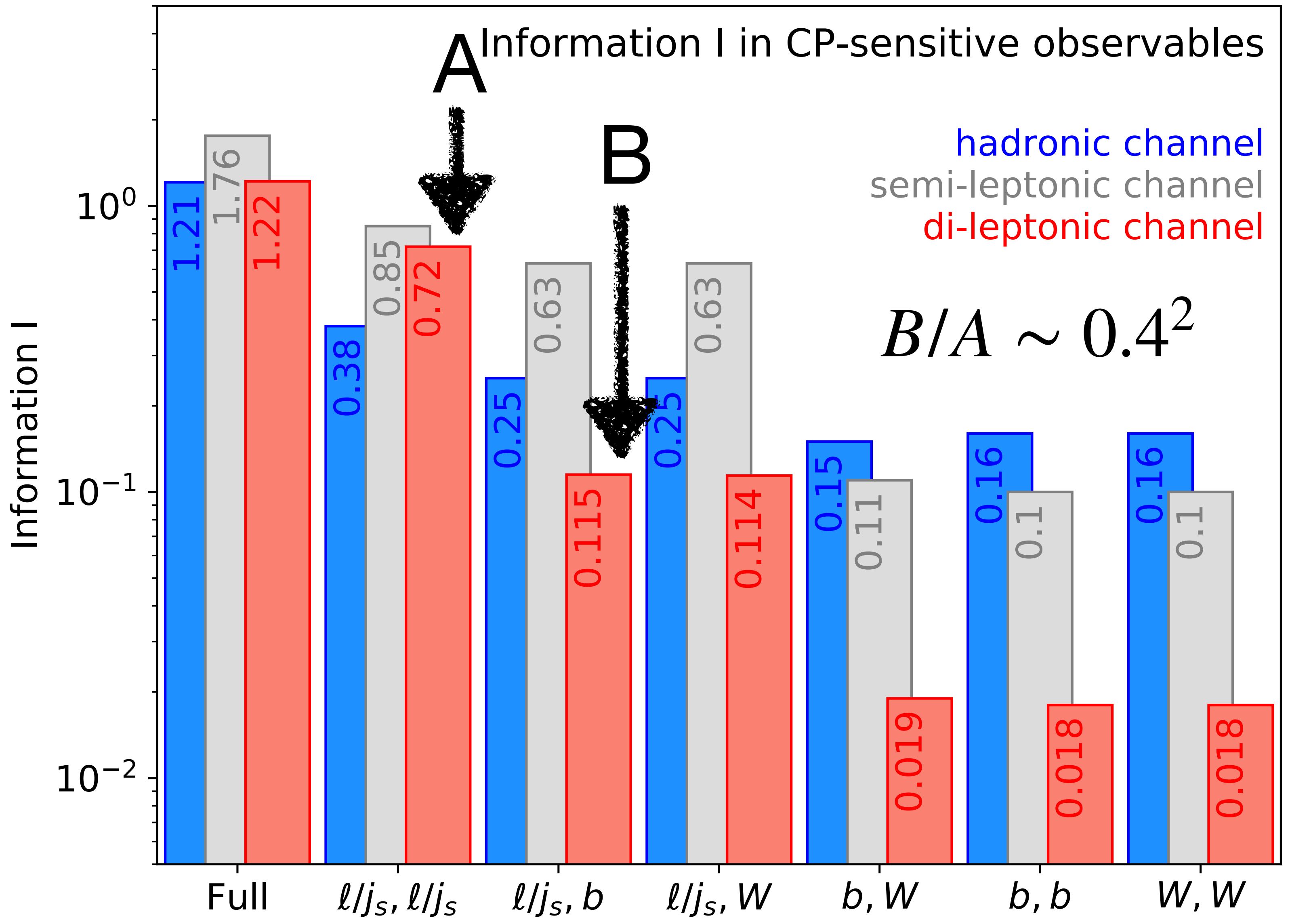
CP-odd observables

- Short lifetime for t $(10^{-25}$ $s)$ $\rightarrow$ Spin correlations can be traced back from their decay products.

- CP-odd observables constructed from antisymmetric tensor products
  $\epsilon(p_t, p_{\bar{t}}, p_i, p_j) \sim \epsilon_{\mu\nu\rho\sigma} p_t^\mu p_{\bar{t}}^\nu p_i^\rho p_j^\sigma$:

$$\Delta\phi_{ij}^{t\bar{t}} = \textbf{sgn}\left[\vec{p}_t \cdot (\vec{p}_i \times \vec{p}_j)\right] \arccos\left[\frac{\vec{p}_t \times \vec{p}_i}{|\vec{p}_t \times \vec{p}_i|} \cdot \frac{\vec{p}_t \times \vec{p}_j}{|\vec{p}_t \times \vec{p}_j|}\right]$$





← Spin correlations scale with the spin analysing power β_i.

[Mileo, Kiers, Szynkman, Crane, Gegner (2016); Goncalves, Kong, Kim (2018)]; RKB, Goncalves, Kling (2021)]

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\xi_i} = \frac{1}{2}\left(1 + \beta_i P_t \cos\xi_i\right) \qquad \text{Fisher Info} = \mathbb{E}\left[\frac{\partial \log \mathrm{p}(\mathrm{x}\,|\,\kappa_t, \alpha)}{\mathrm{d}\alpha}\frac{\partial \log \mathrm{p}(\mathrm{x}\,|\,\kappa_t, \alpha)}{\mathrm{d}\alpha}\right]$$

- Kinematic reconstruction efficiency is limited at the detector level

Use Machine learning techniques to maximize the extraction of NP information from depleted CP-odd and CP-even observables.

Event parametrization

- In the training data, event information at the parton level can be parametrised through the 4-momentum of the final state particles
  → may include redundant d.o.f.

- Reconstruction of sharp intermediate mass peaks can be improved by adding maximum mean discrepancy between the truth and generated distributions in the loss function.

[Butter, Plehn, Winterhalder (2019)]
[Bellagente, Butter, Kasieczka, Plehn, Rousselot, Winterhalder, Ardizzone, Kothe (2020)]

  - ☑ Affects only the target distributions
  - ☑ Avoids large model dependence
  - ☒ Complications in training and performance limitations.

- Alternative approach:

→ invariant mass features can be learnt directly with appropriate phase-space parametrization.
→ also provide direct access to the most important CP-even and CP-odd observables.

$$\vec{p}_{t\bar{t}}, m_{t_\ell}, |\vec{p}^{\,\mathrm{CS}}_{t_\ell}|, \theta^{\mathrm{CS}}_{t_\ell}, \phi^{\mathrm{CS}}_{t_\ell}, m_{t_h},$$
$$\mathrm{sign}(\Delta\phi^{t\bar{t}}_{\ell\nu})\, m_{W_\ell}\, |\vec{p}^{\,t\bar{t}}_{\ell}|, \theta^{t\bar{t}}_{\ell}, \phi^{t\bar{t}}_{\ell}, |\vec{p}^{\,t\bar{t}}_{\nu}|$$
$$\mathrm{sign}(\Delta\phi^{t\bar{t}}_{du})\, m_{W_h}, |\vec{p}^{\,t\bar{t}}_{d}|, \theta^{t\bar{t}}_{d}, \Delta\phi^{t\bar{t}}_{\ell d}, |\vec{p}^{\,t\bar{t}}_{u}|$$

Unfolding $t\bar{t}h$ events

Training dataset: Parton-level: $(t \to \ell \nu b)(\bar{t} \to jj\bar{b})(h \to \gamma\gamma)$

Detector-level: $1\ell + 2b + 2\gamma + MET +$ 2 jet

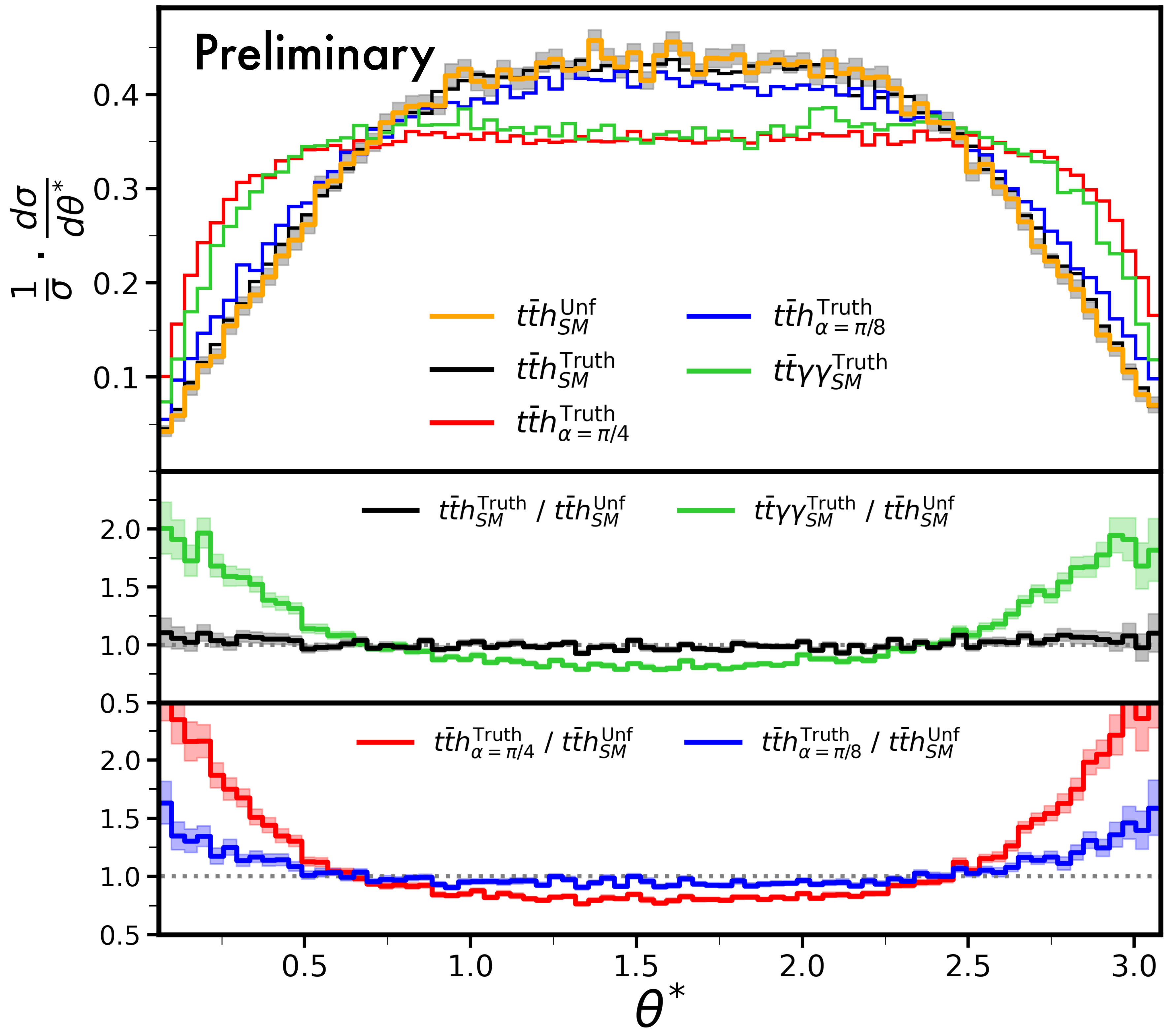
$\leq$ 3 jet inclusive

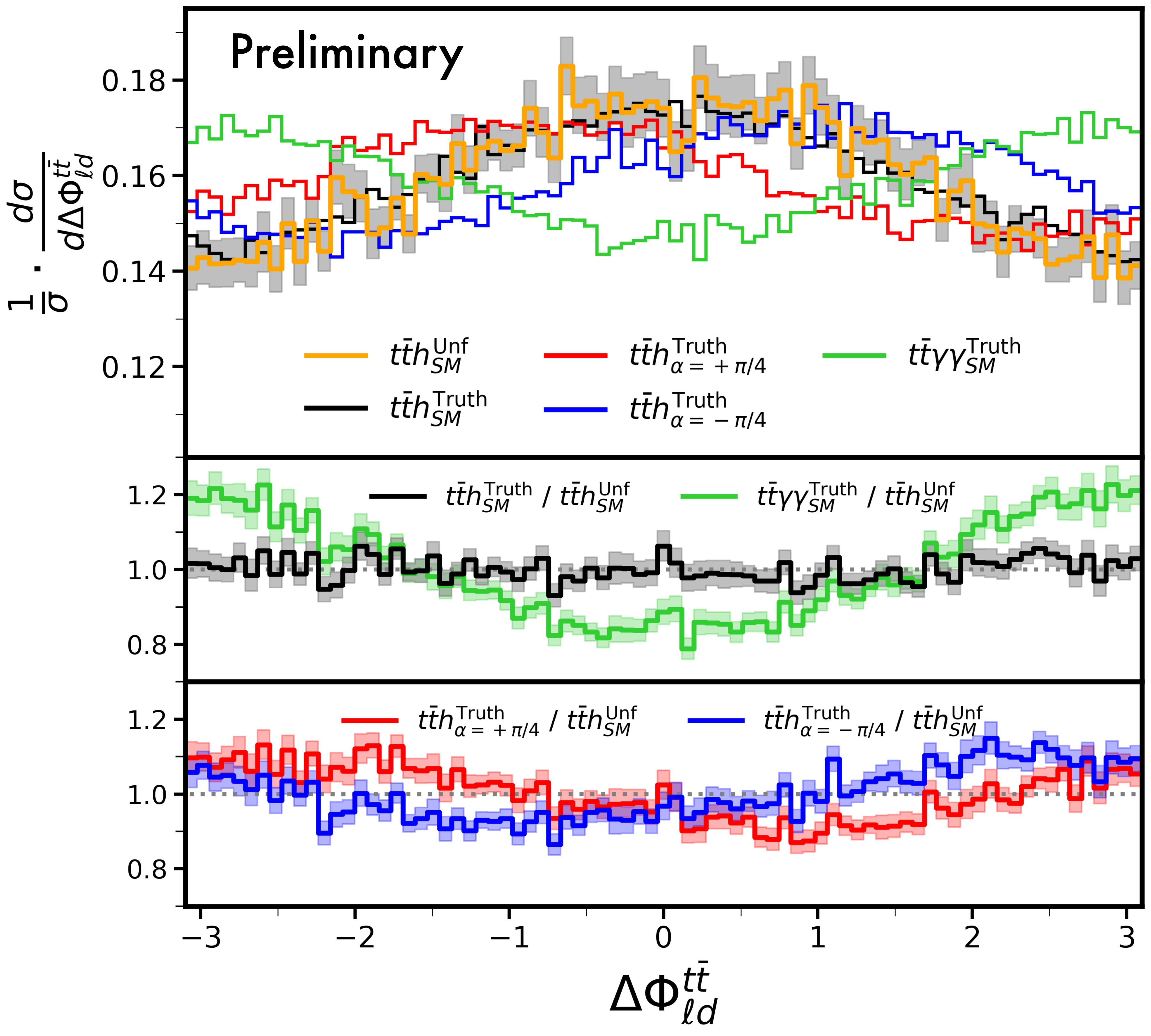
$\leq$ 4 jet inclusive

$\leq$ 5 jet inclusive

Unfolding $t\bar{t}h$ events

Trained on SM $pp \to (t \to \ell\nu b)(\bar{t} \to jj\bar{b})(h \to \gamma\gamma)$ + with upto 4 additional jets





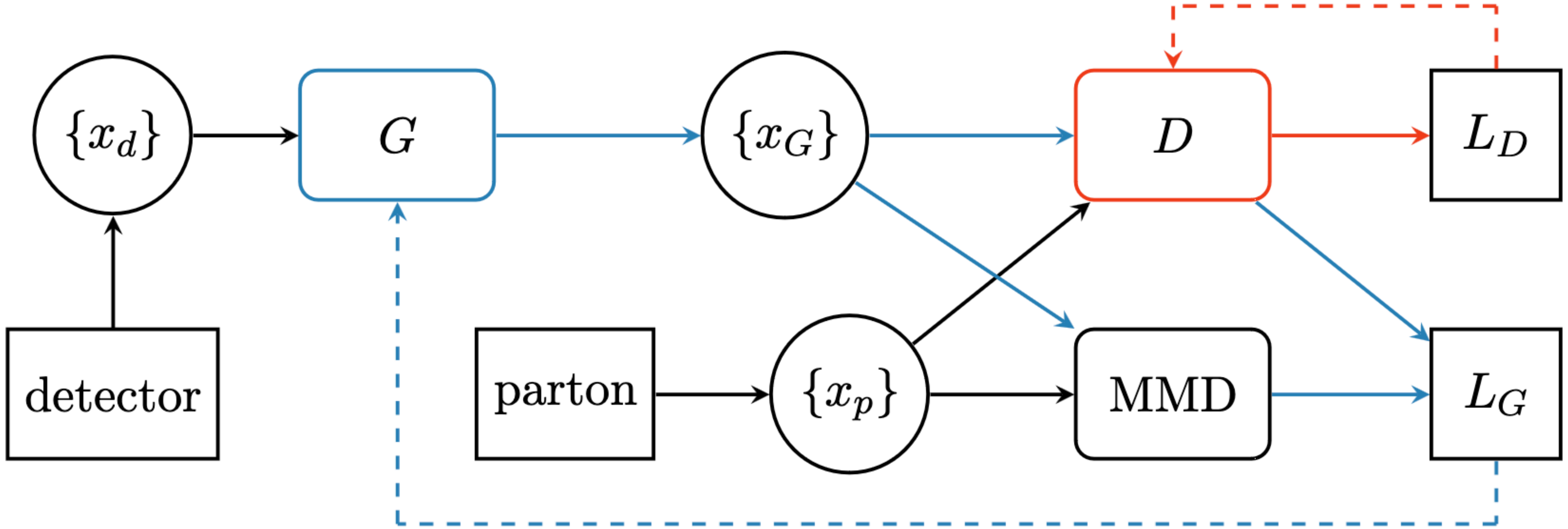
Outlook

- Full inversion to the hard-scattering level ..
- Towards precision studies with unfolding ..
- Explore model dependence of the unfolding setup ..

Back up slides

Unfolding with GANs

[Bellagente, Butter, Kasieczka, Plehn, Winterhalder(2019)]
[Butter, Plehn, Winterhalder(2019)]



[Image from Bellagente, Butter, Kasieczka, Plehn, Winterhalder (2019)]

$$L_{\text{Discriminator}} = \langle -logD(x) \rangle_{x \sim P_p} + \langle -log(1 - D(x)) \rangle_{x \sim P_G}$$

$$L_{\text{Generator}} = \langle -logD(x) \rangle_{x \sim P_G}$$

Event parametrization

- For $pp \to (t_\ell \to W_\ell b_\ell)\,(\bar{t}_h \to udb_h)\,h$, a typical parametrisation could be:

$$\left\{\; m_t, p_{T,t}, \eta_t, \phi_t, m_W, \eta^t_W, \phi^t_W, \eta^W_{\ell,u}, \phi^W_{\ell,u} \;\right\}$$

  - Can reproduce the intermediate mass distributions.
  - Limited spin-correlation information.

- Alternatively, provide direct access to the most important CP-even and CP-odd observables:

$$\vec{p}_{t\bar{t}}, m_{t_\ell}, |\vec{p}^{\,\mathrm{CS}}_{t_\ell}|, \theta^{\mathrm{CS}}_{t_\ell}, \phi^{\mathrm{CS}}_{t_\ell}, m_{t_h},$$
$$\mathrm{sign}(\Delta\phi^{t\bar{t}}_{\ell\nu})\, m_{W_\ell} |\vec{p}^{\,t\bar{t}}_\ell|, \theta^{t\bar{t}}_\ell, \phi^{t\bar{t}}_\ell, |\vec{p}^{\,t\bar{t}}_\nu|$$
$$\mathrm{sign}(\Delta\phi^{t\bar{t}}_{du})\, m_{W_h}, |\vec{p}^{\,t\bar{t}}_d|, \theta^{t\bar{t}}_d, \Delta\phi^{t\bar{t}}_{\ell d}, |\vec{p}^{\,t\bar{t}}_u|$$