

# VINCIA for Hadron Colliders

based on Fischer, Prestel, Ritzmann, Skands – arXiv:1605.06142

Nadine Fischer - August 23rd, 2016

MONASH UNIVERSITY & LUND UNIVERSITY



Australian Government  
Australian Research Council





Conference title: Faced with QCD, QCD, QCD, ... @ the LHC

⇒ use best model for QCD

Predict the full final-state kinematics for data-theory comparisons

⇒ use Monte Carlo Event Generators

Fixed order matrix elements:

- Good for well-separated jets
- Limited number of jets

Parton showers:

- Good for soft and collinear emissions
- Only approximation of multi-jet states

Matching: Combine the two



Based on antenna factorization:

- of (squared) Amplitudes (exact in both the soft and collinear limits).
- of Phase Space ( $d\Phi_{n+1} = d\Phi_{\text{ant}} d\Phi_n$ , with exact momentum conservation).

Probability of **no** resolvable emission in the range  $[t_{\text{end}}, t_{\text{start}}]$ ,

$$\begin{aligned}\Pi_{t_{\text{end}}}^{t_{\text{start}}} &= \exp \left( - \int d\Phi_{\text{ant}} \alpha_s(t) \frac{f_{1'}(x_1', t)}{f_1(x_1, t)} \frac{f_{2'}(x_2', t)}{f_2(x_2, t)} a(t) \right) \\ &= \frac{f_1(x_1, t_{\text{end}})}{f_1(x_1, t_{\text{start}})} \frac{f_2(x_2, t_{\text{end}})}{f_2(x_2, t_{\text{start}})} \Delta_{t_{\text{end}}}^{t_{\text{start}}} \quad \text{with Sudakov factor } \Delta_{t_{\text{end}}}^{t_{\text{start}}}.\end{aligned}$$

- Radiation functions  $a(t)$
- Phase-Space Factorization  $\Rightarrow d\Phi_{\text{ant}}$
- Evolution variable  $t$

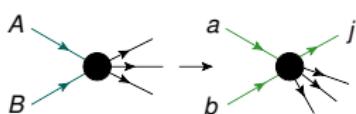
Generate all-order approximation iteratively, based on universal parts of amplitudes.

# Vincia: Antenna Shower

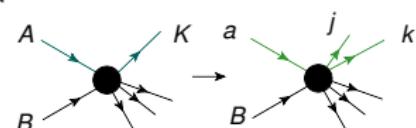


Ingredients for ISR shower:

- Radiation Functions  $a(s_{12}, s_{23}, s_{13})$  [Ritzmann, Kosower, Skands, Phys. Lett. B 718 (2013) 1345]
- Recoil Strategy  $\Rightarrow$  Phase-Space Factorization  $\Rightarrow d\Phi_{\text{ant}}$ :



Initial-Initial:



Initial-Final:

- Form of evolution variable  $t$  and complementary variable  $\zeta$ :

Initial-Initial:

Emission  
(double pole)

$$p_{\perp}^{\parallel} = \frac{s_{aj}s_{jb}}{s_{ab}}$$

$$\zeta^{\parallel} = \frac{s_{aj}}{s_{ab}}$$

Conversion  
(single pole)

$$t = s_{aj} \quad \text{or} \quad s_{jb}$$

Initial-Final:

$$p_{\perp}^{\text{IF}} = \frac{s_{aj}s_{jk}}{s_{AK} + s_{jk}}$$

$$\zeta^{\text{IF}} = \frac{s_{AK}}{s_{AK} + s_{jk}}$$

$$t = s_{aj} \quad \text{or} \quad s_{jk}$$

# Including LO matrix elements



The aim:

- Combine shower and matrix elements

The idea of Matrix-Element Corrections (MECs):

- Start from approximate all-order structure of the shower
- Impose higher orders LO matrix elements as finite multiplicative corrections
- Markovian setup for most efficient calculation
- Fill all of phase space

Other approaches:

- Parton showers are history-dependent and have dead zones
- Add different event samples
- Typically need precalculation of cross sections

# Matrix-Element Corrections for $pp \rightarrow Z + X$



Shower expansion:

$$\mathcal{S}_\mu^{t_{\text{fac}}} \left[ f_0(x_0, t_{\text{fac}}) |\mathcal{M}_Z|^2 d\Phi_Z \right] =$$

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$$f_0(x_0, \mu) \Delta_\mu^{t_{\text{fac}}} |\mathcal{M}_Z|^2 d\Phi_Z$$

no branching  $t_{\text{fac}} \rightarrow \mu$

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no branching  $t_{\text{fac}} \rightarrow \mu$

$$+ f_1(x_1, \mu) \Delta_\mu^{t_1} \alpha_s(t_1) a(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_Z|^2 d\Phi_{Zj}$$

branching at  $t_1$ , no branching  $t_1 \rightarrow \mu$

# Matrix-Element Corrections for $pp \rightarrow Z + X$



Shower expansion: MECs  $\mathcal{O}(\alpha_s)$

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$$f_0(x_0, \mu) \Delta_\mu^{t_{\text{fac}}} |\mathcal{M}_Z|^2 d\Phi_Z$$

no branching  $t_{\text{fac}} \rightarrow \mu$

$$+ f_1(x_1, \mu) \Delta_\mu^{t_1} \alpha_s(t_1) \color{blue}{a(t_1)} \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_Z|^2 d\Phi_{Zj} \cdot \frac{|\mathcal{M}_{Zj}|^2}{\sum a(t_1) |\mathcal{M}_Z|^2}$$

branching at  $t_1$ , no branching  $t_1 \rightarrow \mu$

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$$+ f_1(x_1, \mu) \Delta_\mu^{t_1} \alpha_s(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_{Zj}|^2 d\Phi_{Zj}$$

branching at  $t_1$ , no branching  $t_1 \rightarrow \mu$

$$+ f_2(x_2, \mu) \Delta_\mu^{t_2} \alpha_s(t_2) a(t_2) \Delta_{t_2}^{t_1} \alpha_s(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_{Zjj}|^2 d\Phi_{Zjj}$$

branching at  $t_1$  and  $t_2$ , no branching  $t_2 \rightarrow \mu$

# Matrix-Element Corrections for $pp \rightarrow Z + X$



Shower expansion: MECs  $\mathcal{O}(\alpha_s^2)$

$$\mathcal{S}_\mu^{t_{\text{fac}}} \left[ f_0(x_0, t_{\text{fac}}) |\mathcal{M}_Z|^2 d\Phi_Z \right] =$$

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no branching  $t_{\text{fac}} \rightarrow \mu$

$$+ f_1(x_1, \mu) \Delta_\mu^{t_1} \alpha_s(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_{Zj}|^2 d\Phi_{Zj}$$

branching at  $t_1$ , no branching  $t_1 \rightarrow \mu$

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$$+ f_1(x_1, \mu) \Delta_\mu^{t_1} \alpha_s(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_{Zj}|^2 d\Phi_{Zj}$$

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no branching  $t_{\text{fac}} \rightarrow \mu$

$$+ f_1(x_1, \mu) \Delta_\mu^{t_1} \alpha_s(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_{Zj}|^2 d\Phi_{Zj}$$

branching at  $t_1$ , no branching  $t_1 \rightarrow \mu$

$$+ f_2(x_2, \mu) \Delta_\mu^{t_2} \alpha_s(t_2) \Delta_{t_2}^{t_1} \alpha_s(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_{Zjj}|^2 d\Phi_{Zjj}$$

branching at  $t_1$  and  $t_2$ , no branching  $t_2 \rightarrow \mu$

$$+ \mathcal{S}_\mu^{t_3} \left[ f_3(x_3, t_3) \alpha_s(t_3) a(t_3) \Delta_{t_3}^{t_2} \alpha_s(t_2) \Delta_{t_2}^{t_1} \alpha_s(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_{Zjjj}|^2 d\Phi_{Zjjj} \right]$$

branching at  $t_1$ ,  $t_2$  and  $t_3$

# Matrix-Element Corrections for $pp \rightarrow Z + X$



Shower expansion: MECs  $\mathcal{O}(\alpha_s^3)$

$$\mathcal{S}_\mu^{t_{\text{fac}}} \left[ f_0(x_0, t_{\text{fac}}) |\mathcal{M}_Z|^2 d\Phi_Z \right] =$$

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no branching  $t_{\text{fac}} \rightarrow \mu$

$$+ f_1(x_1, \mu) \Delta_\mu^{t_1} \alpha_s(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_{Zj}|^2 d\Phi_{Zj}$$

branching at  $t_1$ , no branching  $t_1 \rightarrow \mu$

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branching at  $t_1$ ,  $t_2$  and  $t_3$

$$\cdot \frac{|\mathcal{M}_{Zjjj}|^2}{\sum a(t_3) |\mathcal{M}_{Zjj}|^2}$$

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no branching  $t_{\text{fac}} \rightarrow \mu$

$$+ f_1(x_1, \mu) \Delta_\mu^{t_1} \alpha_s(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_{Zj}|^2 d\Phi_{Zj}$$

branching at  $t_1$ , no branching  $t_1 \rightarrow \mu$

$$+ f_2(x_2, \mu) \Delta_\mu^{t_2} \alpha_s(t_2) \Delta_{t_2}^{t_1} \alpha_s(t_1) \Delta_{t_1}^{t_{\text{fac}}} |\mathcal{M}_{Zjj}|^2 d\Phi_{Zjj}$$

branching at  $t_1$  and  $t_2$ , no branching  $t_2 \rightarrow \mu$

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no branching  $t_{\text{fac}} \rightarrow \mu$

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branching at  $t_1$ , no branching  $t_1 \rightarrow \mu$

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branching at  $t_1$ ,  $t_2$  and  $t_3$

# Filling all of Phase Space: First emission



Diff Born **inclusive**  $\sigma$ :  $d\sigma_{\text{Born}}^{\text{incl}}(t_{\text{fac}}) = f_0(x_0, t_{\text{fac}}) |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$

Diff Born **exclusive**  $\sigma$ :  $d\sigma_{\text{Born}}^{\text{excl}}(\mu) = \Pi_{\mu}^{t_{\text{start}}} f_0(x_0, t_{\text{fac}}) |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$

$$= \frac{f_0(x_0, \mu)}{f_0(x_0, t_{\text{start}})} f_0(x_0, t_{\text{fac}}) \Delta_{\mu}^{t_{\text{start}}} |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$$

# Filling all of Phase Space: First emission



$$\text{Diff Born inclusive } \sigma: d\sigma_{\text{Born}}^{\text{incl}}(t_{\text{fac}}) = f_0(x_0, t_{\text{fac}}) |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$$

$$\begin{aligned}\text{Diff Born exclusive } \sigma: d\sigma_{\text{Born}}^{\text{excl}}(\mu) &= \Pi_{\mu}^{t_{\text{start}}} f_0(x_0, t_{\text{fac}}) |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}} \\ &= \frac{f_0(x_0, \mu)}{f_0(x_0, t_{\text{start}})} f_0(x_0, t_{\text{fac}}) \Delta_{\mu}^{t_{\text{start}}} |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}\end{aligned}$$

Different methods to fill all of phase space for the first emission in e.g.  $Z$  production:

- Power shower (e.g. PYTHIA):  $t_{\text{start}} = t_{\text{max}}$   
⇒  $d\sigma_{\text{Born}}^{\text{excl}}(\mu)$  with leftover PDF ratio  $f_0(x_0, t_{\text{fac}})/f_0(x_0, t_{\text{max}})$ .
- Clever evolution variable (e.g. DIRE):  $t_{\text{start}} = t_{\text{max}} = t_{\text{fac}}$   
⇒  $d\sigma_{\text{Born}}^{\text{excl}}(\mu) = f_0(x_0, \mu) \Delta_{\mu}^{t_{\text{fac}}} |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$
- Note: both methods leave inclusive  $\sigma$  untouched.



# Filling all of Phase Space: First emission

$$\text{Diff Born inclusive } \sigma: d\sigma_{\text{Born}}^{\text{incl}}(t_{\text{fac}}) = f_0(x_0, t_{\text{fac}}) |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$$

$$\text{Diff Born exclusive } \sigma: d\sigma_{\text{Born}}^{\text{excl}}(\mu) = \frac{f_0(x_0, \mu)}{f_0(x_0, t_{\text{start}})} f_0(x_0, t_{\text{fac}}) \Delta_\mu^{t_{\text{start}}} |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$$

Our method: Divide events in two samples.

- First sample: Start shower at  $t_{\text{start}} = t_{\text{fac}}$
- Second sample: Reweight with  $f_0(x_0, t_{\text{max}})/f_0(x_0, t_{\text{fac}})$

Start shower  $t_{\text{start}} = t_{\text{max}}$

Veto if no emission with  $t > t_{\text{fac}}$

$$\begin{aligned} d\sigma_{\text{Born}}^{\text{incl}}(t_{\text{fac}}) &= d\sigma_{\text{Born}}^{\text{incl } s_1}(t_{\text{fac}}) + d\sigma_{\text{Born}}^{\text{incl } s_2}(t_{\text{fac}}) \\ &= f_0(x_0, t_{\text{fac}}) |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}} + (1 - \Pi_{t_{\text{fac}}}^{t_{\text{max}}}) f_0(x_0, t_{\text{max}}) |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}} \end{aligned}$$

$$d\sigma_{\text{Born}}^{\text{excl}}(\mu) = d\sigma_{\text{Born}}^{\text{excl } s_1}(\mu) = f_0(x_0, \mu) \Delta_\mu^{t_{\text{start}}} |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$$

# Filling all of Phase Space: First emission



$$\text{Diff Born inclusive } \sigma: d\sigma_{\text{Born}}^{\text{incl}}(t_{\text{fac}}) = f_0(x_0, t_{\text{fac}}) |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$$

$$\text{Diff Born exclusive } \sigma: d\sigma_{\text{Born}}^{\text{excl}}(\mu) = \frac{f_0(x_0, \mu)}{f_0(x_0, t_{\text{start}})} f_0(x_0, t_{\text{fac}}) \Delta_\mu^{t_{\text{start}}} |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$$

Our method: Divide events in two samples.

- First sample: Start shower at  $t_{\text{start}} = t_{\text{fac}}$
- Second sample: Reweight with  $f_0(x_0, t_{\text{max}})/f_0(x_0, t_{\text{fac}})$

Start shower  $t_{\text{start}} = t_{\text{max}}$

Veto if no emission with  $t > t_{\text{fac}}$

$$\begin{aligned} d\sigma_{\text{Born}}^{\text{incl}}(t_{\text{fac}}) &= d\sigma_{\text{Born}}^{\text{incl } s_1}(t_{\text{fac}}) + d\sigma_{\text{Born}}^{\text{incl } s_2}(t_{\text{fac}}) \\ &= f_0(x_0, t_{\text{fac}}) |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}} + \underbrace{(1 - \Pi_{t_{\text{fac}}}^{t_{\text{max}}}) f_0(x_0, t_{\text{max}}) |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}}_{\int_{t_{\text{fac}}}^{t_{\text{max}}} dt f_1(x_1, t) \alpha_s(t) a(t) \Delta_t^{t_{\text{max}}} |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}} \end{aligned}$$

$$d\sigma_{\text{Born}}^{\text{excl}}(\mu) = d\sigma_{\text{Born}}^{\text{excl } s_1}(\mu) = f_0(x_0, \mu) \Delta_\mu^{t_{\text{start}}} |\mathcal{M}_{\text{Born}}|^2 d\Phi_{\text{Born}}$$

# Filling all of Phase Space: Subsequent emissions



Traditional parton showers are

strongly ordered  $\Leftrightarrow t_i > t_{i+1} \Leftrightarrow \Theta(t_i - t_{i+1}) \Leftrightarrow$  dead zones!

Instead: allow unordering with Markovian setup (smooth ordering)

- For  $n$ -parton system calculate Markovian scale  
 $\hat{t}$  = minimum of all possible branching scales in last shower step.
- New ordering criterion,

$$\mathcal{O}(\hat{t}, t) = \begin{cases} \Theta(\hat{t} - t) & \text{branching in an "ordered" antenna,} \\ \frac{\hat{t}}{\hat{t} + t} & \text{branching in an "unordered" antenna,} \\ 1 & \text{for the first branching.} \end{cases}$$

- Modify branching probability,  $a(t) \rightarrow \mathcal{O}(\hat{t}, t)a(t)$ .
- Set restart scales to phase-space maximum after each branching.
- Note: for PDF evaluation factorization scale kept as if strongly ordered.

# Matrix-Element Corrections for $pp \rightarrow Z + X$



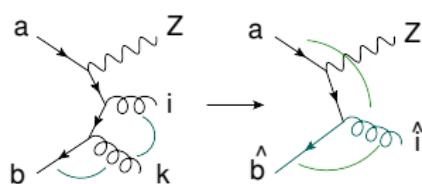
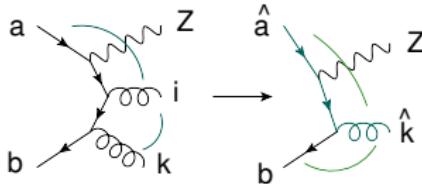
Compare shower to matrix element,

$$R_4 = \frac{\text{PS}}{\text{ME}} = \frac{\sum \mathcal{O}(\hat{t}, t) a(t) |\mathcal{M}_{Zj}(\{\hat{p}_{Zj}\})|^2}{|\mathcal{M}_{Zjj}(\{p_{Zjj}\})|^2} = \text{inverse of MEC factor}$$

with sum over shower paths for  $q_a \bar{q}_b \rightarrow Z g_i g_k$

$$\sum_{Z_{jj} \rightarrow Z_j} \mathcal{O}(\hat{t}, t) a(t) |\mathcal{M}_{Zj}(\{\hat{p}_{Zj}\})|^2 =$$

$$\mathcal{O}(\hat{t}_k, t_i) a_g^{IF}(a, k, i) \left| \mathcal{M}_{Z\hat{g}_k}(\hat{a}, b; Z, \hat{k}) \right|^2 + \mathcal{O}(\hat{t}_i, t_k) a_g^{IF}(b, i, k) \left| \mathcal{M}_{Z\hat{g}_i}(a, \hat{b}, Z; \hat{i}) \right|^2$$

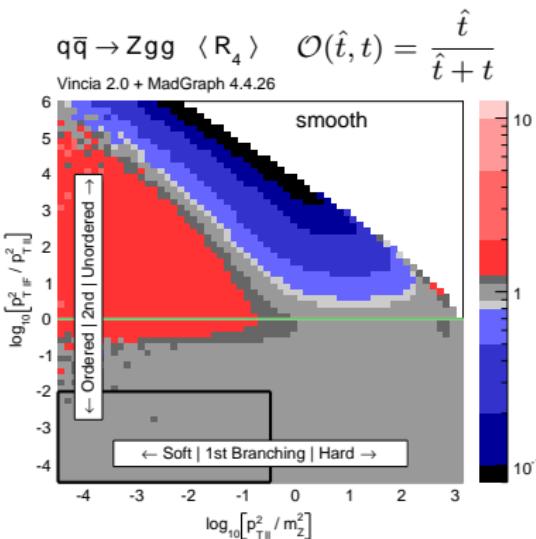
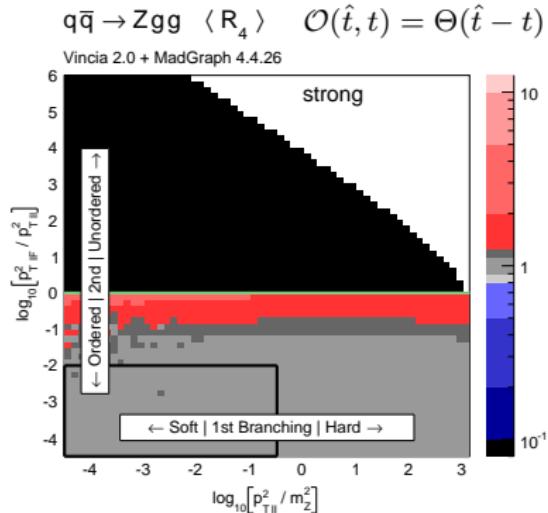


# Matrix-Element Corrections for $pp \rightarrow Z + X$



Compare shower to matrix element for  $q\bar{q} \rightarrow Zgg$ ,

$$R_4 = \frac{\text{PS}}{\text{ME}} = \frac{\sum \mathcal{O}(\hat{t}, t) a(t) |\mathcal{M}_{Zg}(\{\hat{p}_{Zg}\})|^2}{|\mathcal{M}_{Zgg}(\{p_{Zgg}\})|^2} = \text{inverse of MEC factor}$$

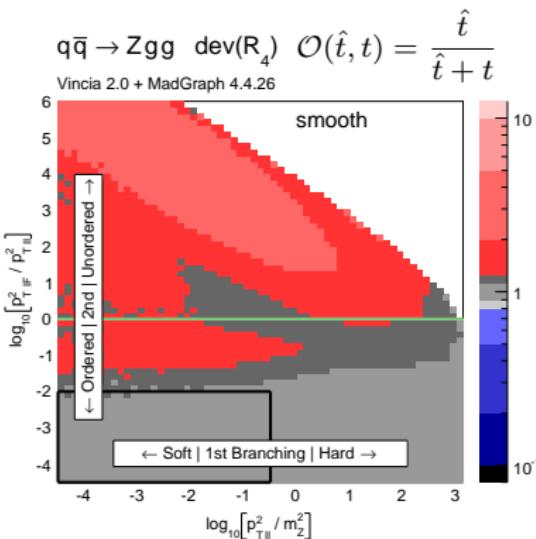
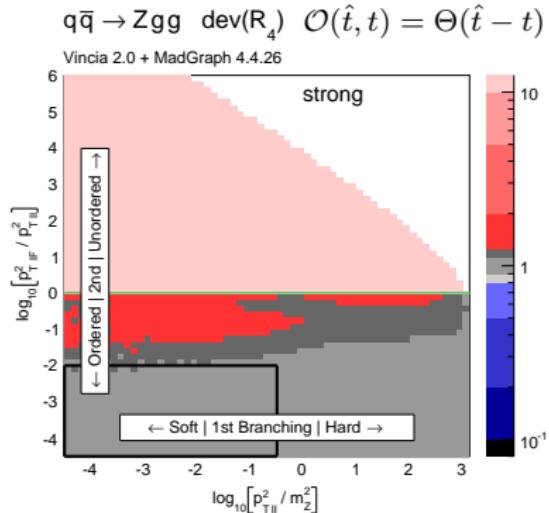


# Matrix-Element Corrections for $pp \rightarrow Z + X$



Deviation (agreement only because of average?):

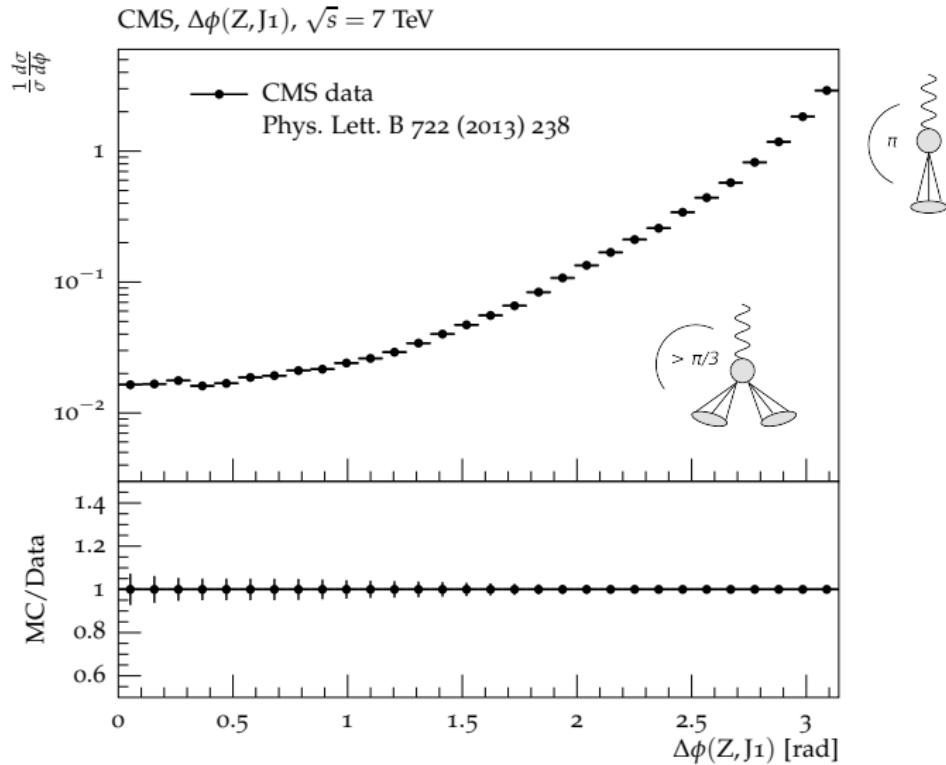
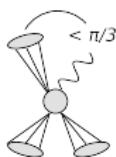
$$\text{dev}(R_4) = 10\sqrt{\langle \log_{10}^2(R_4) \rangle - \langle \log_{10}(R_4) \rangle^2}$$



# A Result



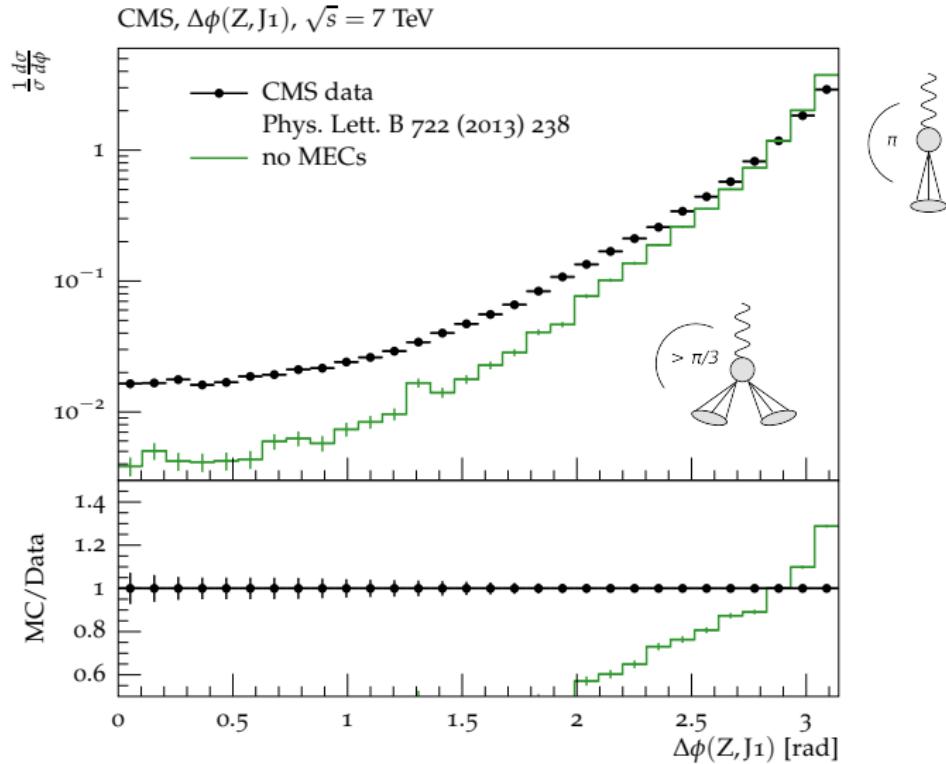
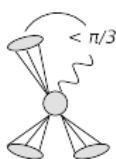
Predictions made with  
publicly available  
VINClA 2.0.01  
(vincia.hepforge.org)  
+ PYTHIA 8  
+ MADGRAPH 4



# A Result



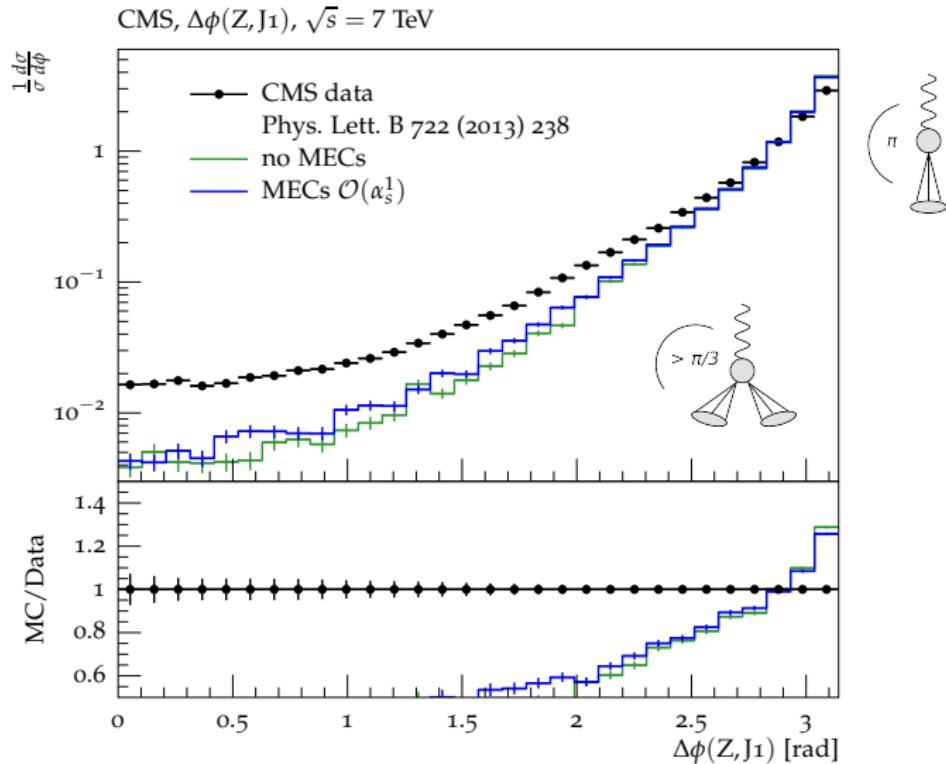
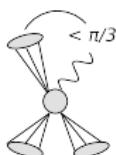
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+ PYTHIA 8  
+ MADGRAPH 4



# A Result



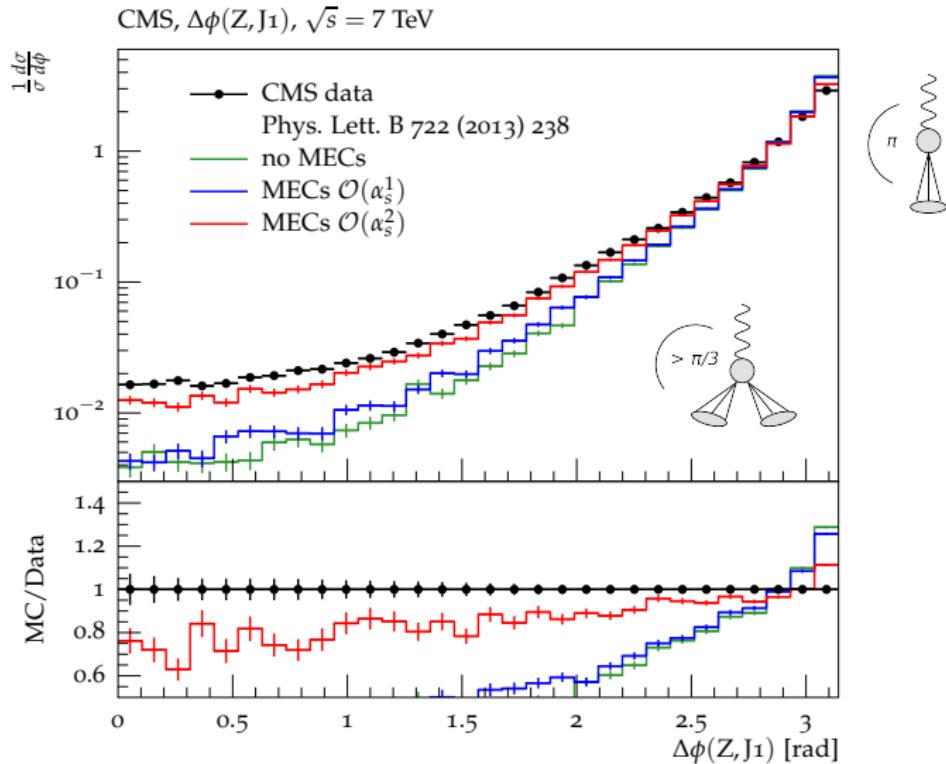
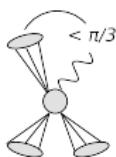
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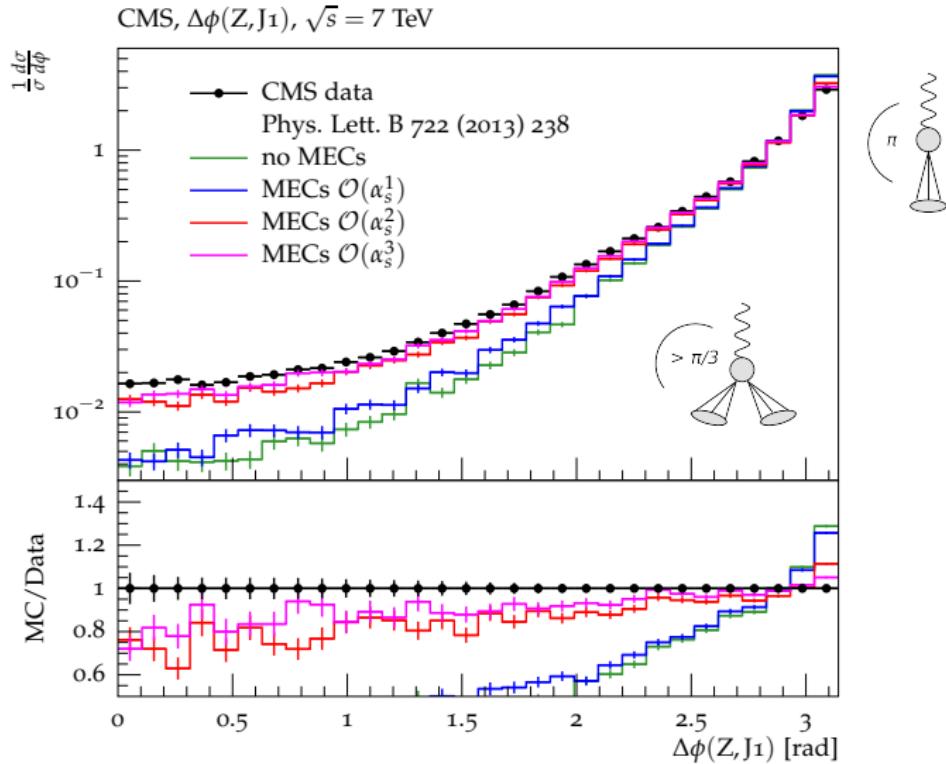
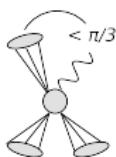
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# A Result



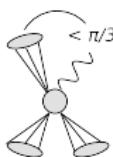
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(vincia.hepforge.org)  
+ PYTHIA 8  
+ MADGRAPH 4



# A Result

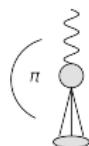
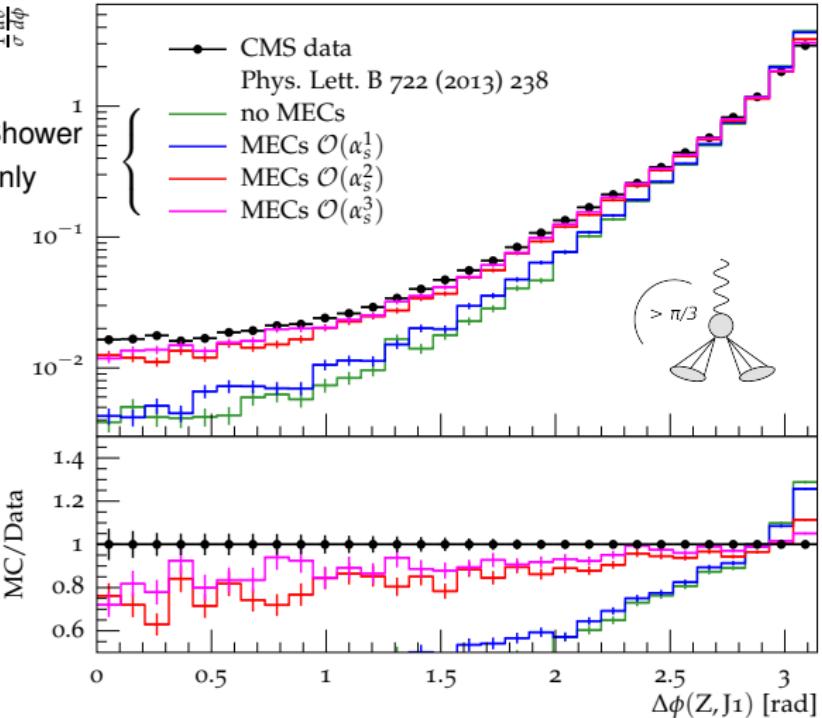


Predictions made with  
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VINClA 2.0.01  
(vincia.hepforge.org)  
+ PYTHIA 8  
+ MADGRAPH 4



$\frac{d\sigma}{d\phi}$

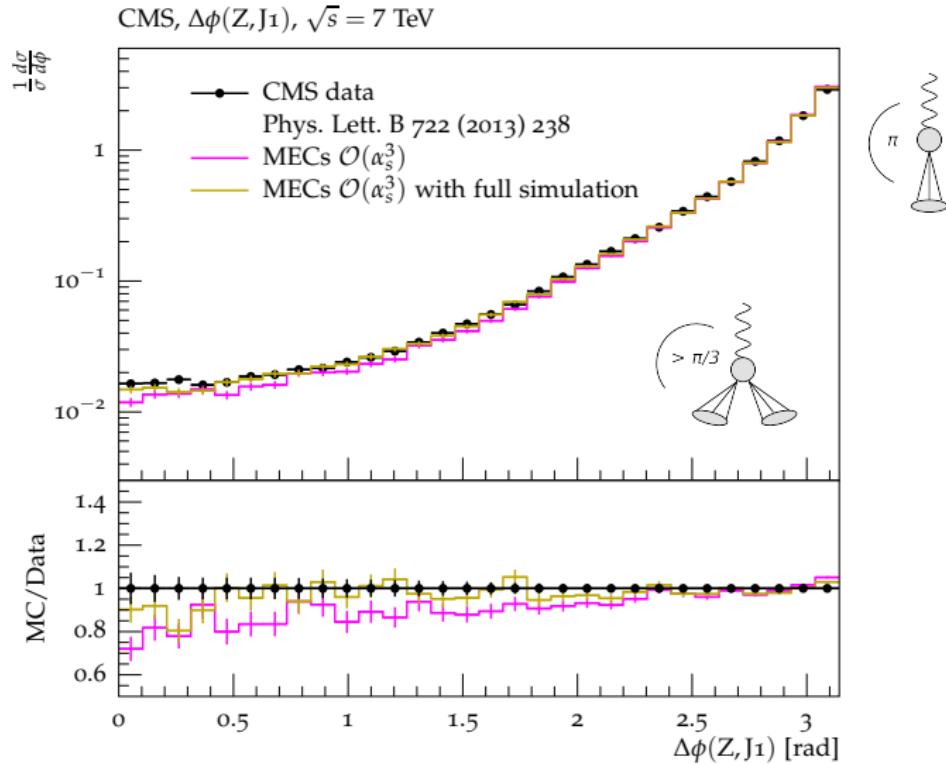
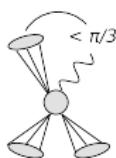
Shower  
only



# A Result



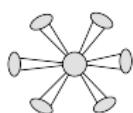
Predictions made with  
publicly available  
VINClA 2.0.01  
(vincia.hepforge.org)  
+ PYTHIA 8  
+ MADGRAPH 4



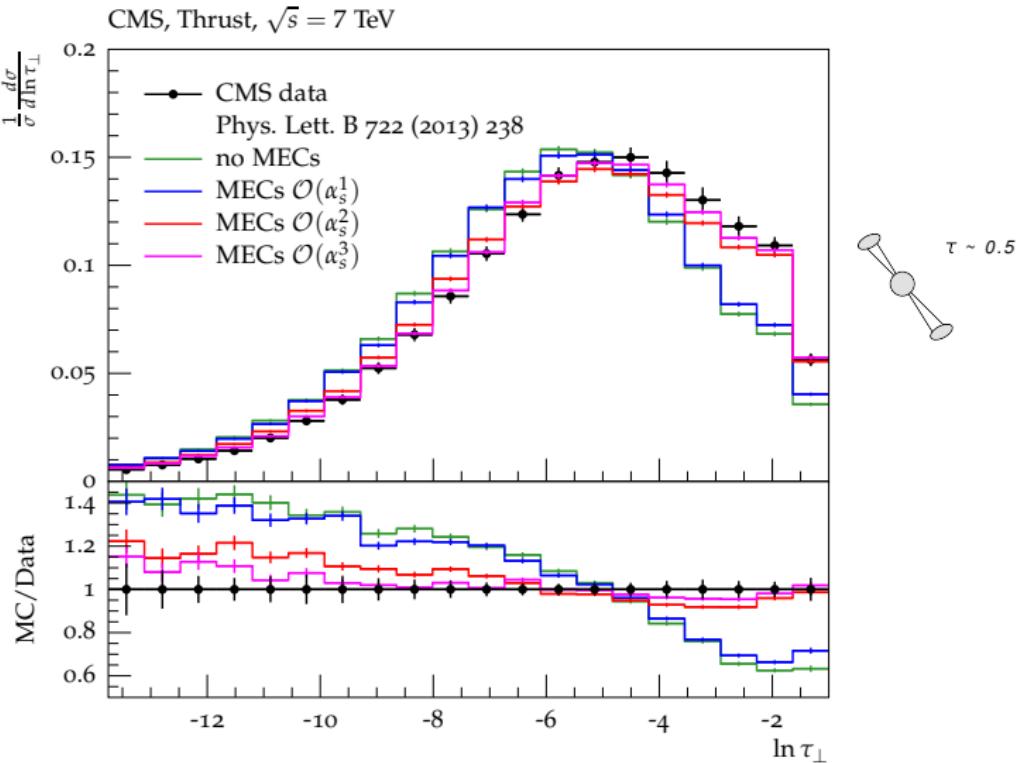
# A Result



Predictions made with  
publicly available  
VINCI 2.0.01  
(vincia.hepforge.org)  
+ PYTHIA 8  
+ MADGRAPH 4



$\tau \sim 1$





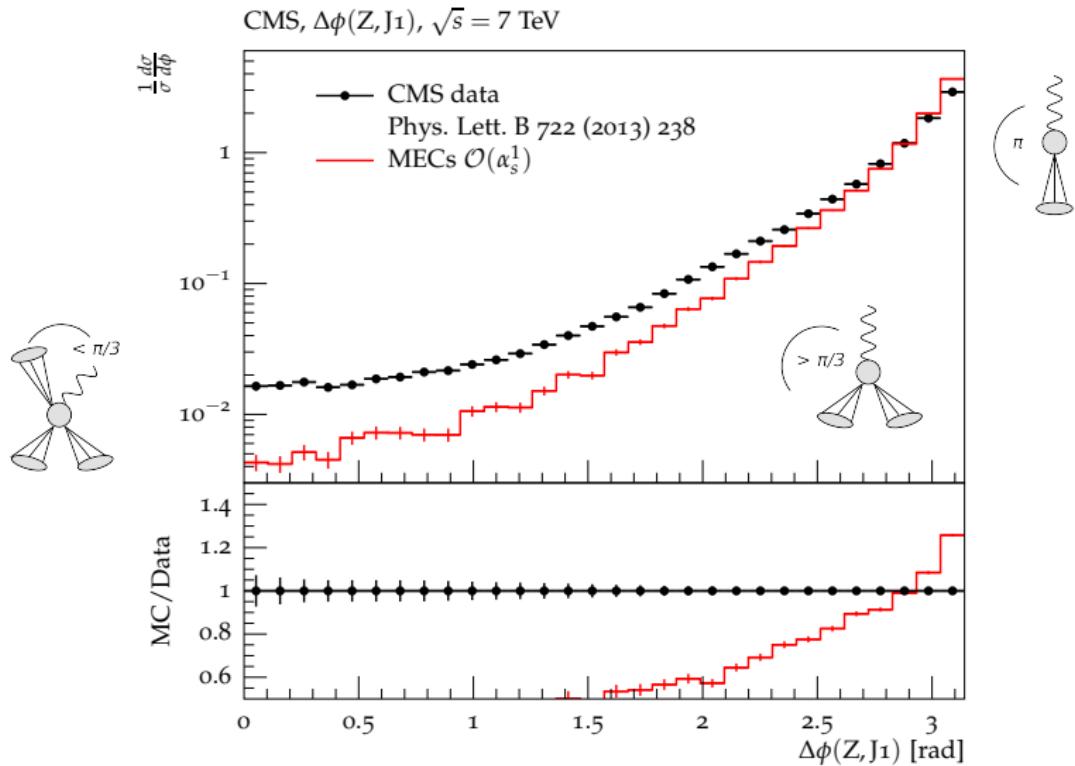
Comparison of different methods,

MECs vs. PYTHIA's CKKW-L merging with VINCIA's shower.

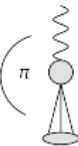
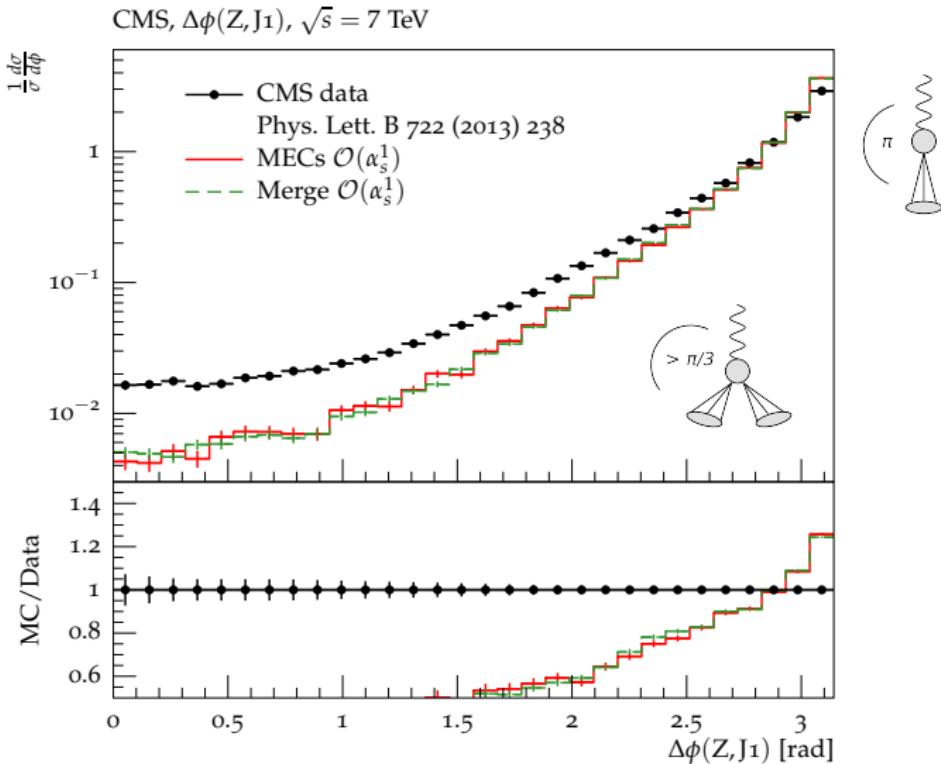
Main differences:

- MECs modify antenna functions → ME exponentiated in Sudakov factor.
- $\Pi_{t_1}^{t_{\max}}$  for hard jets ( $t_1 > m_Z^2$ ) only for MECs.
- No additional Sudakov factors in merging.
- Handling of unordered histories.
- Ideally: Combine MECs and merging (so far only for 1st order).

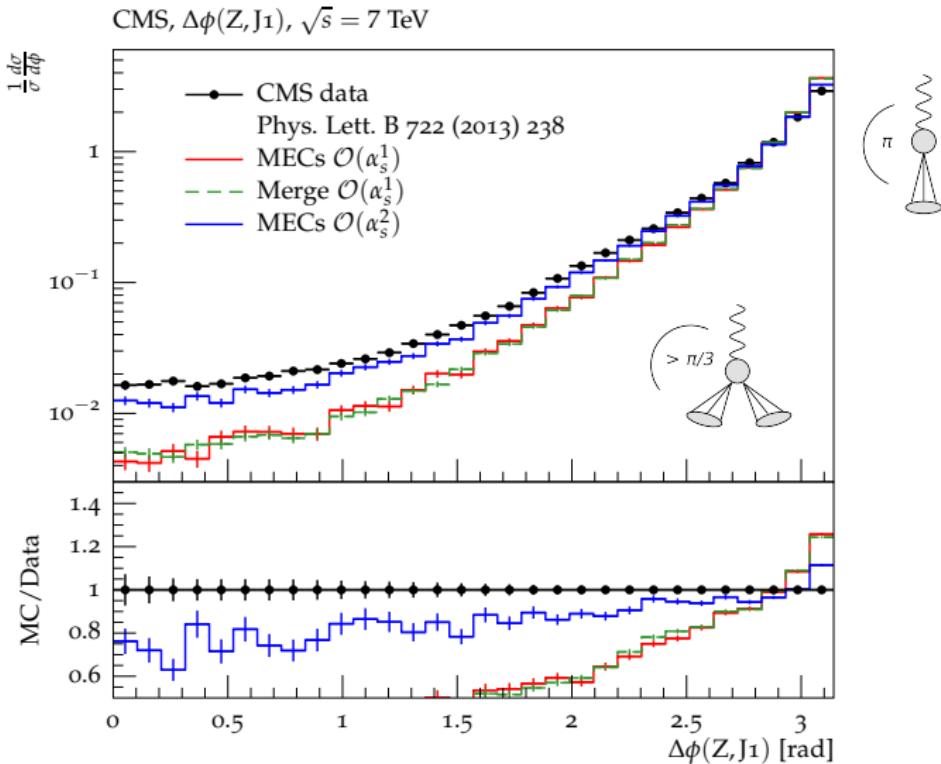
# A Result



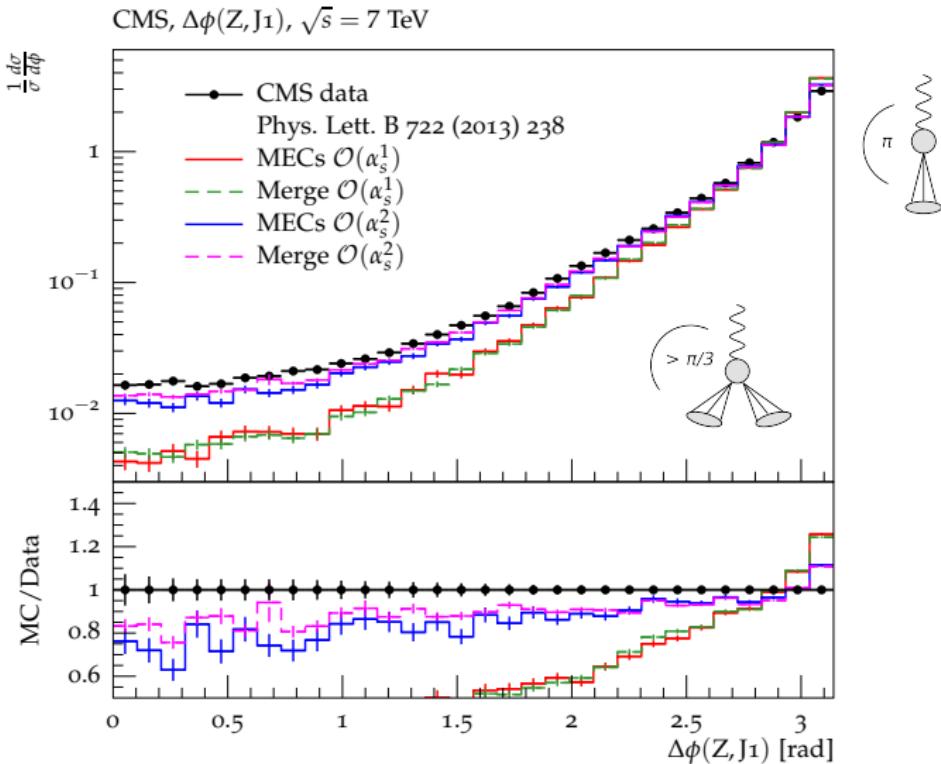
# A Result



# A Result



# A Result



# Summary and Outlook



VINCIA (public version 2.0.01 [[arxiv:1605.06142](#)]):

- Antenna shower extended to LHC physics.
- Iterated matrix element corrections for LHC processes.
- Possible to use VINCIA with PYTHIA's merging (not published yet).

Still a lot of improvements to be done:

- Generalize the matrix element correction framework to arbitrary LHC processes.
- Include mass effects, especially for resonance decays.
- Include loop corrections.
- ...

and now – PYTHIA 8.2 news

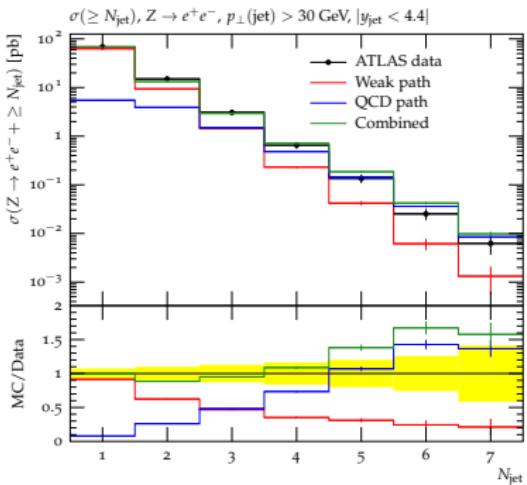
# Weak Shower and Merging



- Weak gauge boson radiation

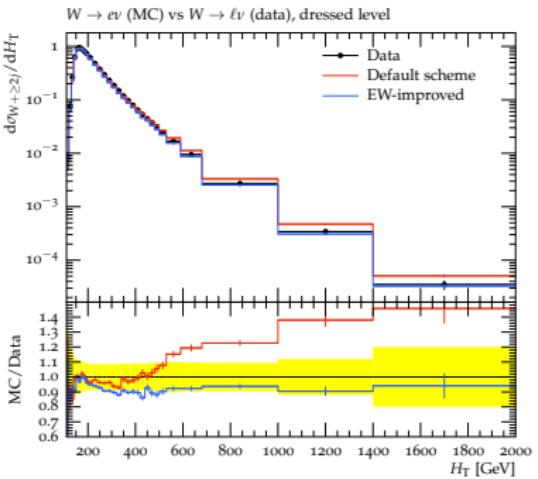
[Christiansen, Sjöstrand – arxiv:1401.5238]

$$q \rightarrow qZ \text{ and } q \rightarrow q'W$$



- Merging weak and QCD showers with matrix elements

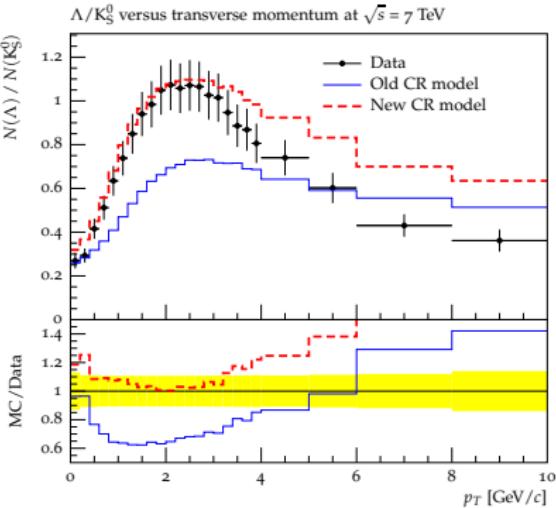
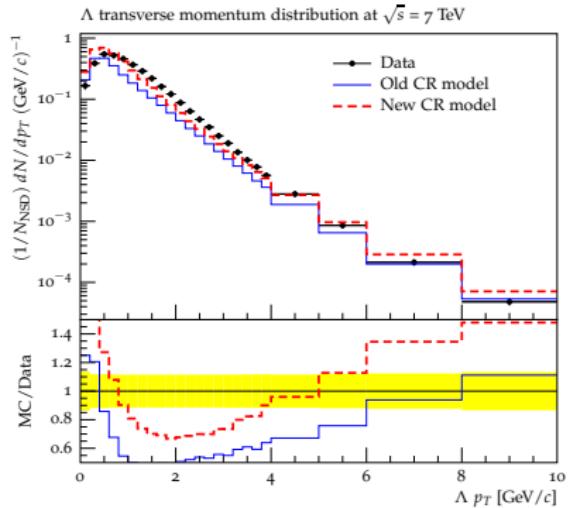
[Christiansen, Prestel – arxiv:1510.01517]



# New Colour Reconnection Model



- String formation beyond leaving colour [Christiansen, Skands – arxiv:1505.01681]
- Randomisation over set of possible subleading-colour topologies, probabilities chosen according to simplified version of SU(3) colour algebra



# Other Updates



- Allow reweighting of rare shower branchings [[Prestel](#)].
- Automated parton-shower uncertainty bands [[Mrenna, Skands – arxiv:1605.08352](#)].
- Extended interface for external shower plugins [[Prestel](#)].  
Currently used by DIRE and VINCIA.
- Matching and Merging updates [[Prestel](#)].
- Work in progress:
  - Diffraction [[Rasmussen, Sjöstrand – arxiv:1512.05525](#)].
  - Hadronization [[Sjöstrand, Fischer](#)].



stay(s) tuned