Invertible Networks for Unfolding

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Universität Heidelberg

CMS Unfolding 2/2021

How to GAN away detector effects

Goal: invert standard simulation [Bellagente, Butter, Kasiczka, TP, Winterhalder]

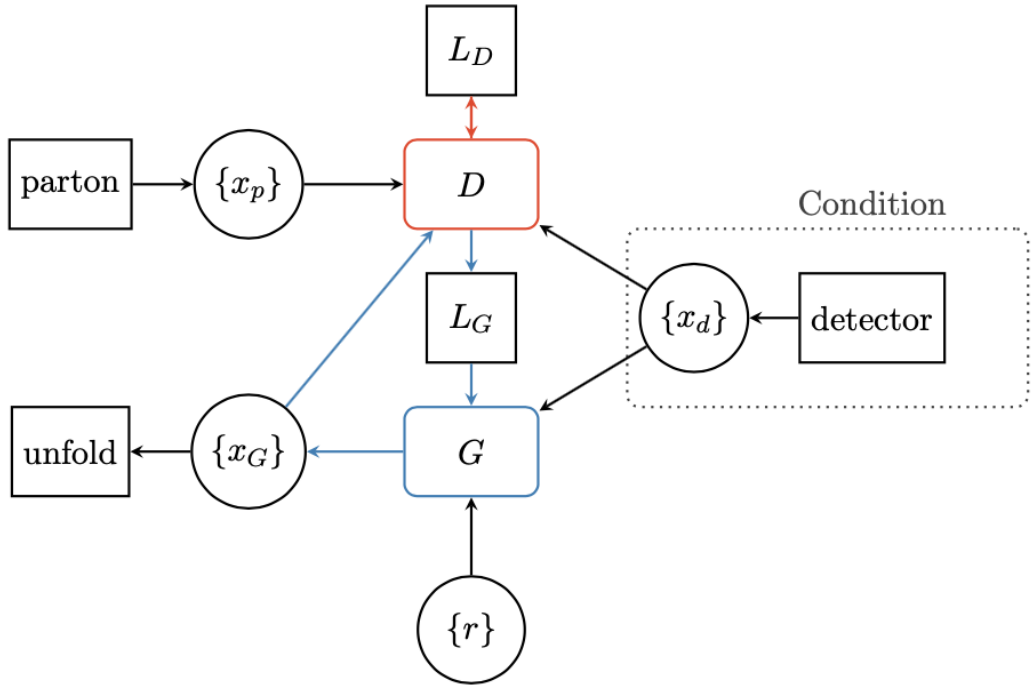
- detector simulation typical Monte Carlo, random-number-driven
- inversion possible, in principle [MEM, but entangled convolutions]
- GAN task

  partons $\xrightarrow{\text{DELPHES}}$ detector $\xrightarrow{\text{GAN}}$ partons

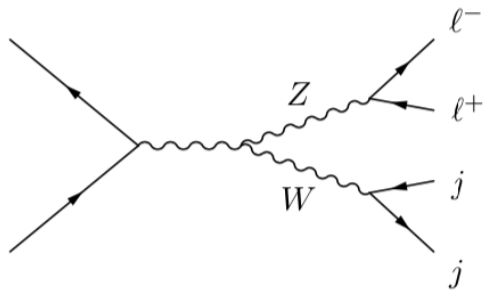
$\Rightarrow$ Full phase space unfolded

Conditional GAN

- random numbers to parton level
  hadron level as condition
  matched event pairs



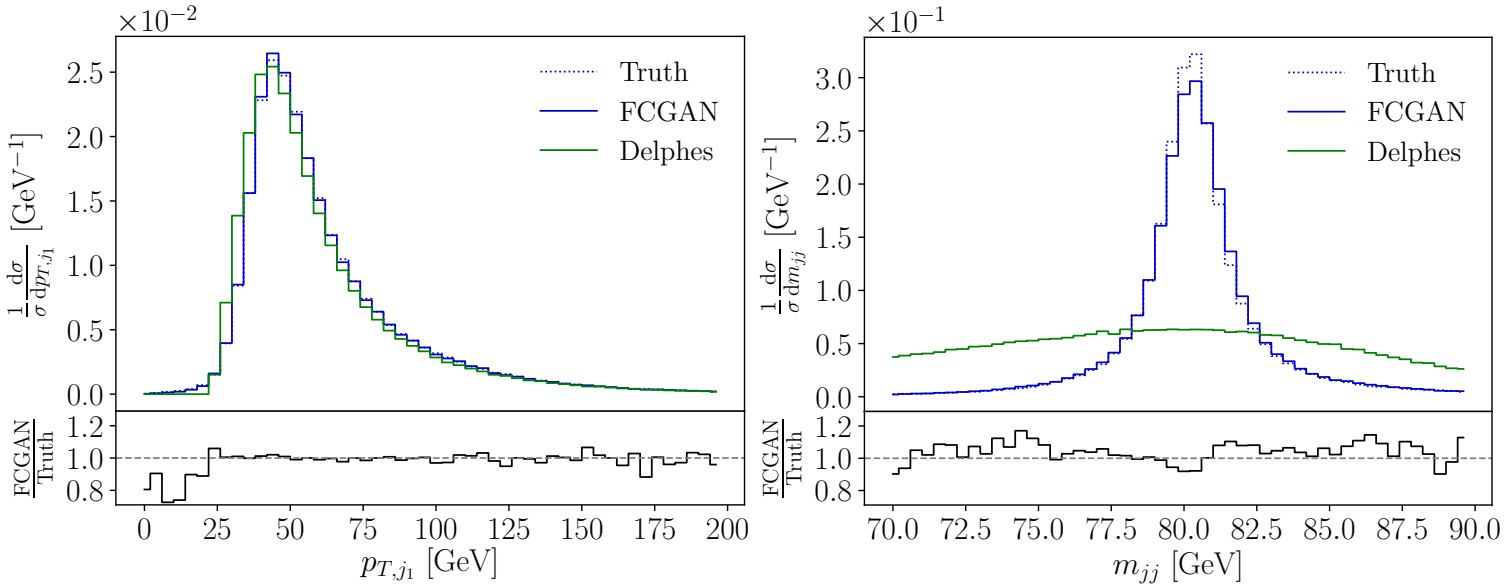
Detector unfolding



Reference process $pp \to ZW \to (\ell\ell)\,(jj)$

- broad jj mass peak
  narrow $\ell\ell$ mass peak
  modified $2 \to 2$ kinematics
  fun phase space boundaries
- GAN same as event generation [with MMD]

Model (in)dependence



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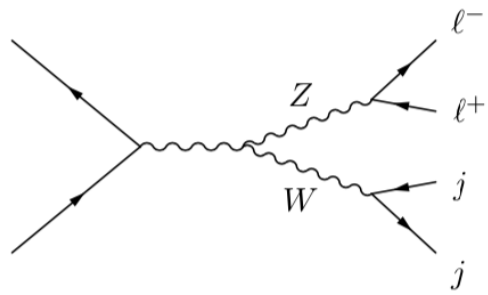

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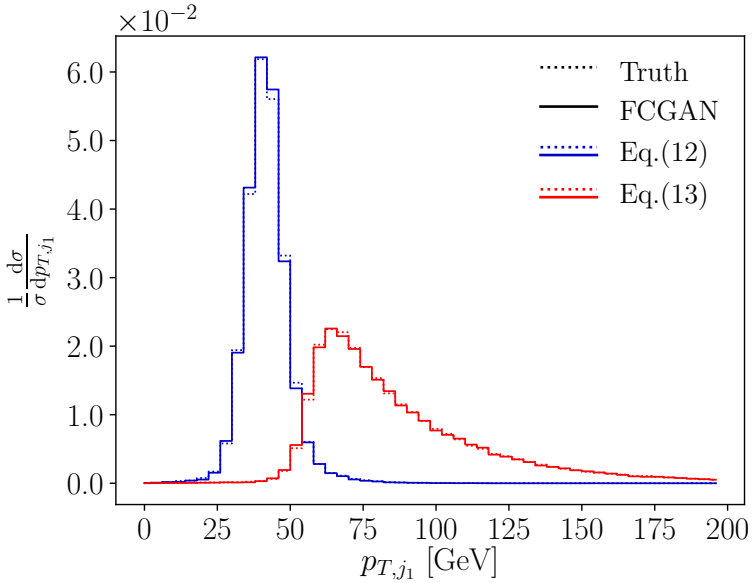
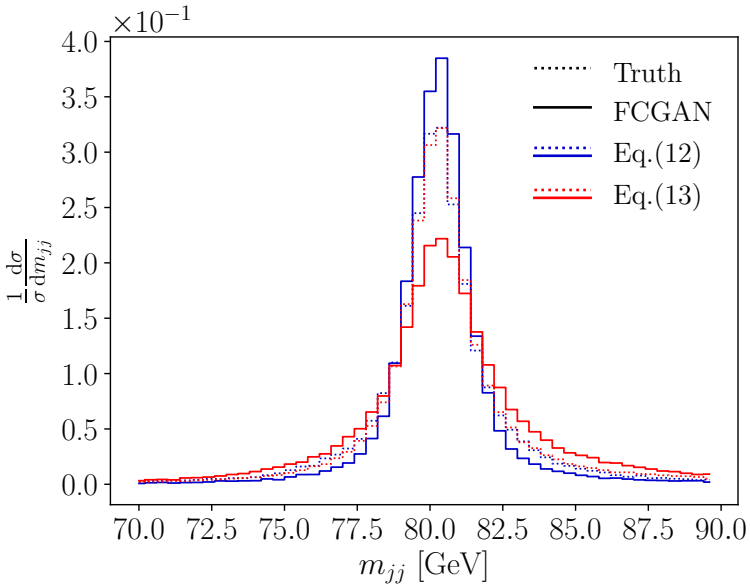
Model (in)dependence

- detector-level cuts [14%, 39% events, no interpolation, MMD not conditional]

$$p_{T,j_1} = 30 \ldots 50 \text{ GeV} \quad p_{T,j_2} = 30 \ldots 40 \text{ GeV} \quad p_{T,\ell^-} = 20 \ldots 50 \text{ GeV} \tag{12}$$

$$p_{T,j_1} > 60 \text{ GeV} \tag{13}$$





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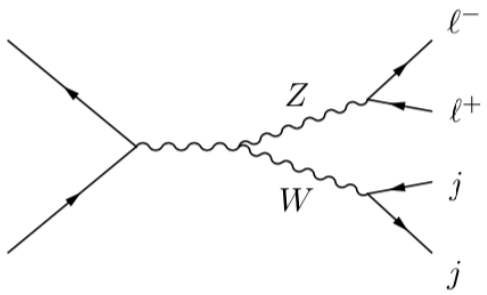

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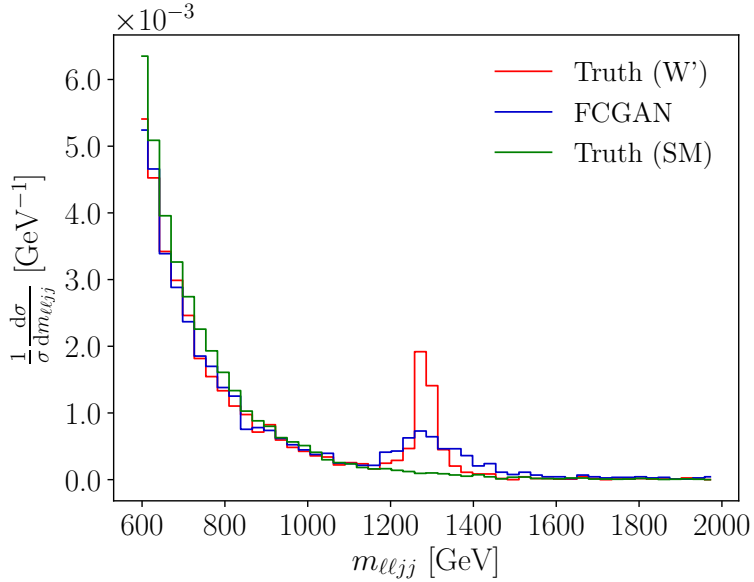
- model dependence of unfolding
- train: SM events
  test: 10% events with W' in s-channel

$\Rightarrow$ Working fine, but ill-defined



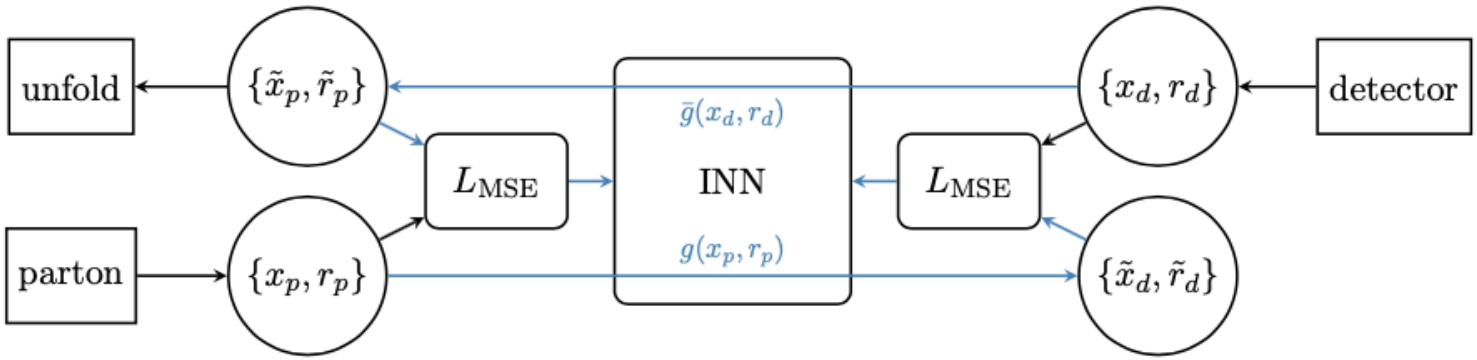
Invertible networks

Standard invertible networks [Bellagente, Butter, Kasieczka, TP, Rousselot, Winterhalder, Ardizzone, Köthe]

- network as bijective transformation — normalizing flow
  Jacobian tractable [specifically: coupling layer]
  evaluation in both directions — INN [Ardizzone, Rother, Köthe]
- mapping parton and detector phase spaces
  padding with random numbers [eINN, dimensionality, sampling for poor]

$$\begin{pmatrix} x_p \\ r_p \end{pmatrix} \xleftarrow[\leftarrow \text{unfolding:} \bar{g}]{\text{PYTHIA,DELPHES:} g \rightarrow} \begin{pmatrix} x_d \\ r_d \end{pmatrix}$$

- training on event pairs (MSE) or samples (MMD) [thank you to Jessica]



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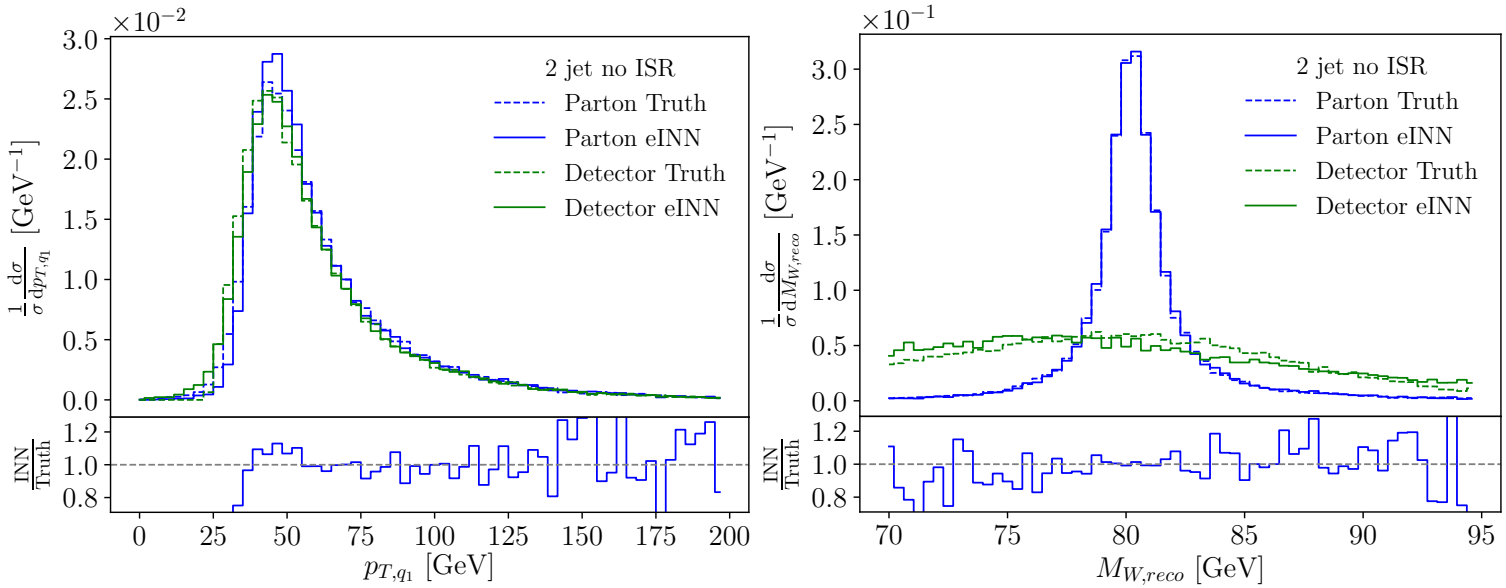

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$\Rightarrow$ Working okay, still ill-defined

Proper inverting with cINN

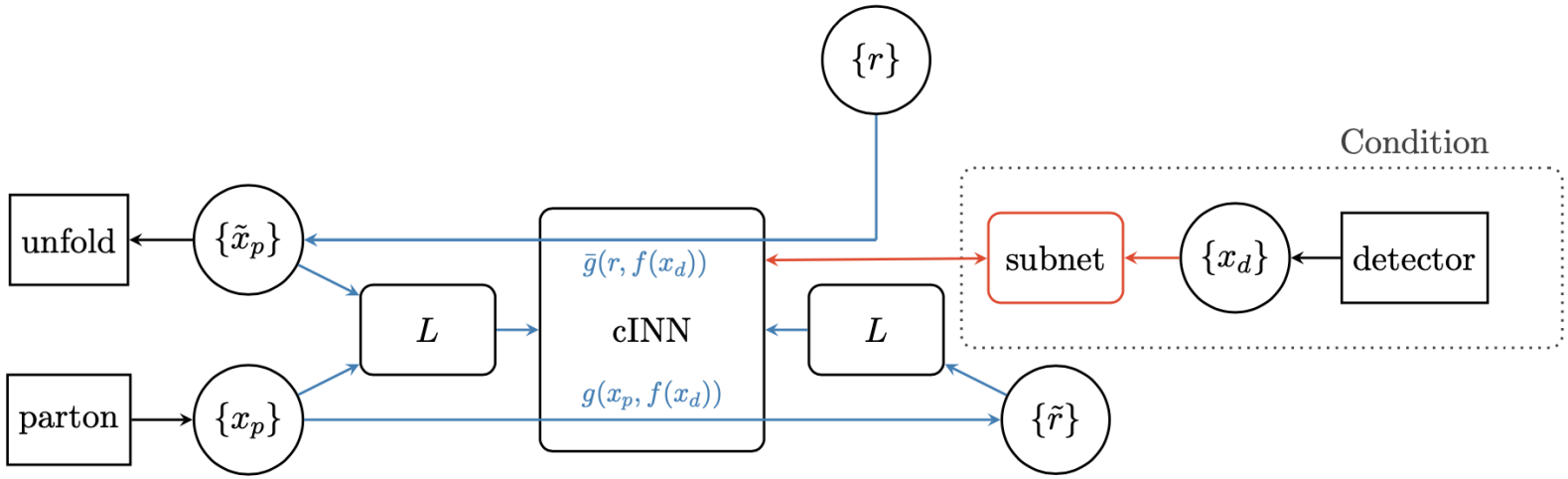
Statistical inversion [Bellagente, Butter, Kasieczka, TP, Rousselot, Winterhalder, Ardizzone, Köthe]

– task: construct parton-level pdf for (single) detector-level event

1- conditional INN: parton-level events from $\{r\}$

2- maximum likelihood loss

$$
\begin{aligned}
L &= -\langle \log p(\theta|x_p, x_d) \rangle_{x_p, x_d} \\
&\approx -\left\langle \log p(g(x_p, x_d)) + \log \left| \frac{\partial g(x_p, x_d)}{\partial x_p} \right| \right\rangle_{x_p, x_d} - \log p(\theta) \\
&= -\left\langle -\frac{||g(x_p, x_d))||_2^2}{2} + \log \left| \frac{\partial g(x_p, x_d)}{\partial x_p} \right| \right\rangle_{x_p, x_d} - \log p(\theta)
\end{aligned}
$$



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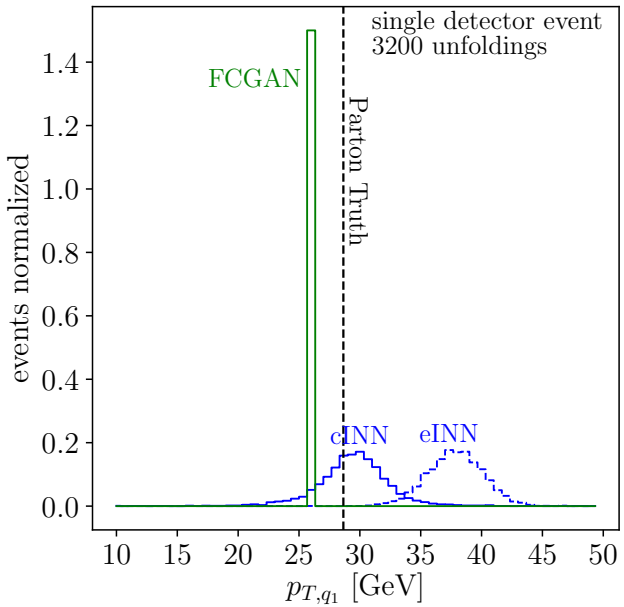
– performance like FCGAN

– distribution: single pair (x_p, x_d), unfolded many times [FCGAN is out]



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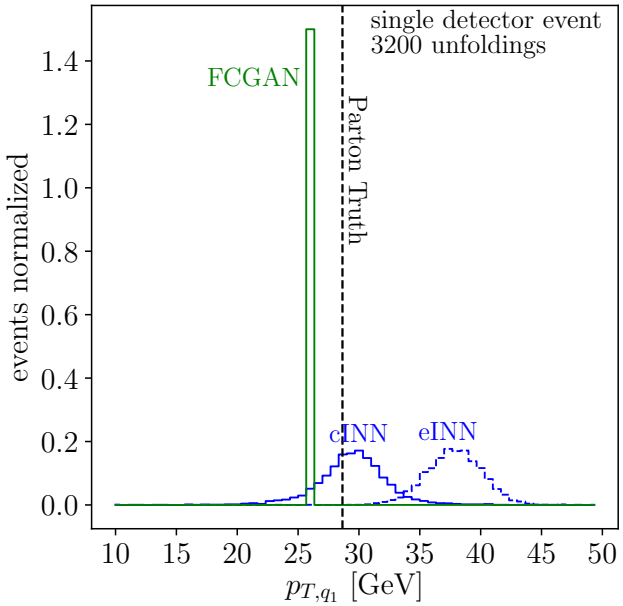
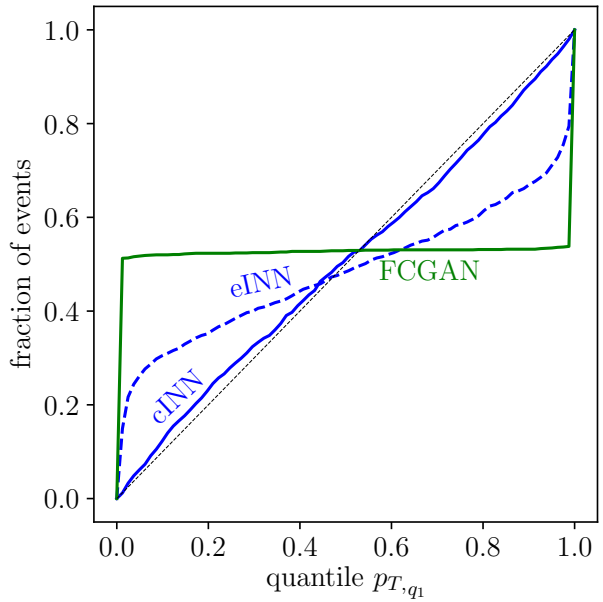
– performance like FCGAN

– distribution: single pair (x_p, x_d), unfolded many times [FCGAN is out]

– calibration: 1500 pairs (x_p, x_d), each unfolded 60 times, check for truth

$\Rightarrow$ cINN well-defined!

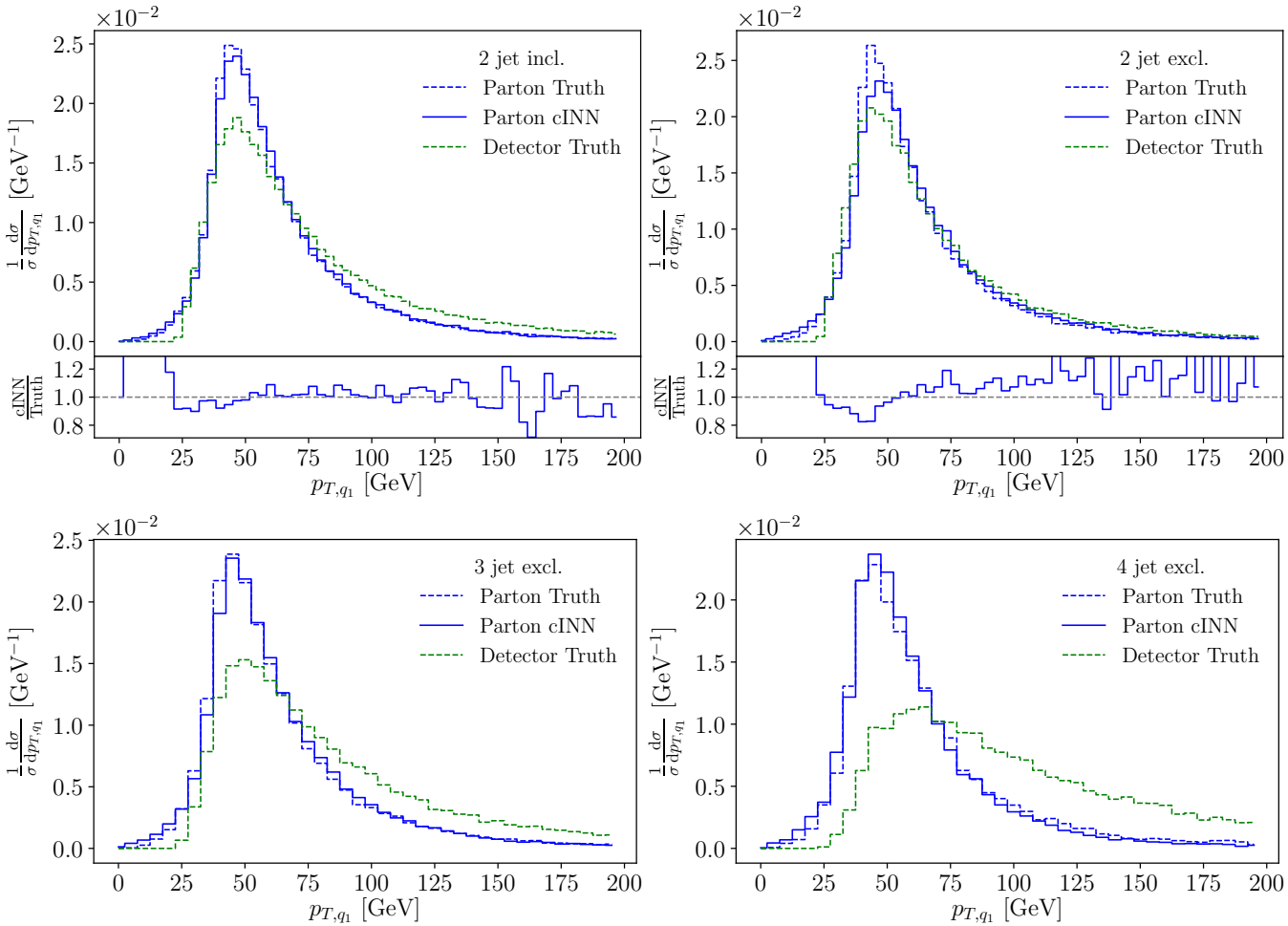




Inverting to hard process

What theorists want: unfolding ISR

- detector-level process $pp \to ZW$+jets [variable number of objects]
- ME vs PS jets decided by network
- training jet-inclusively or jet-exclusively
  parton-level hard process extracted as $2 \to 2$



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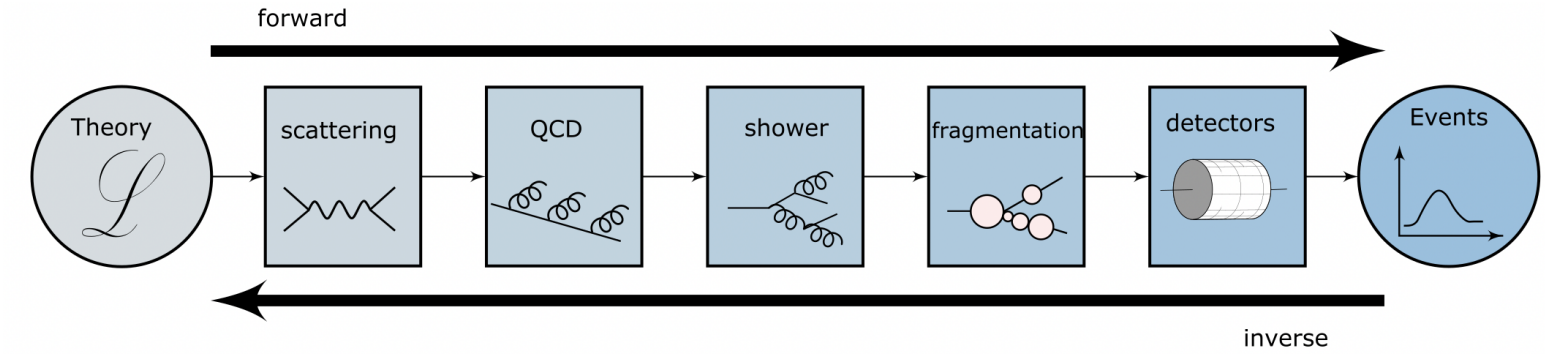
Towards systematic inversion

- detector unfolding on way
- QCD parton from jet algorithm standard
- jet radiation possible

$\Rightarrow$ Hard matrix element a proper goal?



Things are moving

Machine learning for LHC theory

- big data for fundamental physics
- GANs the cool kid
- INNs the theory hope
- Full inversion in reach?