Studies on Double-Parton-Scattering in Photon-3-Jet Final States

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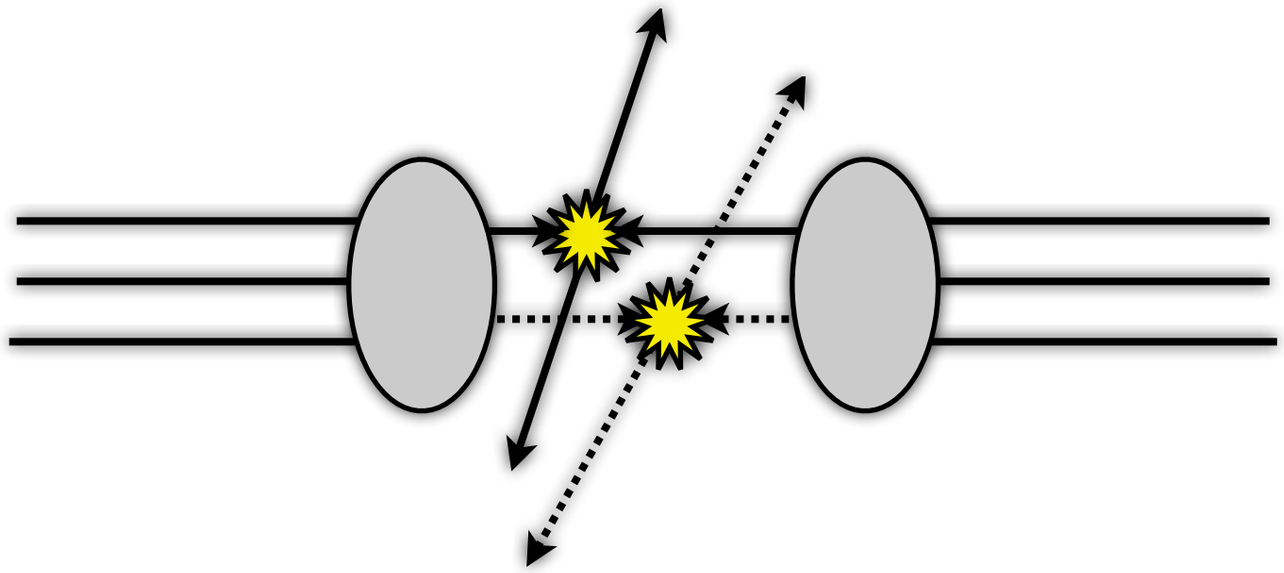


Thanks to: *Workshop Organizers*
Torbjörn Sjöstrand
Manuel Bähr
CMS QCD and Generator Tools Groups

MCnet

Monte Carlo net

Outline

- **Simulation of Multiple Interactions**
  - Pythia 8 and Herwig++
- **Double-Parton-Scattering**
  - Previous studies and parametrization
- **Generator Study of Double-Parton-Scattering in Photon-3-Jet events**
  - Model Predictions

Simulation of Multiple Scatters

New models ready to use

- **Sjöstrand, Skands (Pythia 8)**
  - Flavour and colour correlations, junction topologies and the relationship to beam remnants *JHEP 0403:053, 2004*
  - Interleaving with initial-state radiation making use of transverse-momentum-ordered initial- and final-state showers *Eur. Phys. J. C39: 129-154, 2005*

- **Bähr, Gieseke, Seymour (Herwig++)**
  - Eikonal model
  - Forced splittings and colour connections *JHEP 0807:076,2008*

- **Aim: Study models for**

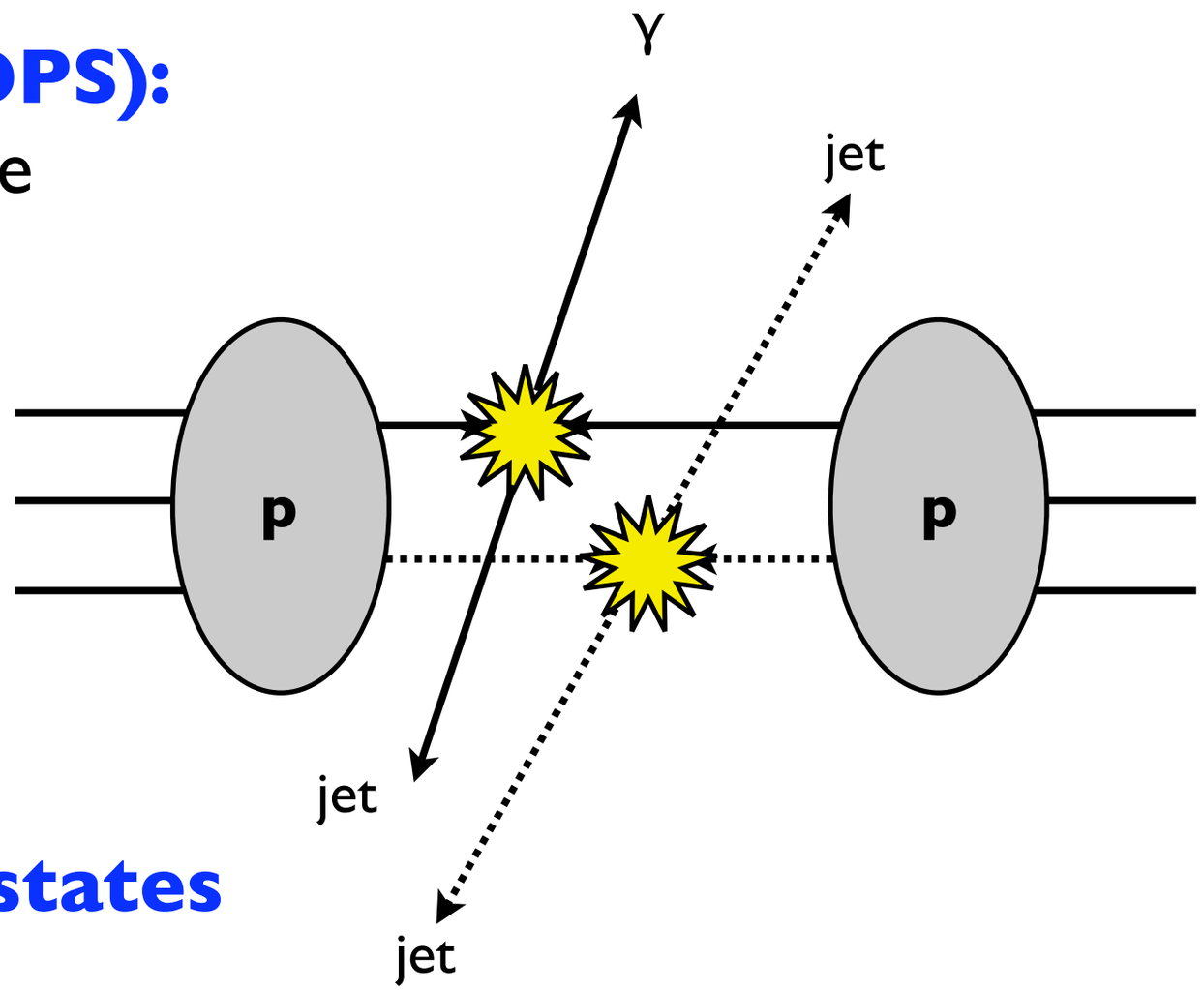
  Double-Parton-Scattering in $pp \to \Upsilon\, j\, j\, j$ @ $\sqrt{s} = 14$ TeV

Double-Parton-Scattering

- ***Double-Parton-Scattering* (DPS):**
  - Two hard interactions in the same proton-(anti-)proton-scattering

- **Information on...**
  - Spatial distribution of partons in proton
  - Parton-parton-correlations

- **Contributes to exotic final states**
  - Example: like-sign W pairs



- **Double-Parton-Scattering in pp → γ j j j @ √s = 14 TeV**
  - Process A creates photon-jet-pair, process B creates dijet-pair

DPS-Parametrization

- **DPS comprised of scatterings A and B (A ≠ B):**

$$\sigma_{\mathrm{DP}} = \frac{\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{\sigma_{\mathrm{eff}}}$$

➡ σ_{eff} - **effective cross section**, process-independent

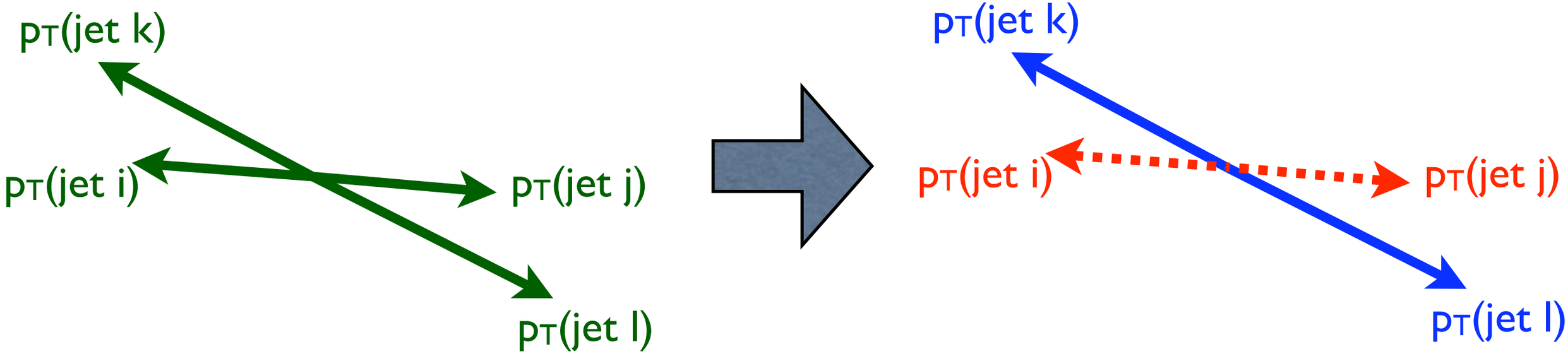
- **σ_{eff} related to number of collisions N:**

$$\langle \mathrm{N}(\mathrm{N}-1) \rangle = \langle \mathrm{N} \rangle^2 \, \frac{\sigma_{\mathrm{hard}}}{\sigma_{\mathrm{eff}}}$$

- **Pythia: $\sigma_{AB} = \langle f_{impact} \rangle \, \sigma_A \, \sigma_B \, / \, \sigma_{Non\text{-}Diffractive}$**
  - f_{impact} - enhancement/depletion factor for MPI
  - → Pythia "predicts" $\sigma_{eff} = \sigma_{Non\text{-}Diffractive} / \langle f_{impact} \rangle$

DPS Analysis: Jet Assignment

- **Find p_T-balanced pairs:**



- **AFS solution:**

$$\min\left(\left|\vec{p}_{Ti} + \vec{p}_{Tj}\right|^2 + \left|\vec{p}_{Tk} + \vec{p}_{Tl}\right|^2 \right)$$

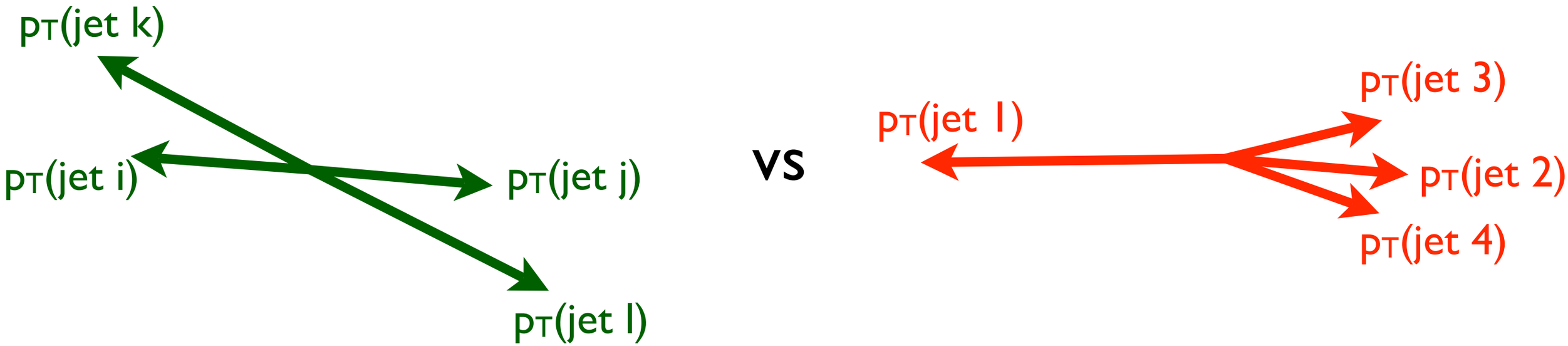
- **UA2 solution (→ CDF):**

$$\min\left(\frac{\left|\vec{p}_{Ti} + \vec{p}_{Tj}\right|^2}{\left|\vec{p}_{Ti}\right| + \left|\vec{p}_{Tj}\right|} + \frac{\left|\vec{p}_{Tk} + \vec{p}_{Tl}\right|^2}{\left|\vec{p}_{Tk}\right| + \left|\vec{p}_{Tl}\right|} \right)$$

- **This study: Follow UA2/CDF approach**

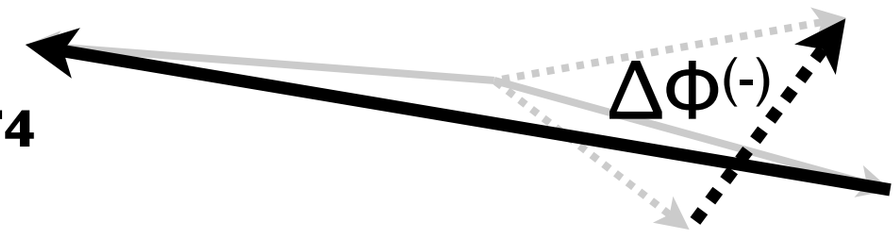
Angular Correlations

- **Disentangle DPS from Double-Bremsstrahlung (DB)**

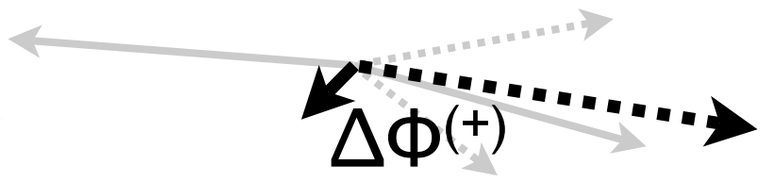


- **Make use of different correlations between jet pairs**
  - No correlation (DPS) versus strong correlation (BS)

- **AFS solution:**
  - Study $\Delta\Phi^{(-)}$ between $\mathbf{p_{T1} - p_{T2}}$ and $\mathbf{p_{T3} - p_{T4}}$



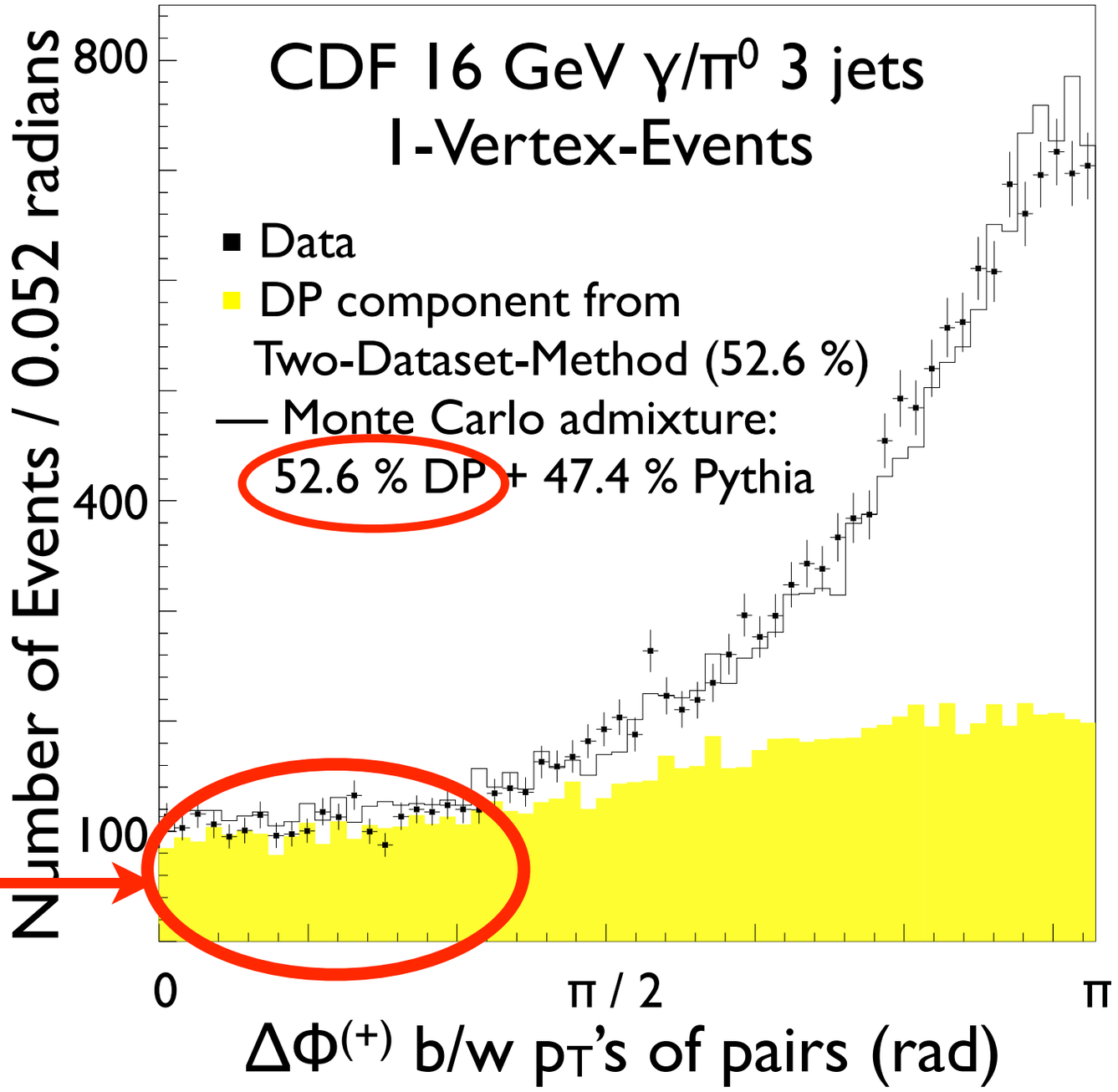
- **CDF solution:**
  - Study $\Delta\Phi^{(+)}$ between $\mathbf{p_{T1} + p_{T2}}$ and $\mathbf{p_{T3} + p_{T4}}$



Tevatron Results

- **CDF analysis**
  - Choose pairs which minimize event imbalance
  - study $\Delta\Phi^{(+)}$
- **DPS model: admixture**
  - Pythia, MPI switched off
  - add sum of min-bias and γ +jet datasets
- **σ_{eff} = 11 mb**

Phys.Rev.D76:076006,2007



Simulation Settings

- **Pythia 8.108**
  - **Default**: Multiple Interactions, ISR and FSR switched **on**
  - **MI**: Multiple Interactions **on**, ISR and FSR **off**
  - **Shower**: Multiple Interactions **off**, ISR and FSR **on**

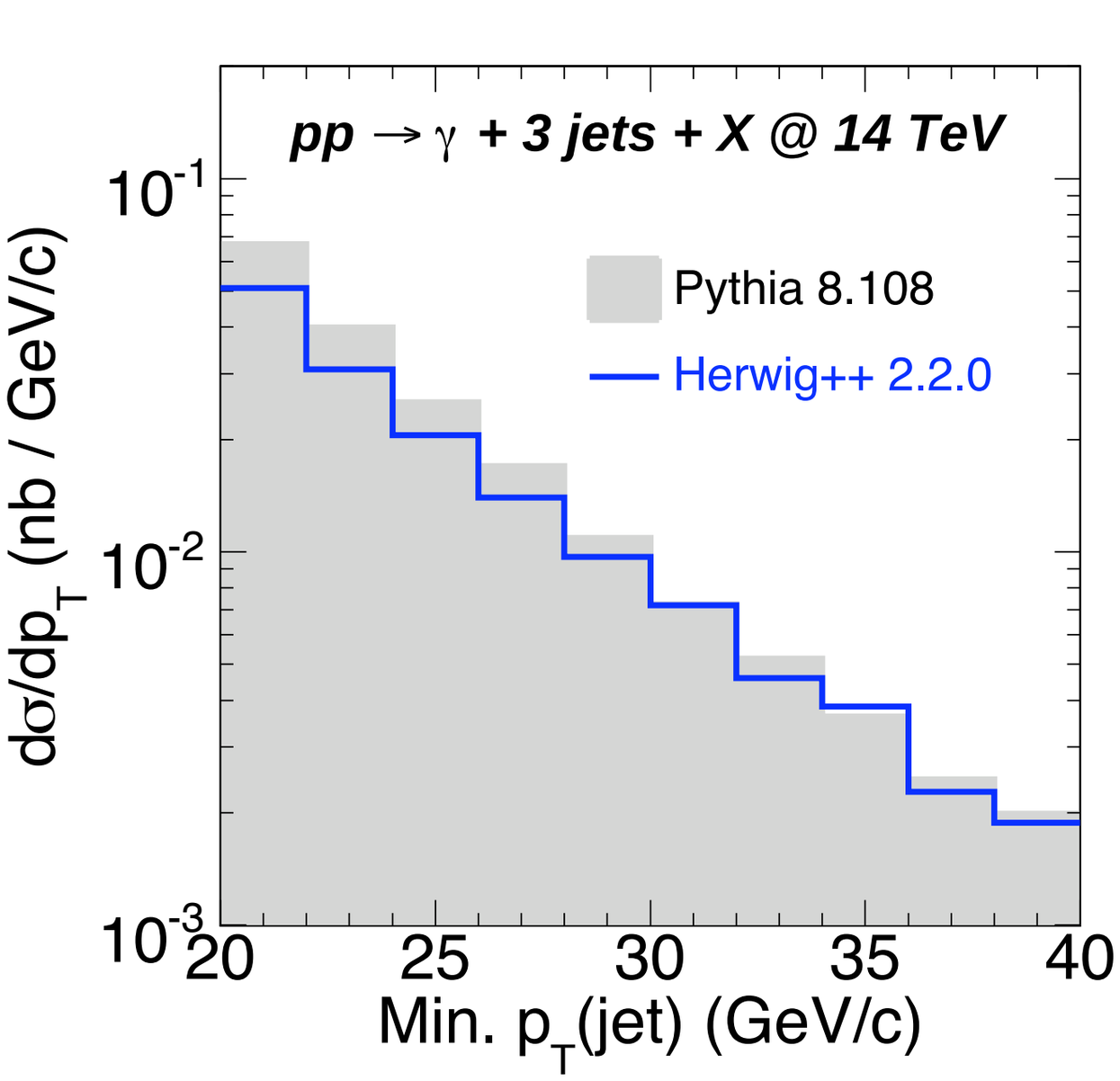
```
PromptPhoton:all = on
PartonLevel:ISR  = on / off
PartonLevel:FSR = on / off
PartonLevel:MI    = on / off
```

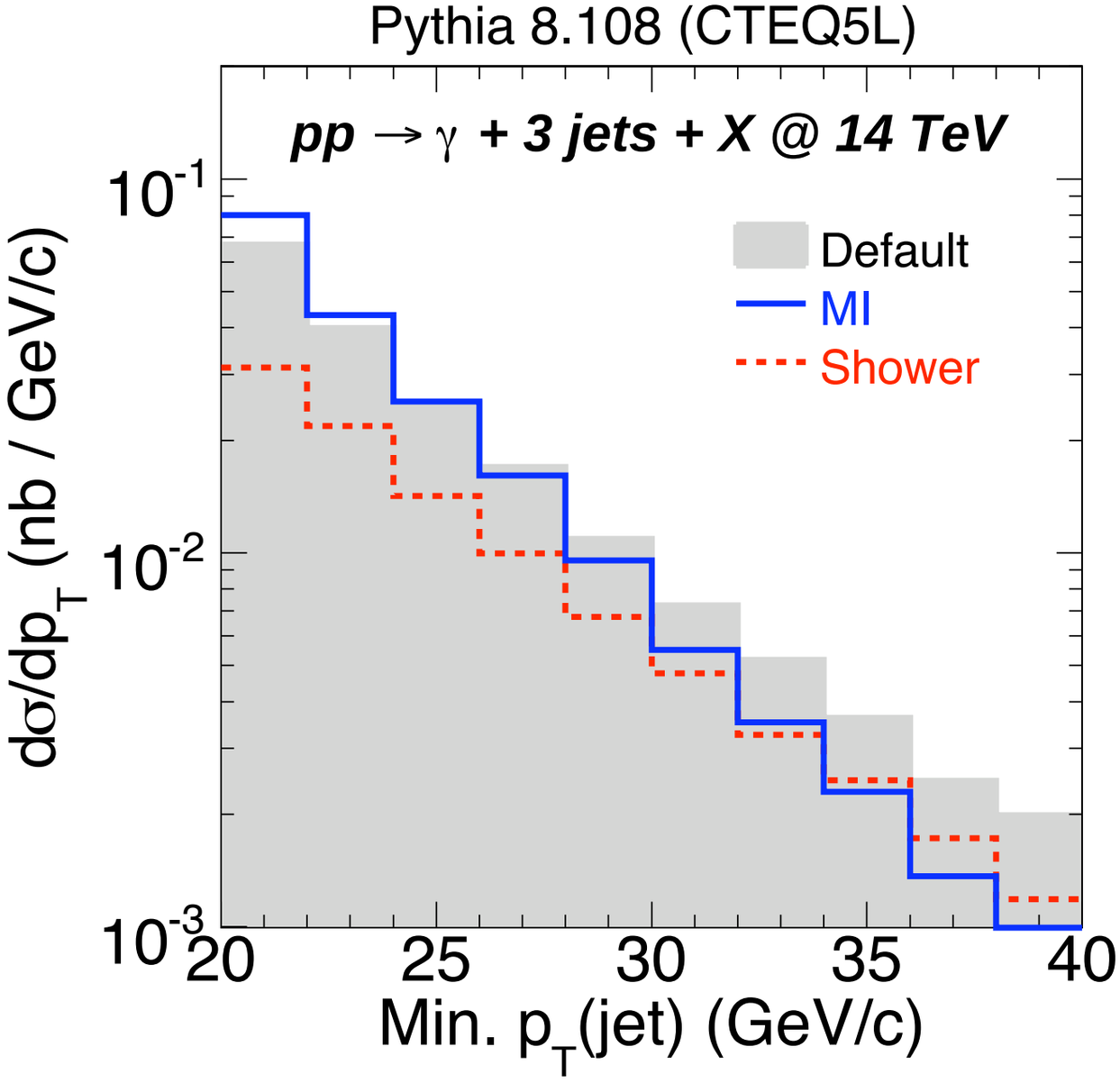
- **Herwig++ 2.2.0**
  - Multiple Interactions, ISR and FSR switched **on**

```
insert SimpleQCD:MatrixElements[0] MEGammaJet
insert SimpleQCD:MatrixElements[1] MEGammaGamma
```

Jet Kinematics @ LHC I

Jet transverse momentum threshold:

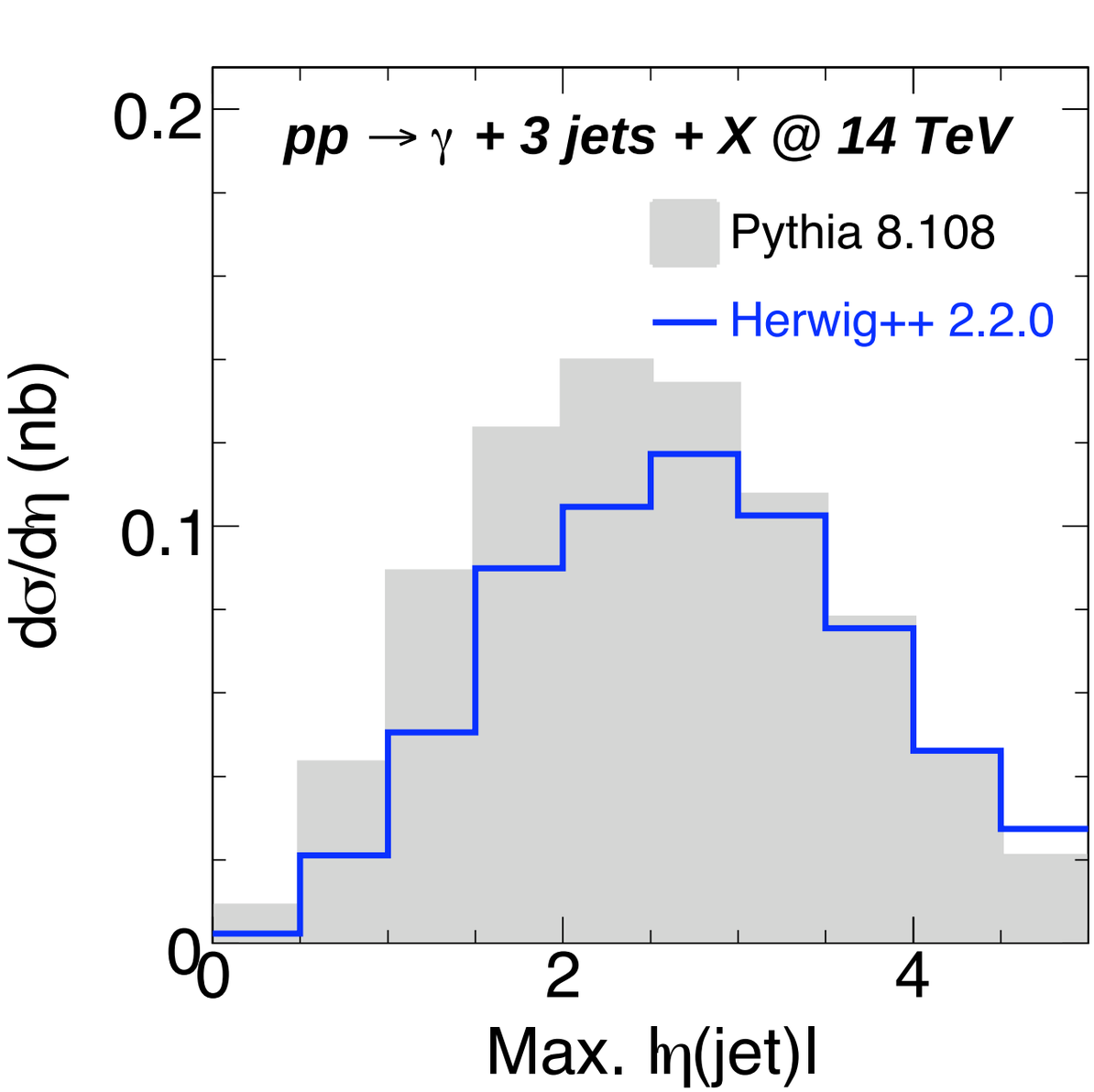


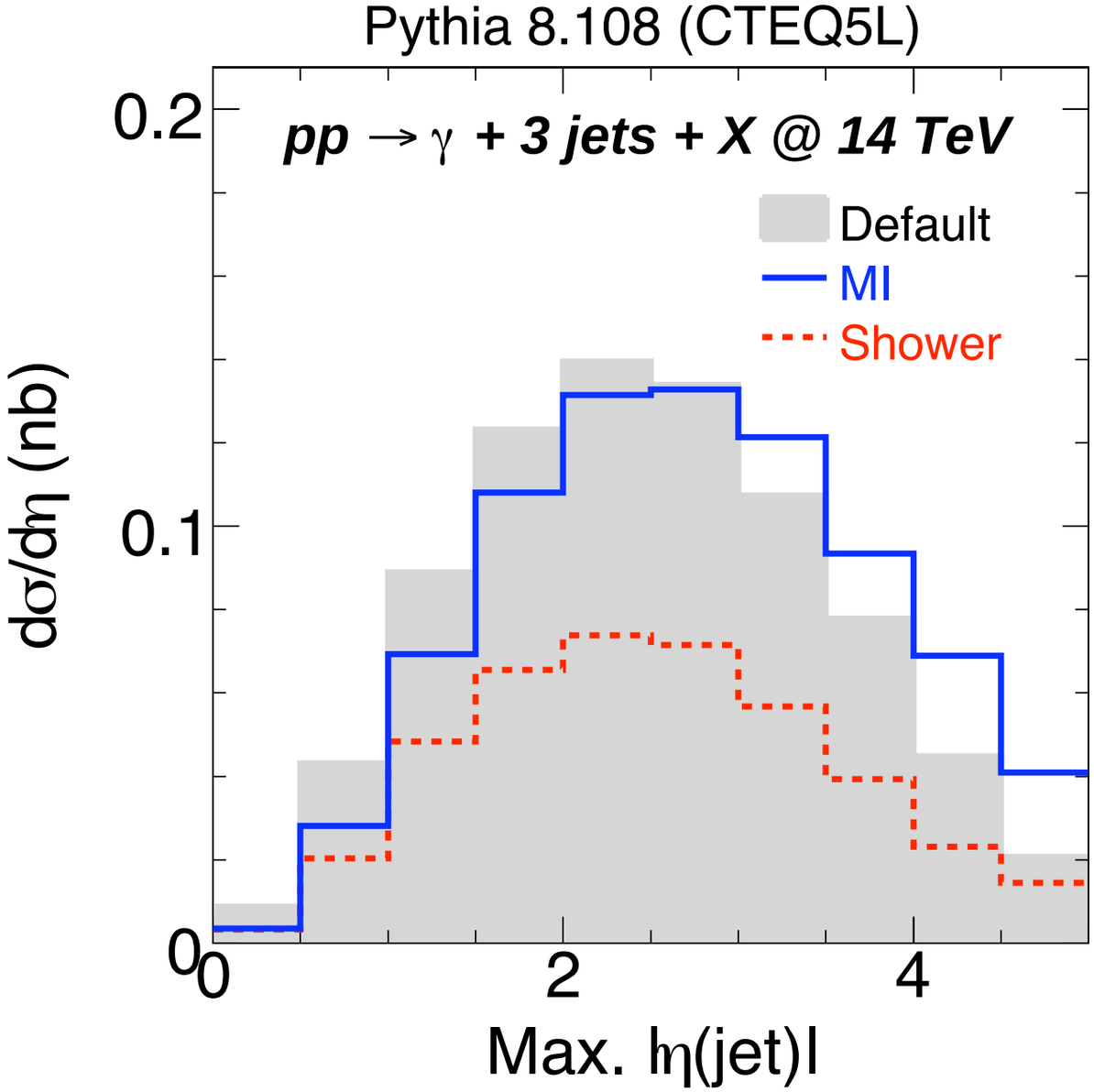


Jets from Multiple Interactions (MI) are soft

Jet Kinematics @ LHC 2

Jet pseudorapidity range:





Jets from MI produced in forward direction

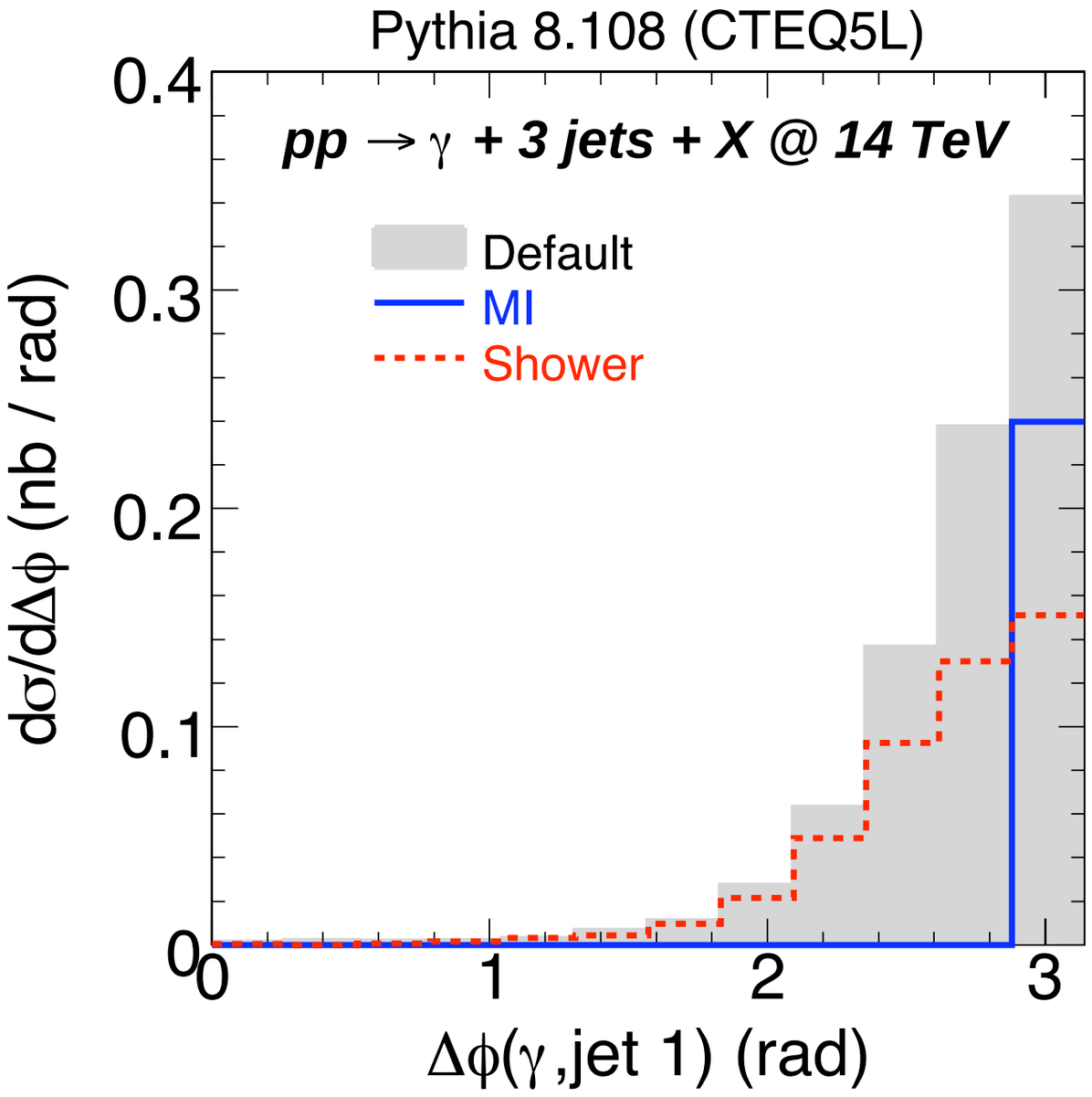
Event selection

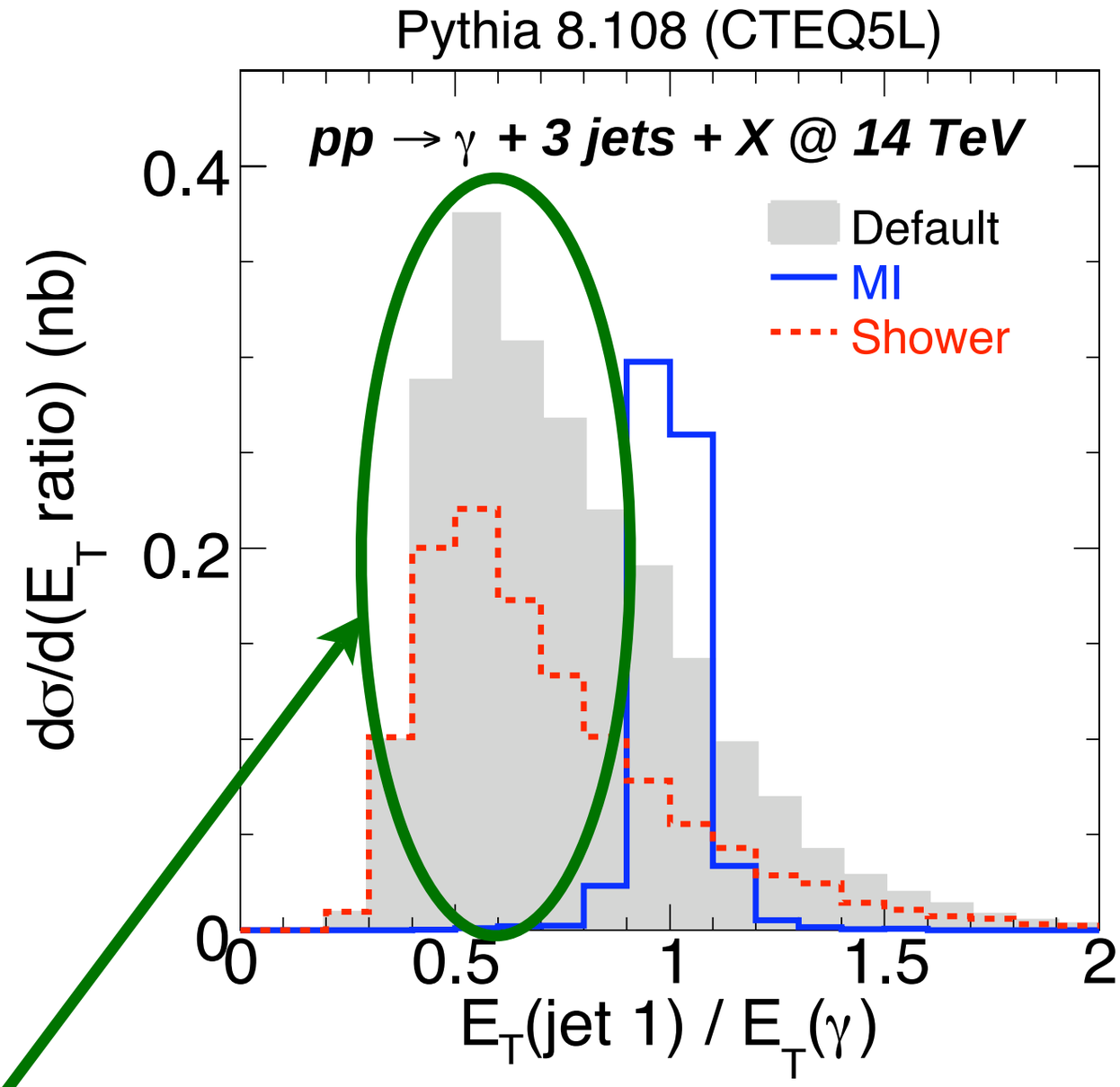
	Tevatron	***LHC***
Photon	$\lvert\eta\rvert < 1.1$	$\lvert\eta\rvert < 2.5$
	$E_T > 16$ GeV	$E_T > 50$ GeV
	Cone 0.7	k_T *0.4*
Jets	$\lvert\eta\rvert < 4.2$	$\lvert\eta\rvert < 5$
	$E_T > 5$ GeV	$E_T > 20$ GeV
	$E_{T4} < 5$ GeV	$E_{T4} < 10$ GeV
	$E_{T2}, E_{T3} < 7$ GeV	$E_{T2}, E_{T3} < 30$ GeV

This study: Hadron-Level Analysis

Photon-Jet Kinematics @ LHC

Study balance between photon and hardest jet:

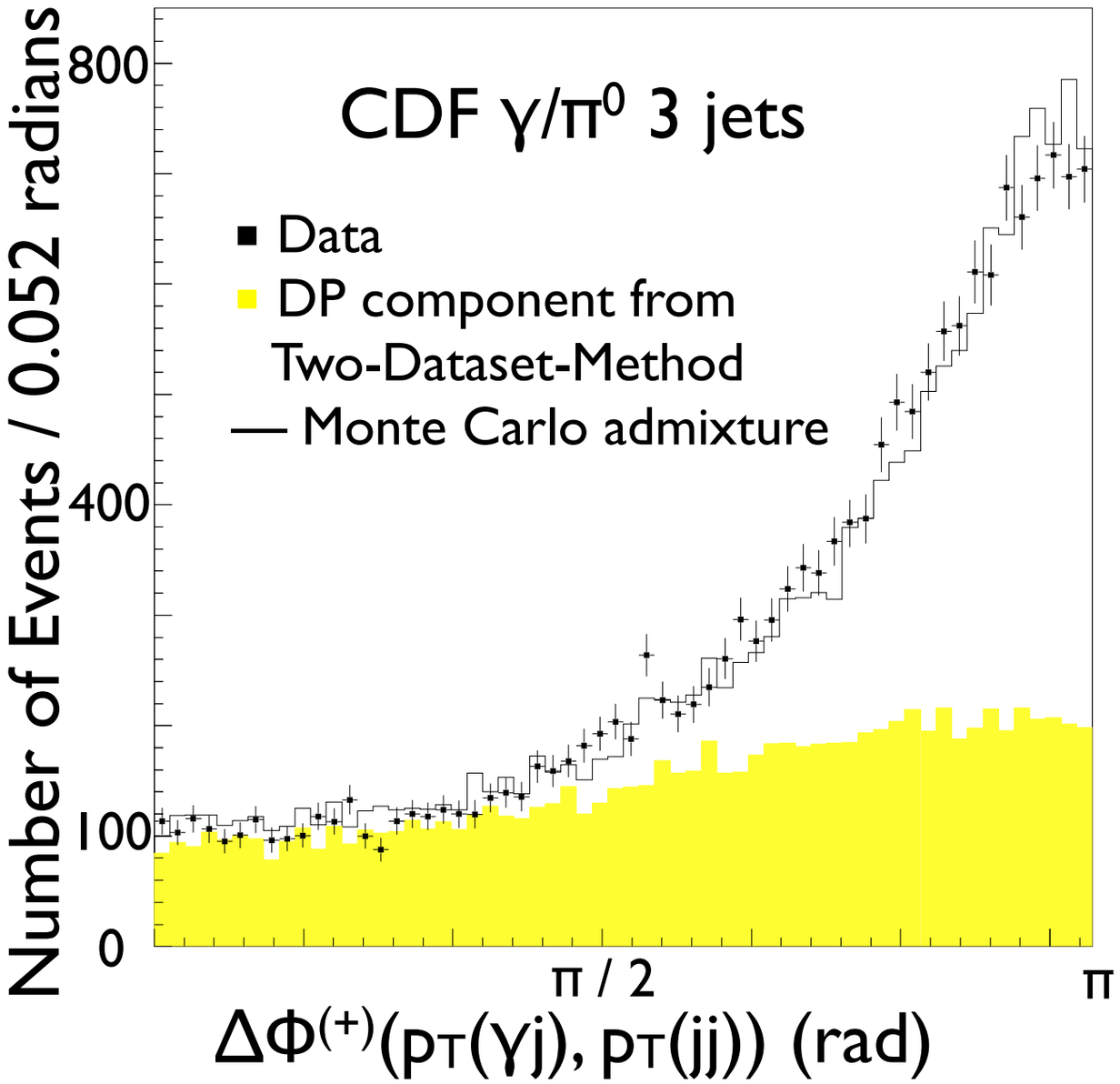


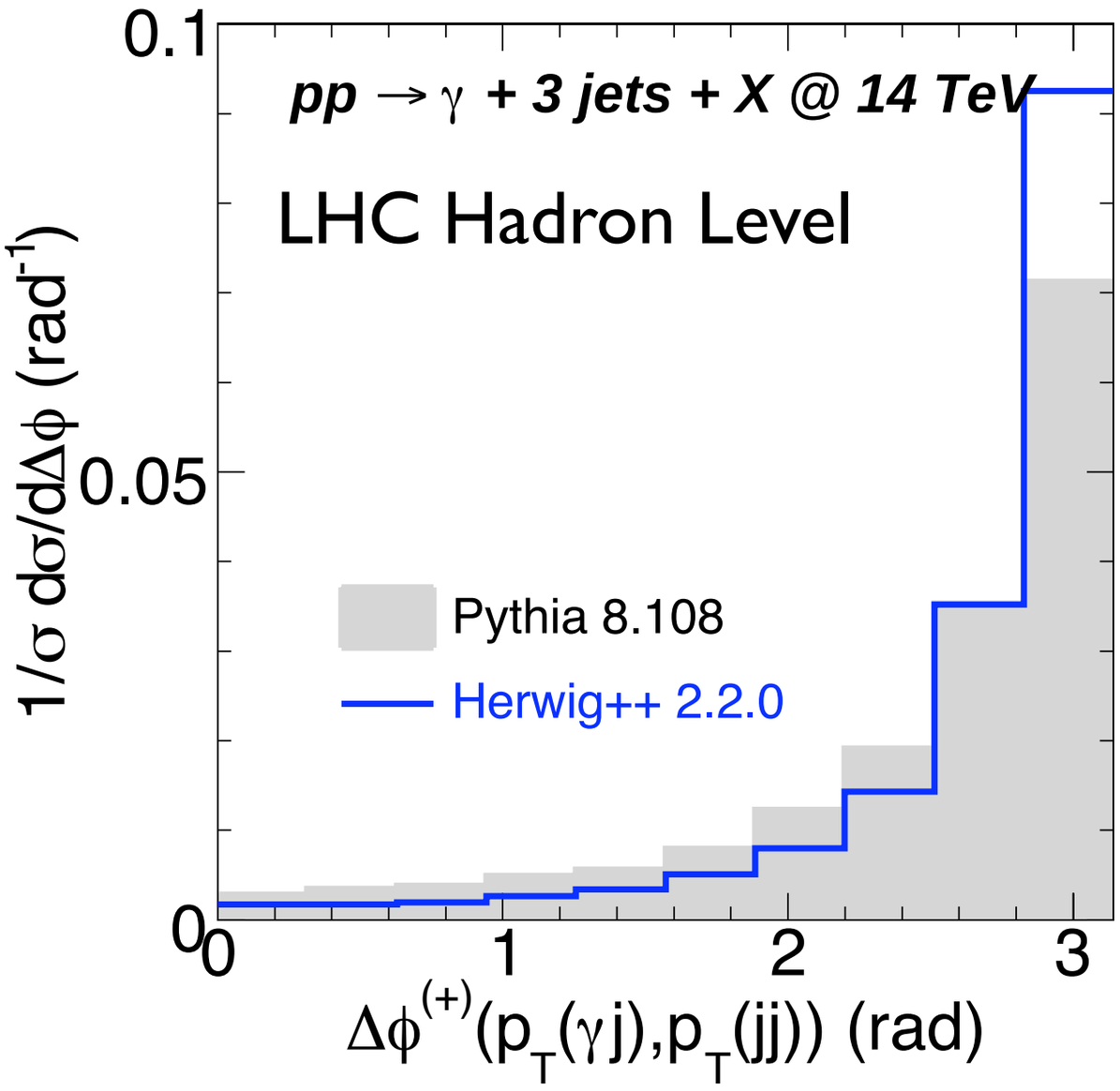


⟨E_T1/E_T(γ)⟩ < 1 → Significant contribution from FSR

DPS @ Tevatron and LHC

Study azimuthal angle between pairs (CDF method):

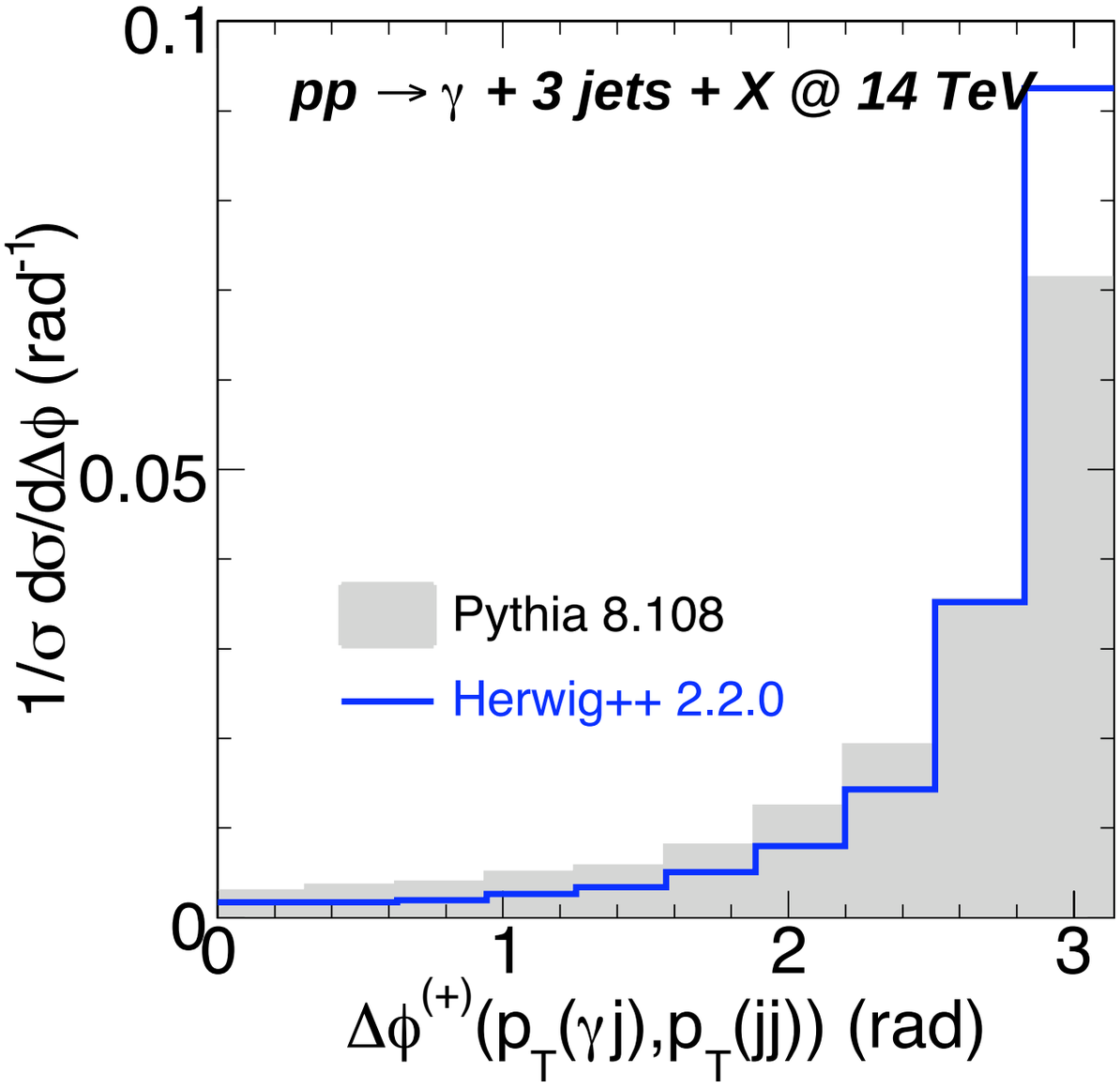


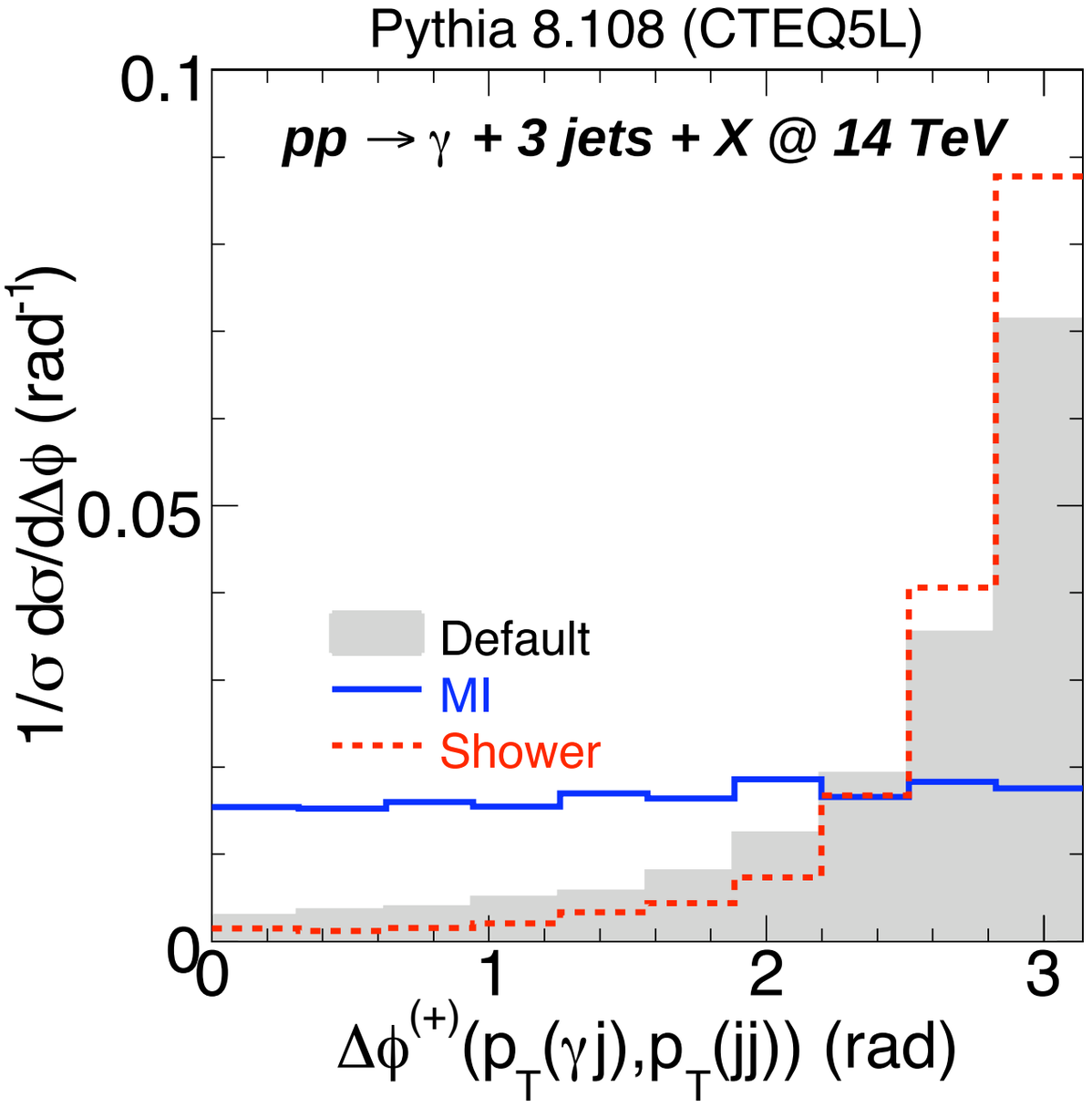


Both simulations reproduce main features

Separation Variables @ LHC I

Study azimuthal angle between pairs (CDF method):

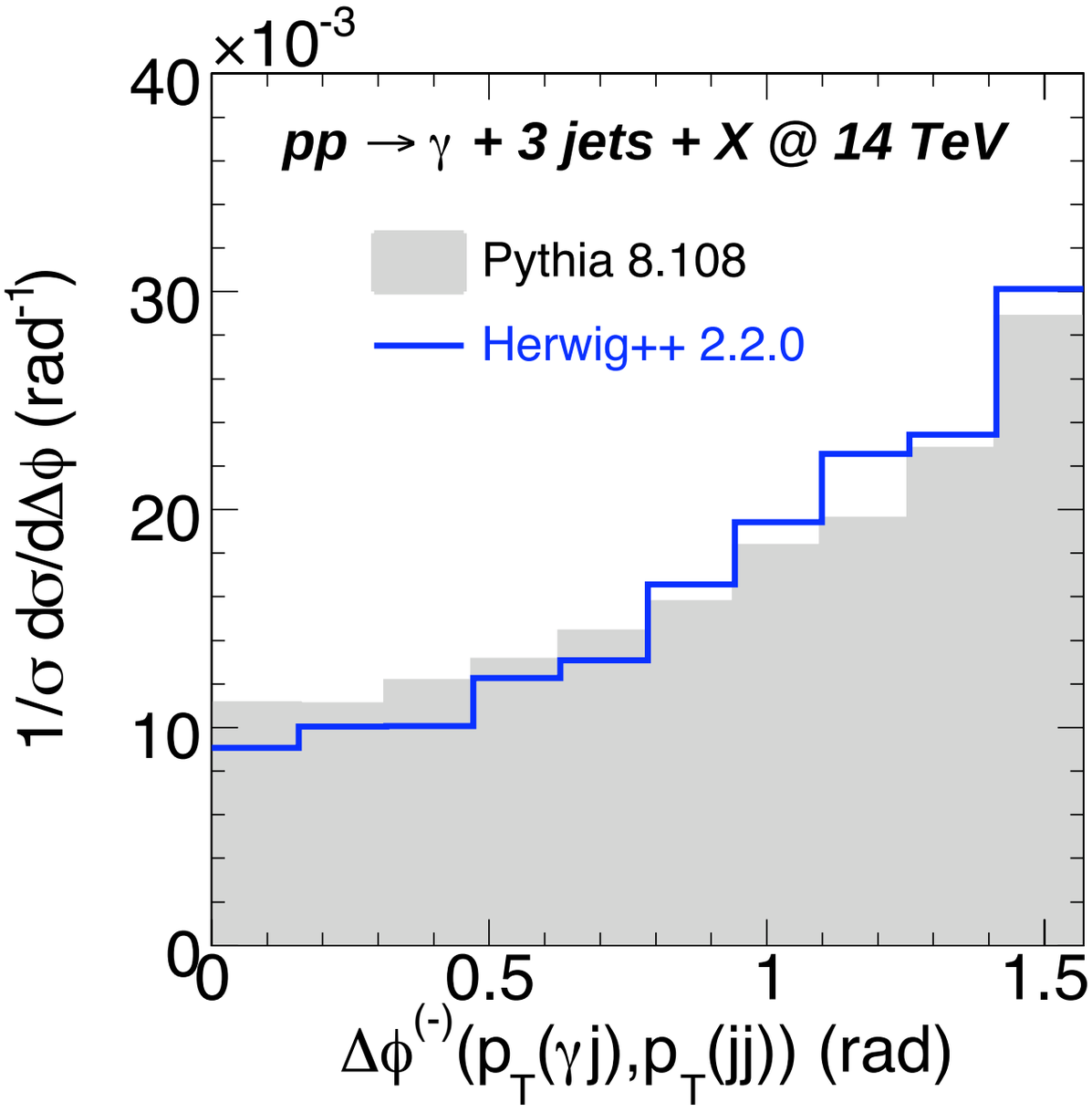


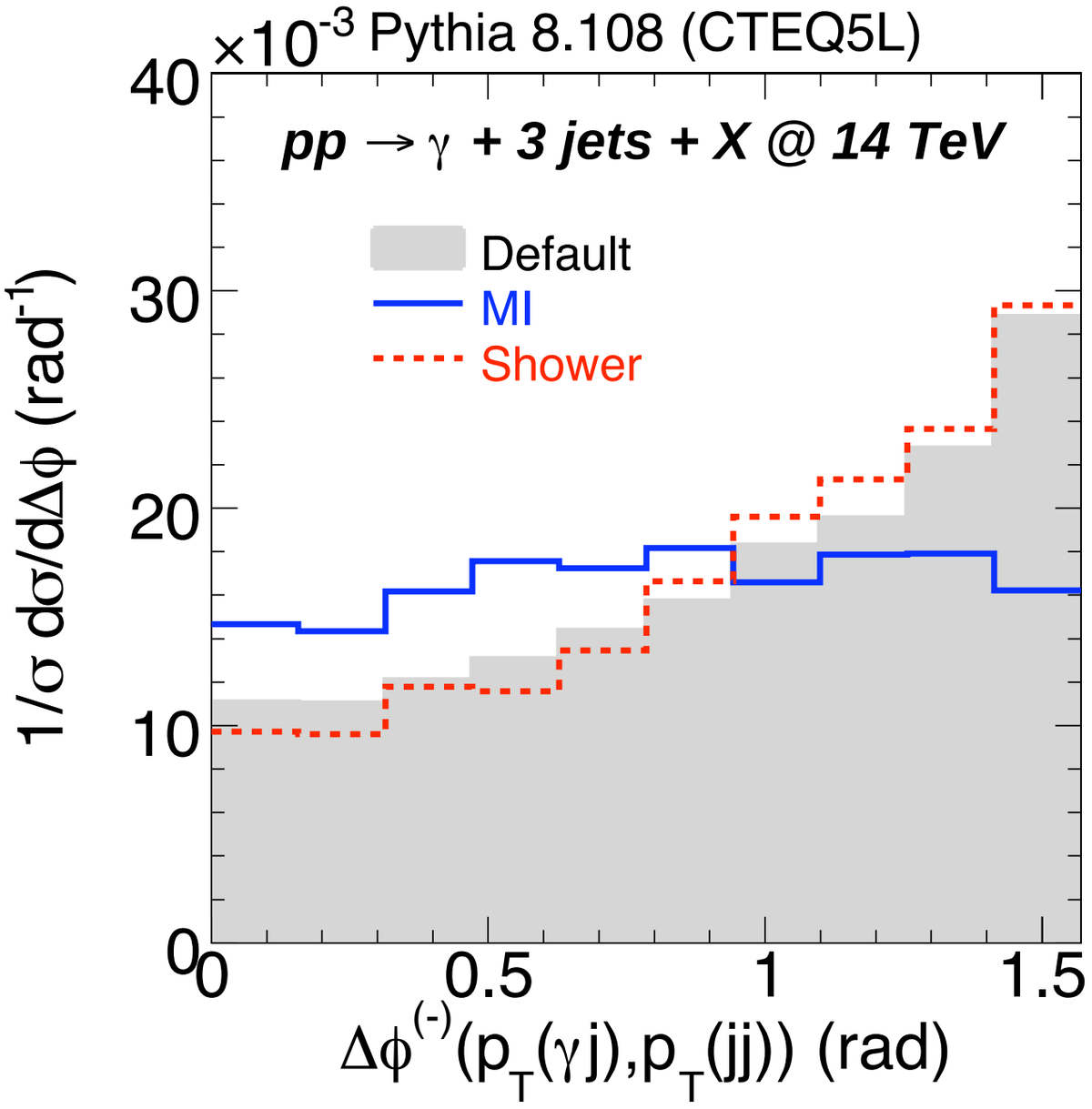


Herwig++ and Pythia w/o MI have similar shape

Separation Variables @ LHC 2

Study azimuthal angle between pairs (AFS method):





Jets 2 and 3 from MI only weakly correlated with γ-jet pair

Momentum Correlations

Bjorken-x correlations:

- For each event, study pairs

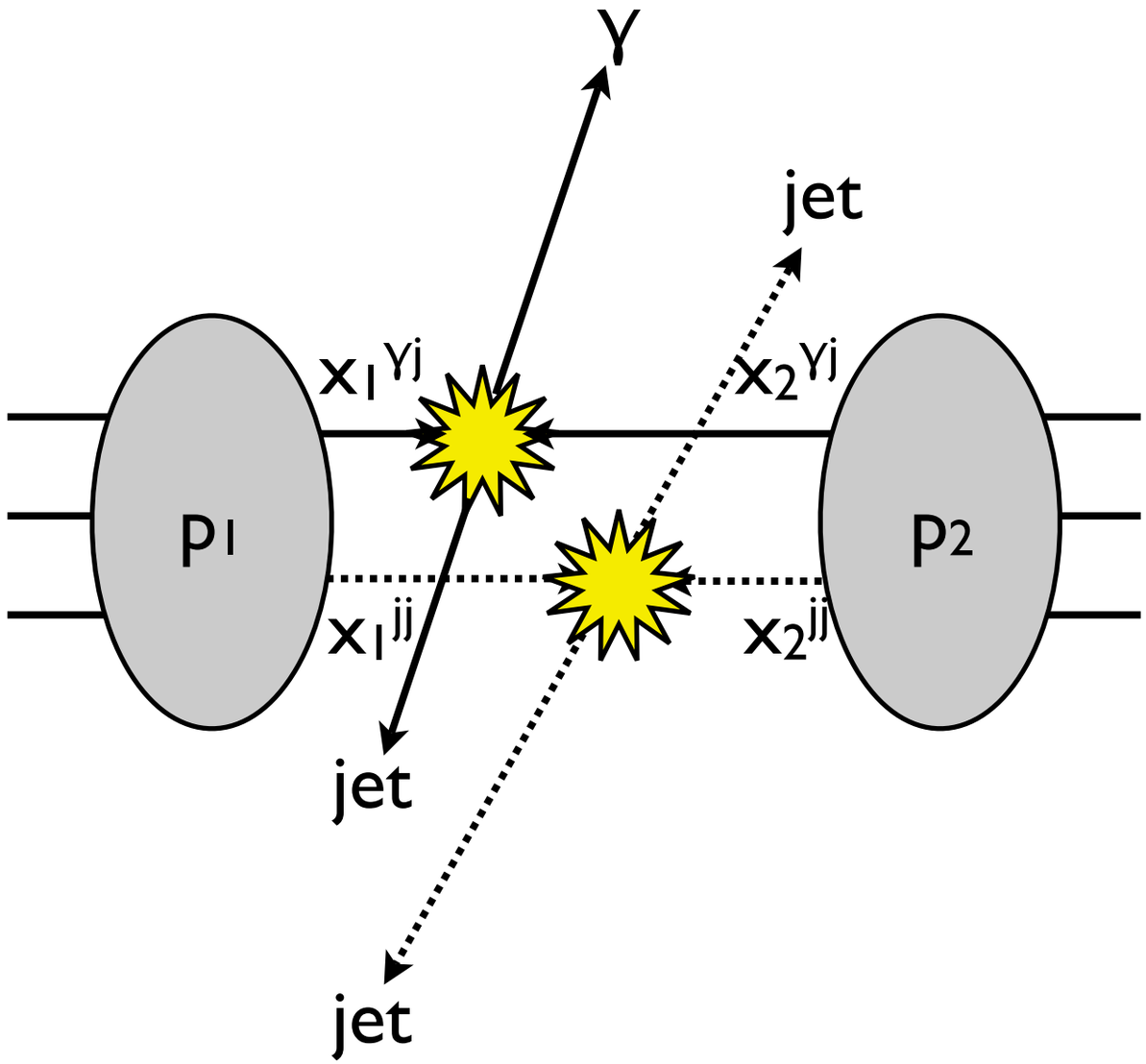
$$(x_1^{\gamma j}, x_1^{jj}), (x_2^{\gamma j}, x_2^{jj})$$

$$x_1^{\gamma j} = \frac{p_T(\gamma)}{\sqrt{s}} \left(e^{\eta(\gamma)} + e^{\eta(\mathrm{jet})} \right)$$

$$x_1^{jj} = \frac{E_{T2} + E_{T3}}{2\sqrt{s}} \left(e^{\eta_2} + e^{\eta_3} \right)$$

$$x_2^{\gamma j} = \frac{p_T(\gamma)}{\sqrt{s}} \left(e^{-\eta(\gamma)} + e^{-\eta(\mathrm{jet})} \right)$$

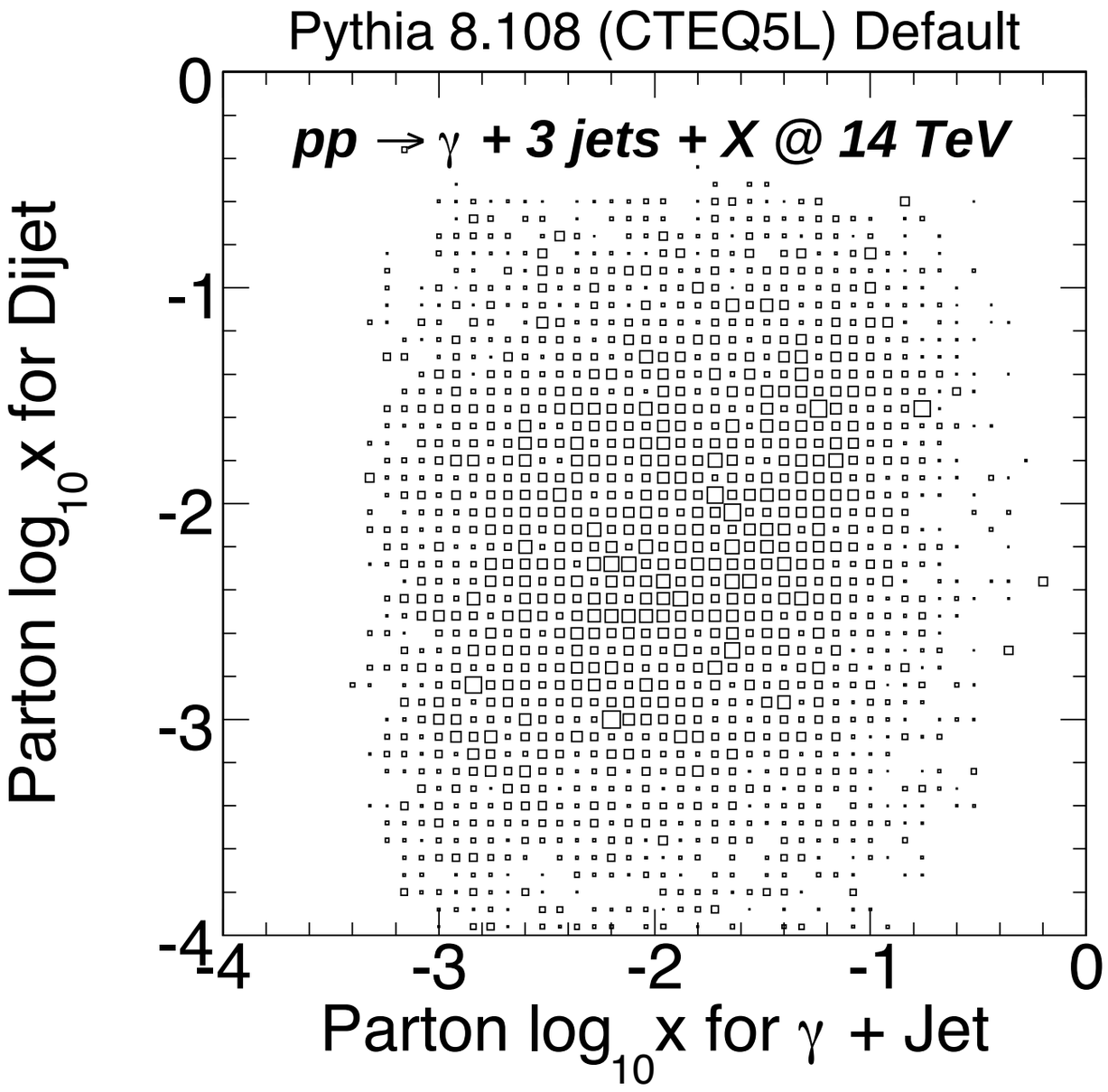
$$x_2^{jj} = \frac{E_{T2} + E_{T3}}{2\sqrt{s}} \left(e^{-\eta_2} + e^{-\eta_3} \right)$$

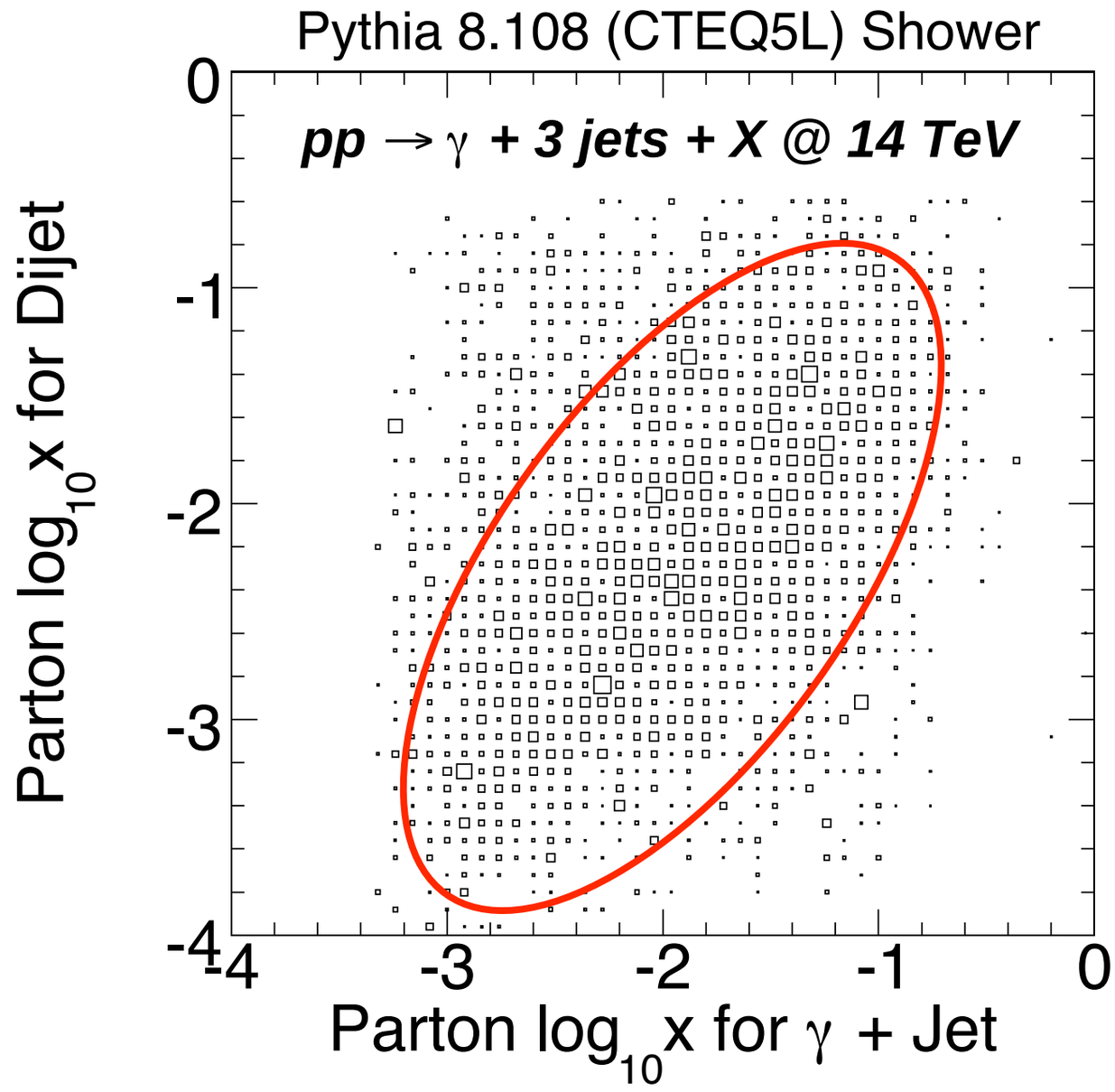


Enrich DPS content: cos Δφ(γ, j_1) ≤ -0.9 & Δφ(j_2, j_3) ≤ -0.9

Bjorken-x Analysis @ LHC

Bjorken-x correlation with and without MI





Observe weak correlation for jets from parton shower

Summary

- **Double-parton-scattering: Direct evidence for multiple parton-parton interactions**

- **New multiple interaction models studied and validated for LHC energies**

- **Correlations in angle and momentum studied**

- **Status: Herwig and Pythia suggest only small impact of Double-Parton-Scattering at the LHC**

- **Studies with full detector simulation ongoing**

BACKUP

Event selection @ Tevatron

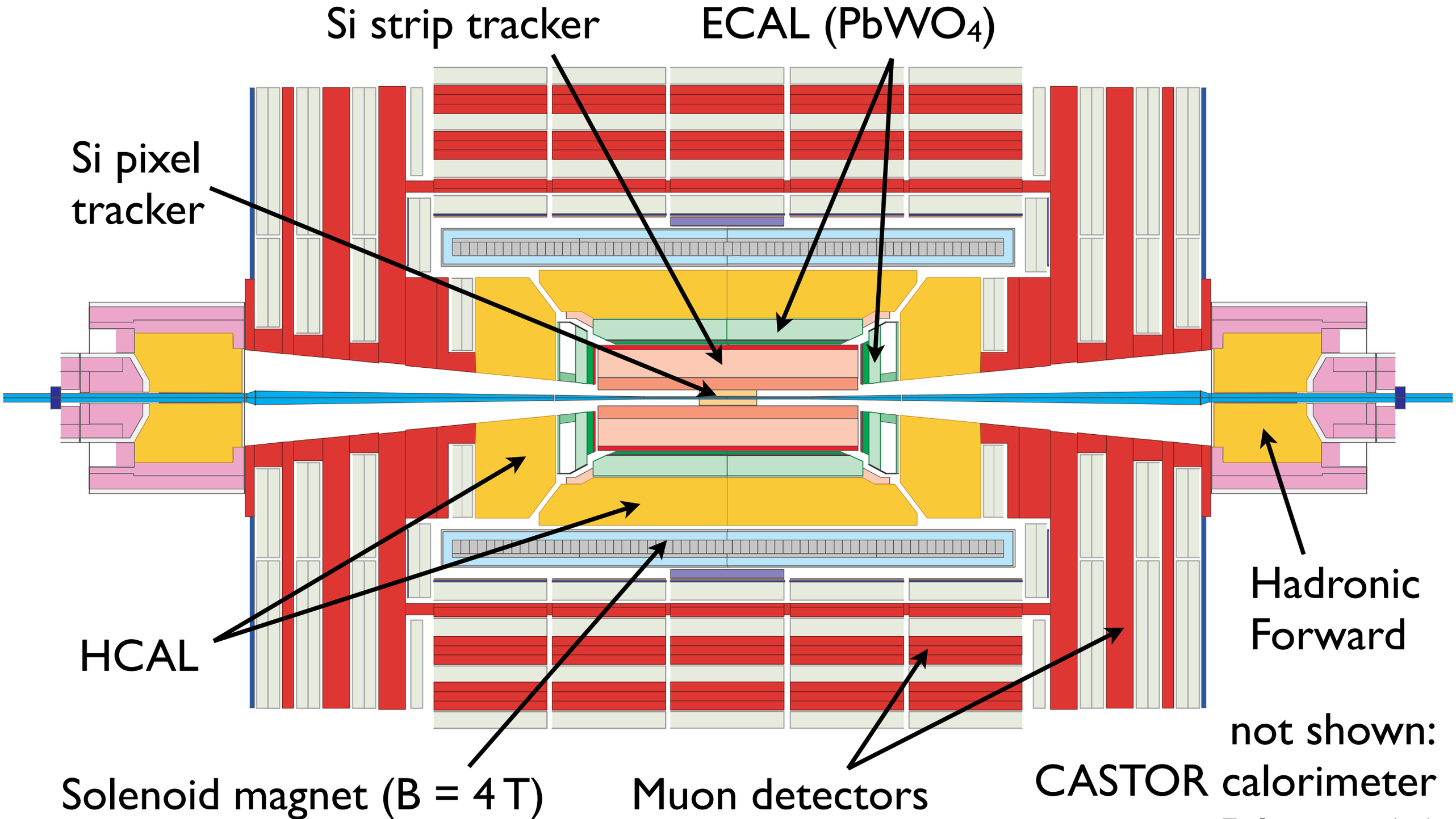
- **CDF analysis ($p\bar{p} \rightarrow \gamma/\pi^0$ + 3 jets, 16 pb^{-1})**

Phys. Rev. D56:3811-3832, 1997

- **Photon:**
  - $|\eta| < 1.1$
  - $E_T > 16$ GeV ($\rightarrow$ CDF inclusive photon trigger)

- **Jets:**
  - Run cone-algorithm on calo-towers (R=0.7)
  - $|\eta| < 4.2$
  - $E_T > 5$ GeV
  - exactly three jets
  - two lowest E_T-jets: $E_T < 7$ GeV

Compact Muon Solenoid

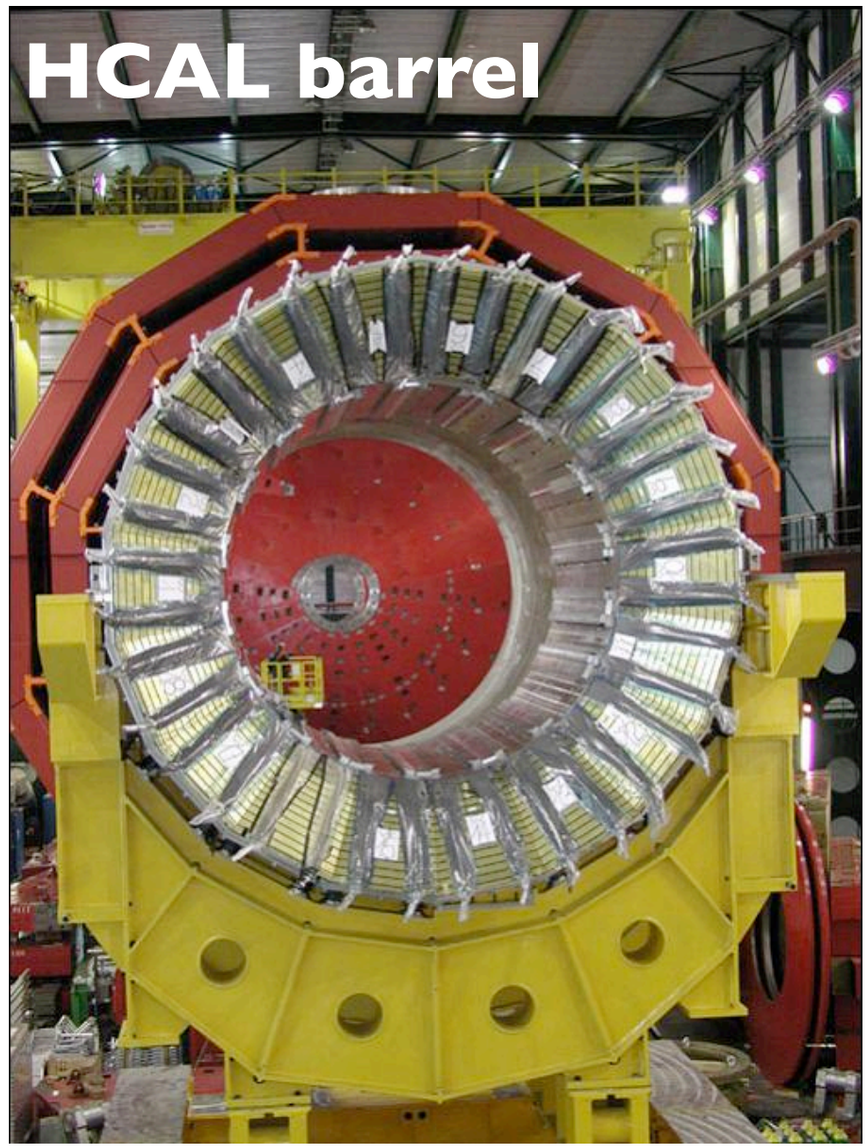


CMS Calorimeter

- **ECAL: Lead Tungstate ($PbWO_4$) crystals**
  - Coverage $|\eta| \leq 3$
  - High granularity $\Delta\eta \times \Delta\varphi = 0.0175 \times 0.0175$ (~80k crystals)
  - ~ 26 X_0

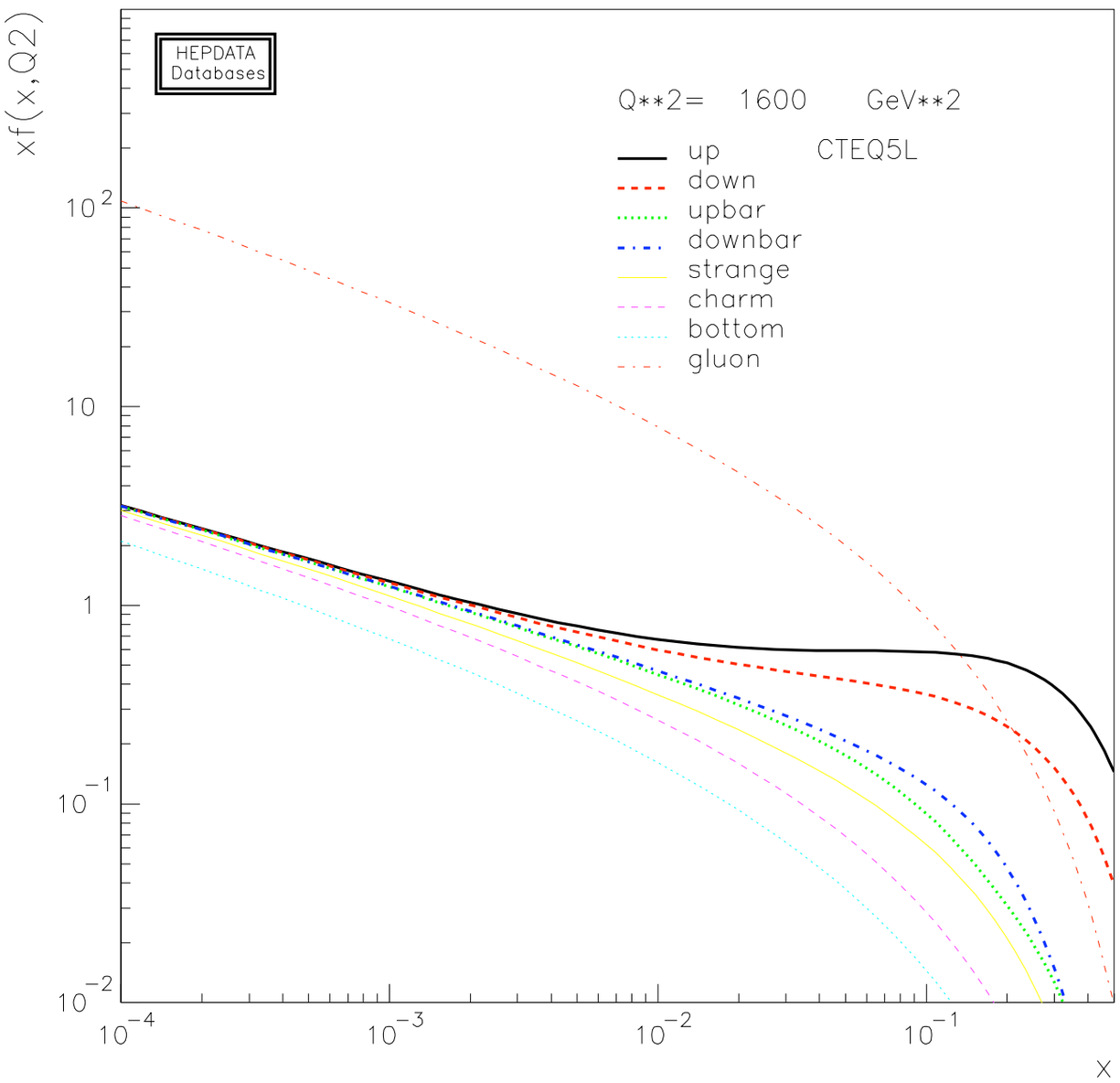
- **HCAL: Copper (brass) / scintillator sampling calorimeter**
  - Coverage: $|\eta| \leq 5$
  - Granularity (barrel)
    $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$ (~40k cells)
  - ~ 7-11 λ (+ 4 λ from HO in barrel)

- **Calorimeter towers**
  - One HCAL cell and 5x5 crystals
  - Overall tower threshold 0.5 GeV
  - 82 towers in η and 72/36/18 towers in φ

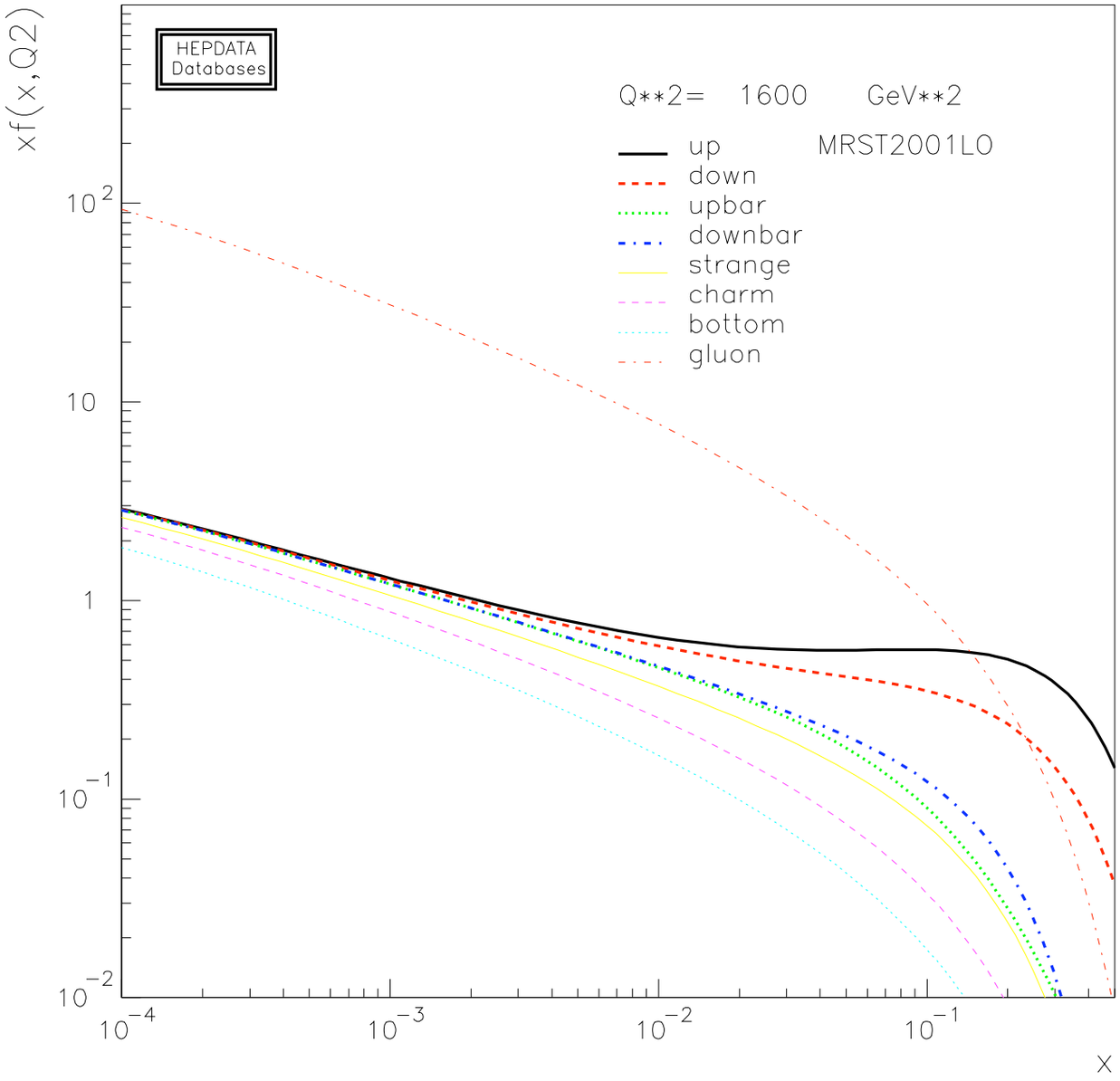


Default PDF Sets

Pythia 8: CTEQ5L

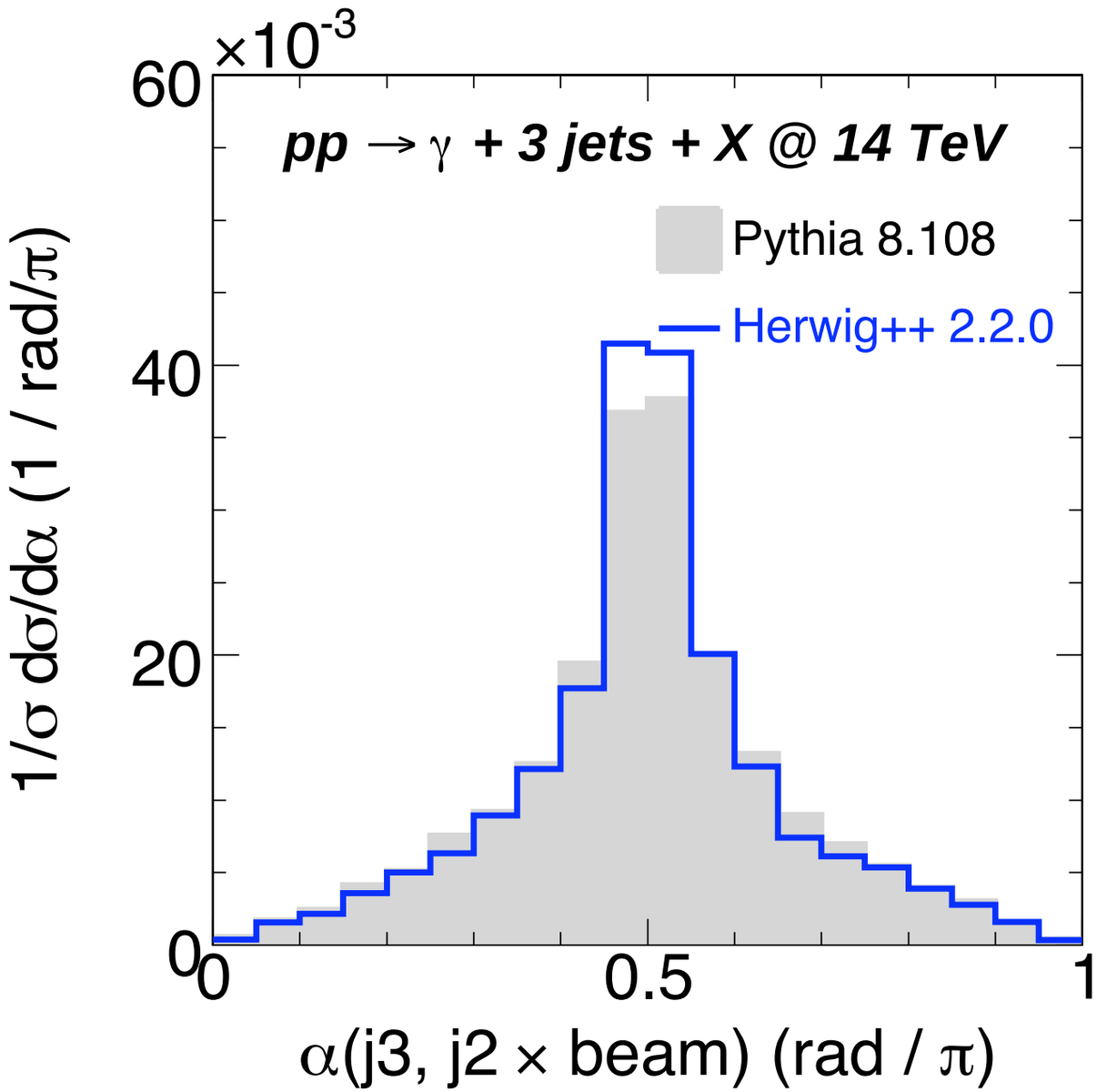


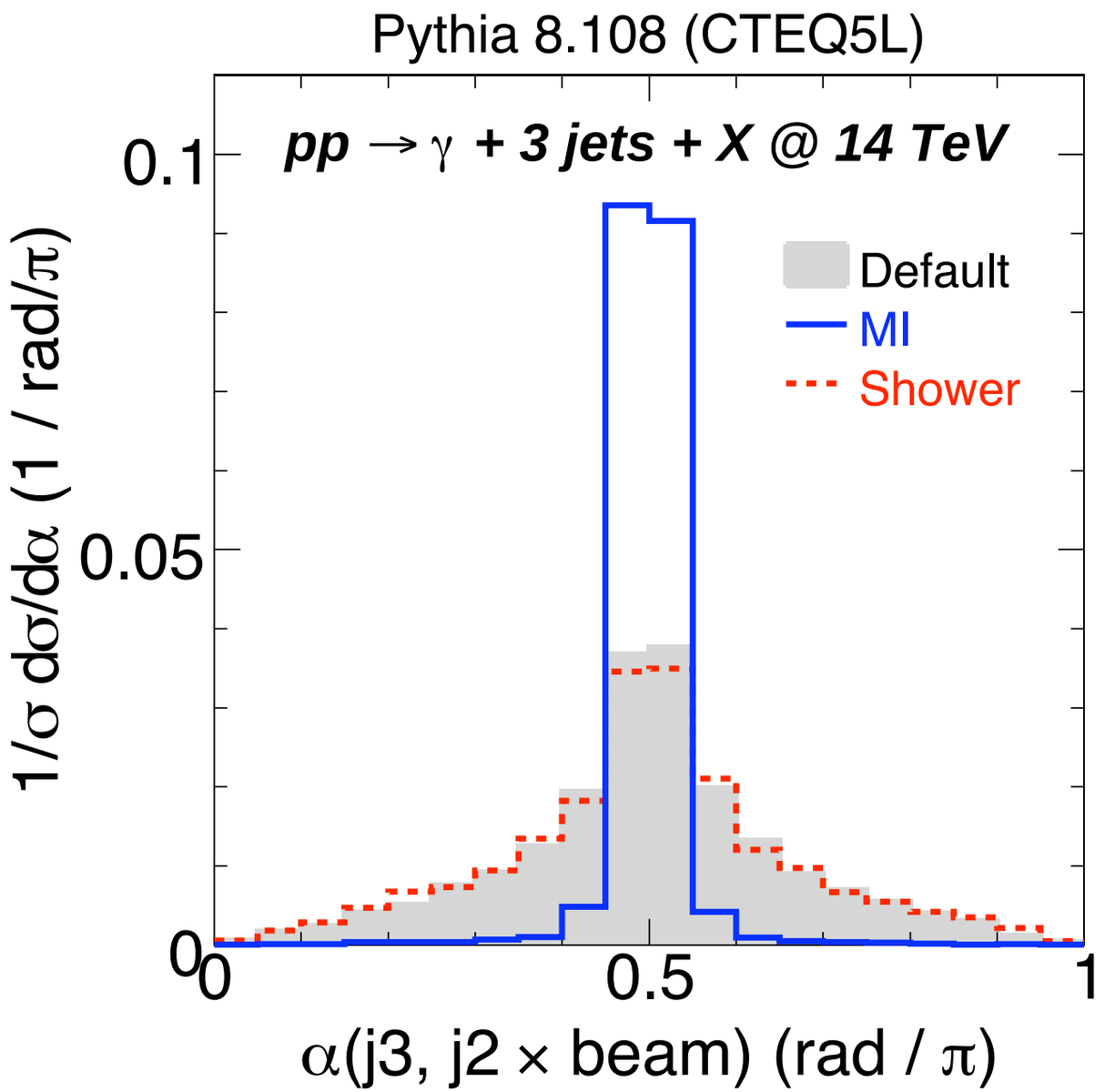
Herwig++ 2: MRST2001LO



Angular Correlations I

Angle between Jet 3 and Jet 2 / beam plane

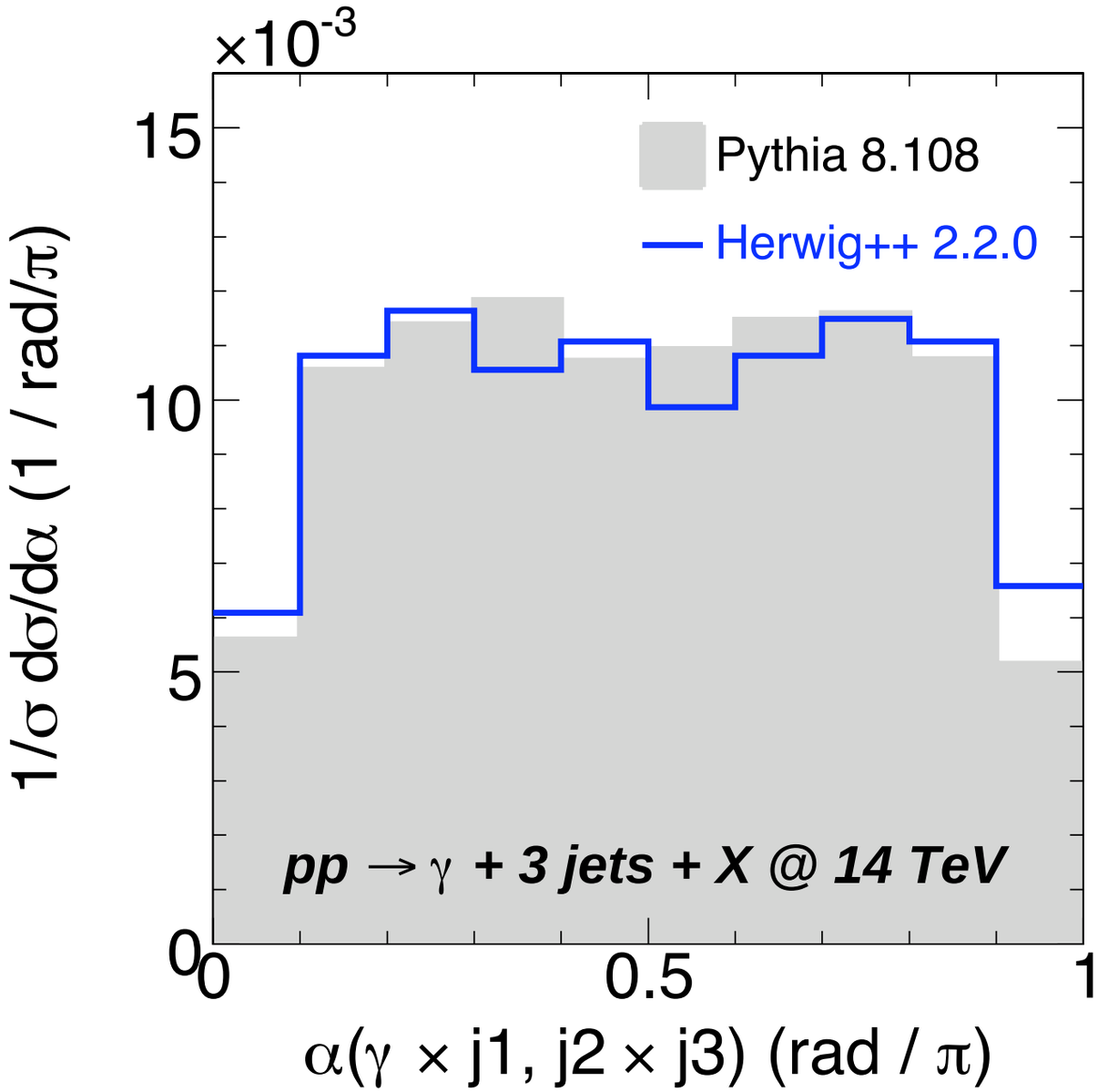


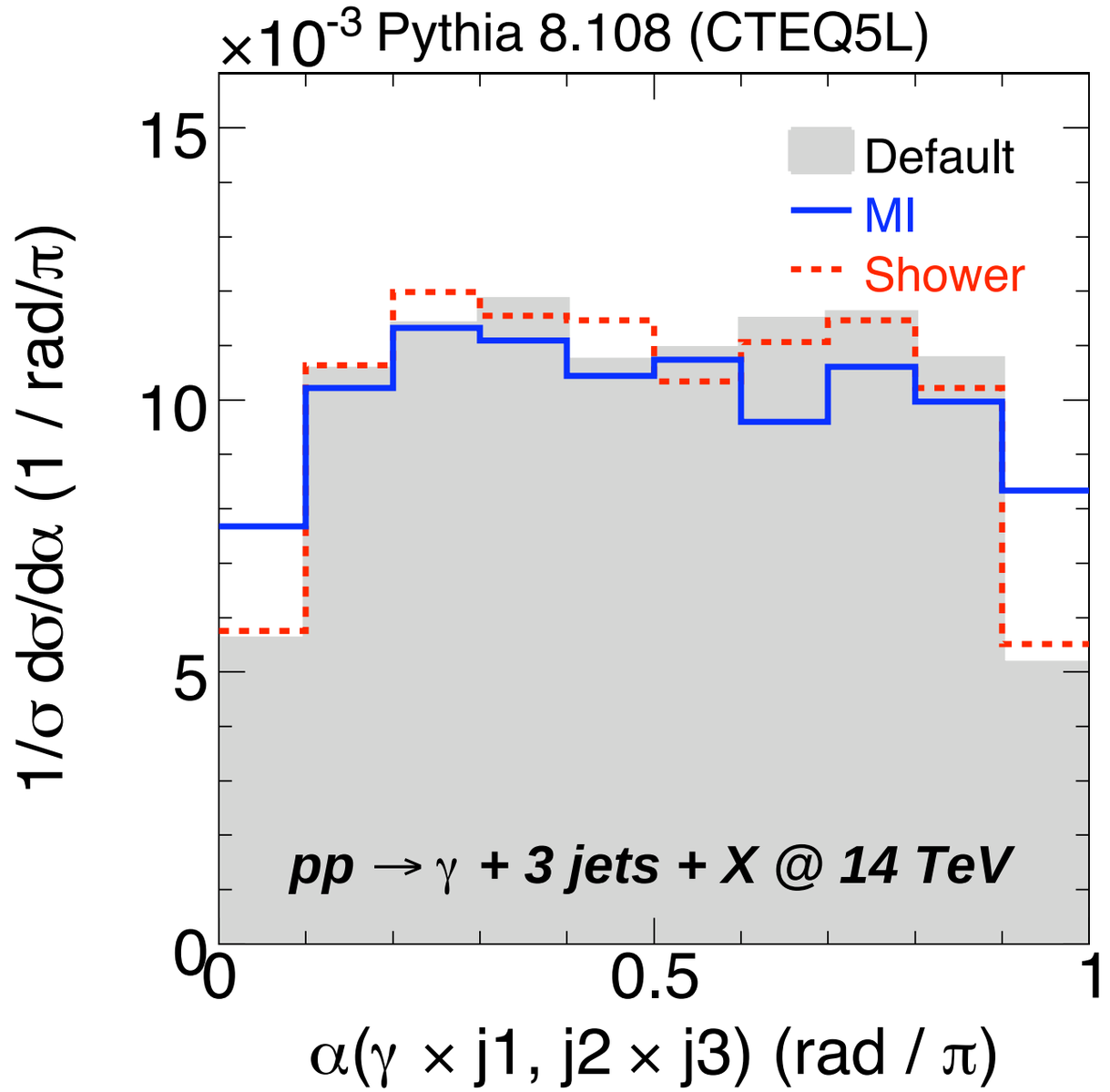


Jet 3 mostly in plane of Jet 2 and beam

Angular Correlations 2

Angle between pair's decay planes





Decay planes ~ orthogonal