BSM Parton Shower
in Herwig7

1. Generalized angular-order parton showers in Herwig 7
[Lee, Masouminia, Seymour, Yang, JHEP 08 (2024) 064]
2. Searching for New Physics Inside Jets with the Herwig 7
Generalised Parton Shower
[Lee, Kim, Masouminia, Seymour, Yang]

Joon-Bin Lee[1] • M.R. Masouminia[3] • Taehee Kim[1] • Un-ki Yang[1] • Michael H. Seymour[2]

1 Seoul National University
2 University of Manchester
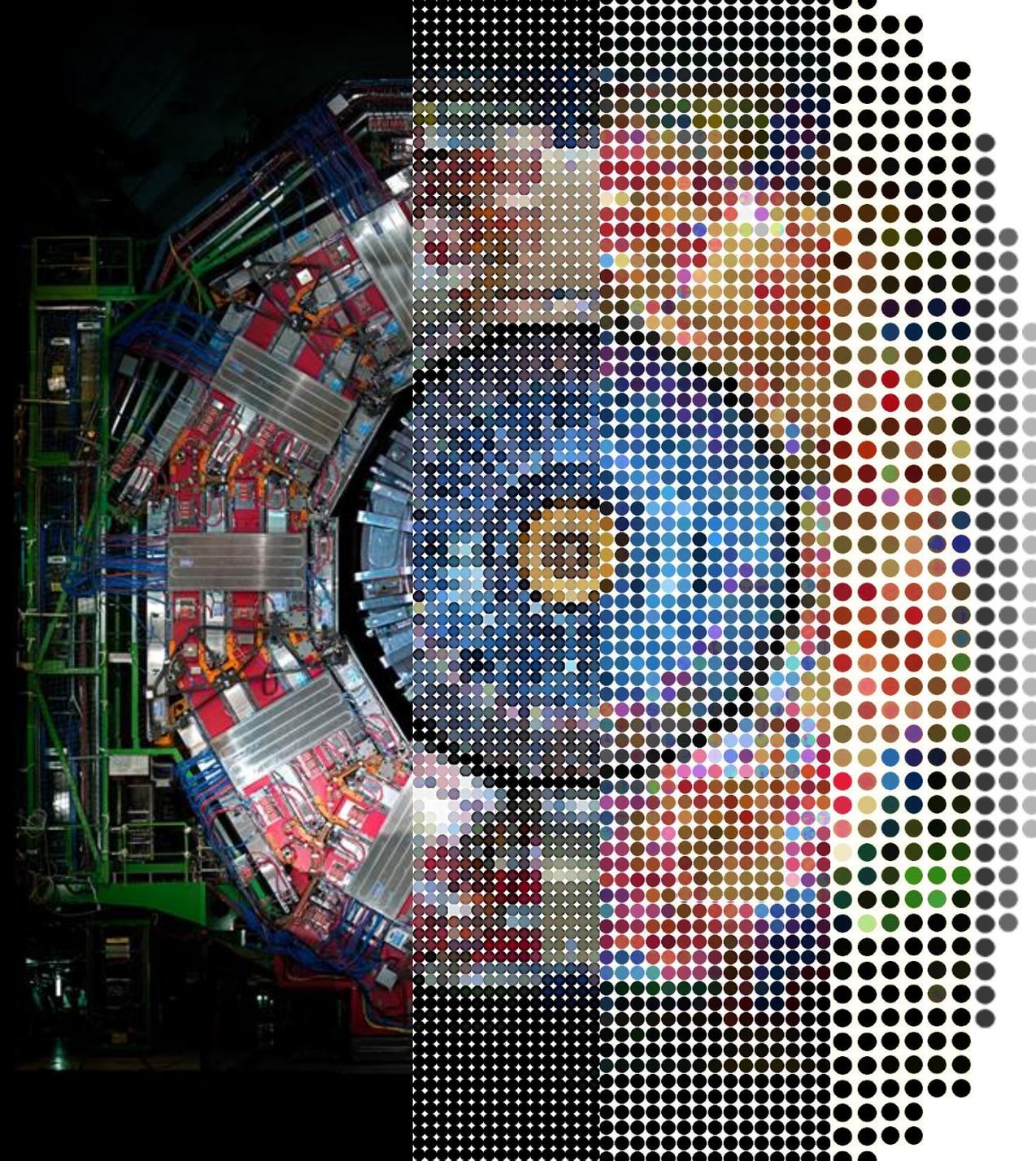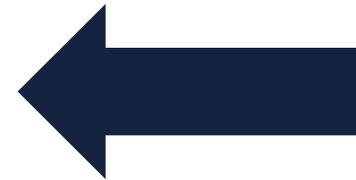**3** IPPP, Durham University
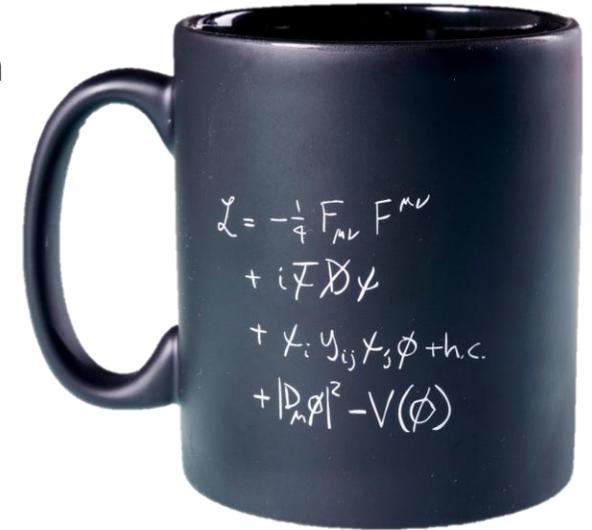
MCnet project

Marie Curie Actions

Event Generator = Translator

Ultra-high dimension integration

"MC method"

ME event generators
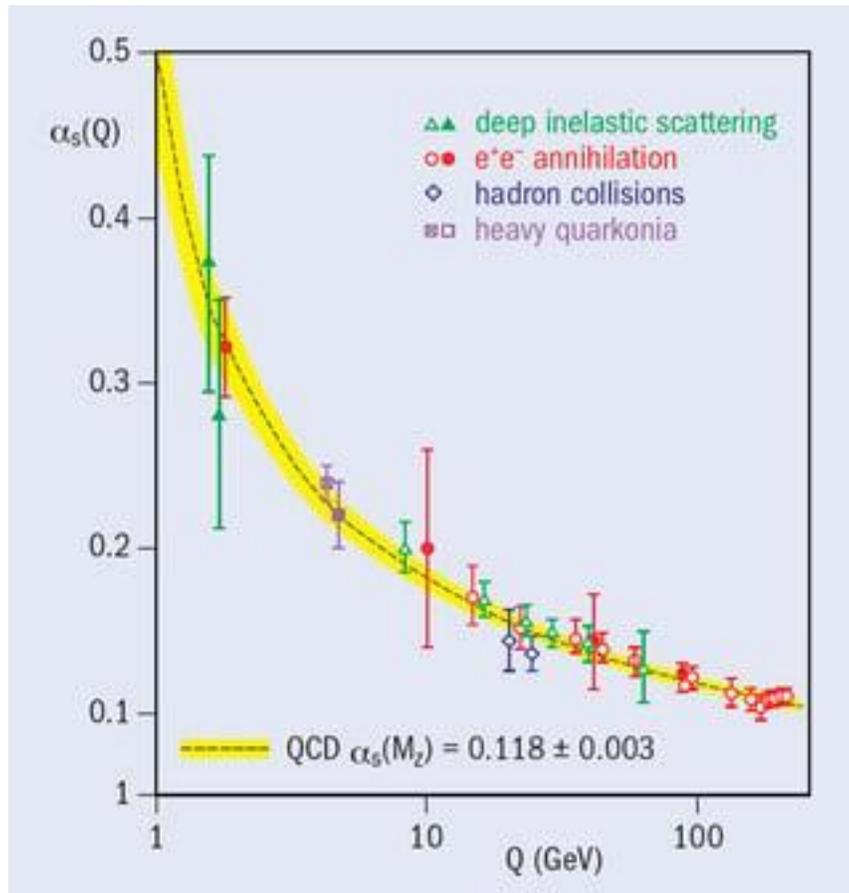- MadGraph5, POWHEG, Sherpa, …

General purpose (Parton Shower) event generators
- Pythia8, Herwig7, …

Event Simulation in pp Collisions

@ low Q^2, running α_s = infinite number of diagrams

QCD simulation

> How to control soft & collinear physics (divergences)?

> For processes with separate scales $Q \gg Q_0$, higher-order corrections are enhanced by large logarithms

$$\alpha_s^n \ln^m Q/Q_0$$

> Hadron physics needs **logarithmic resummation = Parton Shower**

Angular-order shower program (Herwig7)

> Handle colour coherence

> **QCD shower (1988) → QED (2006) → EW (2022) → "BSM (2024)"** extensions in the parton shower regime

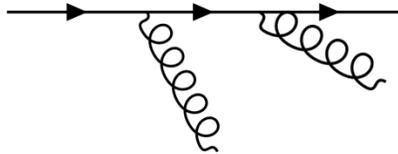[Lee, Masouminia, Seymour, Yang, JHEP 08 (2024) 064]

Parton Shower Algorithms

Comparing Approaches: Angular-Ordering vs. Dipole Shower

Herwig7
Angular-Ordered Shower

Strength

🕐 **Color Coherence** Captures the "Chudakov effect" naturally via angular ordering property (simple).

🔗 **Shower History** Perfectly tracks shower history, making it ideal for recursive BSM implementations.

⭐ **BSM Suitability** Splitting functions are more intuitive. Excellent for implementing new radiation.
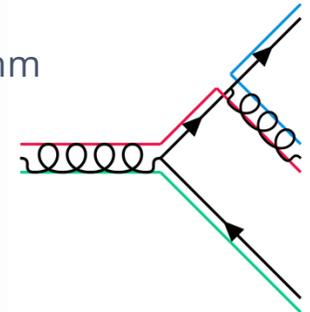
VS

Pythia8
pT-Ordered Dipole Shower

Strength

⏱ **Color Coherence** Dipole algorithm (with p_T ordering).

👥 **Adoption** CMS default parton shower generator with extensive tuning.

⚠ **Trade-off:** Shower history reconstruction can be more complex.

💡 **Why Angular Ordering?**
Tracking shower history explicitly → Fits to new physics search

Factorization Essentials

Total Cross Section Formula

$$d\sigma_{i+j} \simeq \frac{\alpha_{\text{int}}(\tilde{q}^2)}{2\pi} \frac{d\tilde{q}^2}{\tilde{q}^2} dz \, P_{\widetilde{ij} \to i+j}(z, \tilde{q}) \quad \times \quad d\sigma_{\widetilde{ij}}$$

⛶ Splitting Functions

> Governs probability of parton emission (Altarelli-Parisi)

> Resums collinear & soft emissions into parton showers

> **Dependent on:**   **Spins, Masses, Ordering Variable**

⚙ Practical Impact

✓ Modular computation: Calculate pieces individually

✓ Validation: Isolate hard process from shower effects

Factorization Theorem Workflow

1. PDF Convolution
Parton Distribution Functions

×

2. Hard Scattering
Matrix Element Calculation

×

3. Parton Shower/Hadronisation/Decay
Resummation of QCD Effects

↓

Final Hadronic Observables

BSM Showers in Herwig7

Model-Independent Framework for New Physics Simulation

Phenomenology
Universal Splittings

- Only depends on spins, masses, and ordering variables of participating particles
- Based on the **Master Formula by Altarelli and Parisi** [NPB 126, 2 (1977)]

$$P_{0 \to 12}(z, \tilde{q}) = \frac{1}{2(q_0^2 - m_0^2)} \sum_{s_0, s_1, s_2} |\mathcal{M}_{s_0, s_1, s_2}|^2$$

- **Covers all spin combinations for emitters & spectators:**

  spin-0   spin-1/2   spin-1

Universal Coverage

⚛ **Hand Calculation**

⚖ **Coding**

In Herwig7
Automated & General

- **Full automation**: Reads BSM model information automatically from **UFO model files without manual intervention**
- Flexibility: can be interfaced with various matrix-element generators such as Herwig7's internal ME calculator and MG5, ...
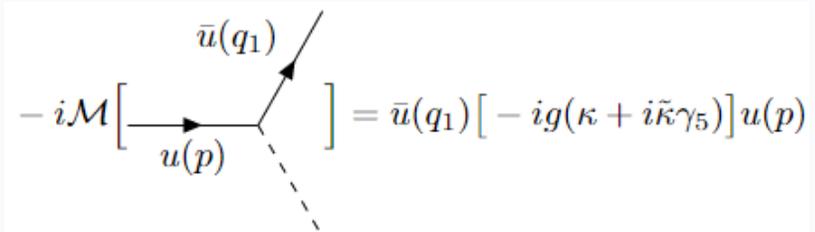
Automation is Key

[Lee, Masouminia, Seymour, Yang, JHEP 08 (2024) 064]   6

Example Splitting: q → q φ

Spin-Dependent Matrix Elements & General Coupling

Matrix Element Calculation

$$-i\mathcal{M}\left[\begin{array}{c}\bar{u}(q_1) \\ \xrightarrow{\hspace{1cm}} \\ u(p)\end{array}\right] = \bar{u}(q_1)\left[-ig(\kappa + i\tilde{\kappa}\gamma_5)\right]u(p)$$

Generalized Splitting Function

$$P_{f \to f'\phi}(z, \tilde{q}) =$$

$$\frac{g^2}{2}\left[\left(\rho_+|\kappa + i\tilde{\kappa}|^2 + \rho_-|\kappa - i\tilde{\kappa}|^2\right) \cdot \left[(1-z) - m_{2,t}^2\right] + (\rho_+ + \rho_-)\left[|\kappa|^2(m_{0,t} + m_{1,t})^2\right.\right.$$

$$\left.+ |\tilde{\kappa}|^2(m_{0,t} - m_{1,t})^2\right] + 2(\rho_+ - \rho_-)\Im(\kappa\tilde{\kappa})\left[(1-2z)m_{0,t}^2 + m_{1,t}^2\right]\right],$$

[Lee, Masouminia, Seymour, Yang, JHEP 08 (2024) 064]

✓ Validation

1. SM Limit Recovery

$$g = g_W m_0/2m_W, \; g_W = e/\sin\theta_W$$
$$m_0 = m_1, \; \kappa = 1, \; \tilde{\kappa} = 0, \text{ and } \rho_0 + \rho_1 = 1,$$

$$P_{f \to f\phi}^{SM}(z, \tilde{q}) = \frac{g_W^2}{8}\left(\frac{m_0}{m_W}\right)^2\left[(1-z) + \frac{4m_0^2 - m_2^2}{z(1-z)\tilde{q}^2}\right]$$
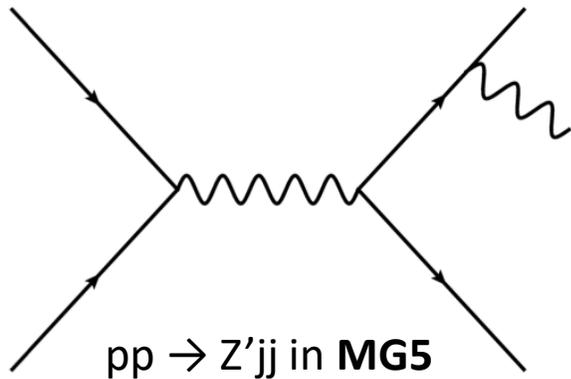
2. Performance test with FO

[JHEP 08 (2024) 064]

Performance Test

Comparing Fixed-Order (FO) and Resummed Shower (RS) Approaches

Fixed-Order (FO)
Full MadGraph5 Simulation

pp → Z'jj in **MG5**

VS

Resummed Shower (RS)
Herwig7 Parton Shower

pp → jj in **MG5**

+

q → qZ' in **HW7**
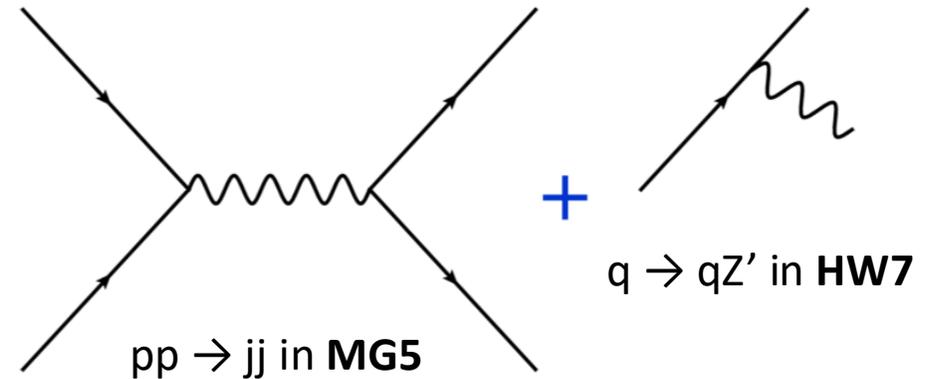
✔ **Expected Agreement**

Comparing "HW(Z'+SM PS) - HW(only Z' PS)" with "HW(only Z' PS) - MG(Z')" should show similar phenomena in the **collinear regime**.

Z' shower in U(1)$_{\text{B-L}}$

Model Features

Gauge Symmetry

U(1)$_{\text{B-L}}$

Covariant Derivative

$$D_\mu = \partial_\mu + ig'\ Y_{B-L}\ Z'_\mu$$

Lagrangian

$$\mathcal{L}_f = \sum_k i\,\bar{\psi}_k \gamma^\mu D_\mu \psi_k$$

$$\mathcal{L}_{\text{int}} \supset g'_1\, Z'_\mu \sum_f \left(Y^f_{B-L}\, \bar{f}\gamma^\mu f \right)$$

Properties

Vector coupling only

Anomaly Free **Mass = Gauge Eigenstate** **No mixing**

- The original splitting function

$$P_{f\to f'V}(z,\tilde{q}) = (|g_R|^2\rho_+ + |g_L|^2\rho_-)\left[\frac{1+z^2}{1-z}(1+m^2_{f,t}) - \frac{1+z}{1-z}m^2_{f',t} - m^2_{V,t}\right]$$
$$+ (|g_R|^2\rho_- + |g_L|^2\rho_+)zm^2_{f,t} - 2\text{Re}(g_L g_R^*)(\rho_+ + \rho_-)m_{f,t}m_{f',t},$$

- Symmetric property: $g_L = g_R = g'_1(B-L)$ from the model

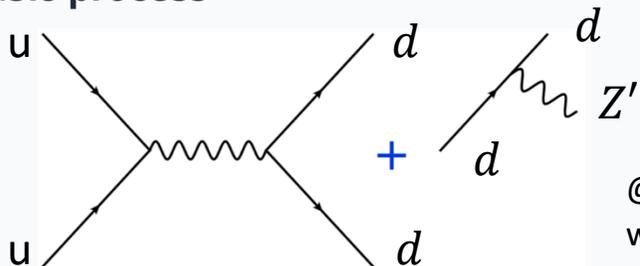$$P_{f\to fV}(z,\tilde{q}) = \frac{g^2}{2}\left(\frac{1+z^2}{1-z} - 2m^2_{f,t} - m^2_{V,t}\right)$$

- The mass terms = dead-cone effect

Performance test: q → q V

Minimal extension of Z' from SM, U(1)$_{B-L}$

Basic process

u — d

d

+ Z'

d

u — d

@ 13.6 TeV
w/ m(Z') = 10 GeV

Validation results
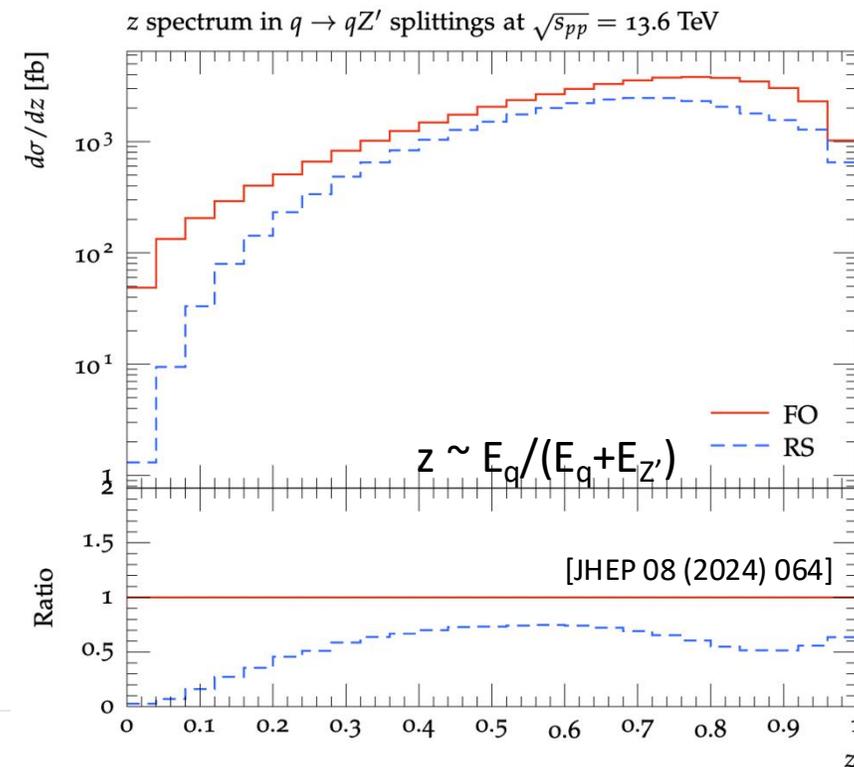
FO: $u\bar{u} \to d\bar{d}Z'$ (MG5)   **RS**: $u\bar{u} \to d\bar{d}$ (MG5) + $u \to uZ'$ (HW7)

Wonderful agreement @ collinear region

notable decrease @ non-collinear region

✓ No SM shower is included

✓ Only a single Z' emission is allowed in HW7

$\Delta R(q, Z')$ spectrum in $q \to qZ'$ splittings at $\sqrt{s_{pp}} = 13.6$ TeV

$d\sigma/d\Delta R(q,Z')$ [fb]

— FO
--- RS

ΔR(q, Z')

Ratio

[JHEP 08 (2024) 064]

$\Delta R(q, Z')$

z spectrum in $q \to qZ'$ splittings at $\sqrt{s_{pp}} = 13.6$ TeV

$d\sigma/dz$ [fb]

z ~ E$_q$/(E$_q$+E$_{Z'}$)

— FO
--- RS

Ratio

[JHEP 08 (2024) 064]

z

Validation

20
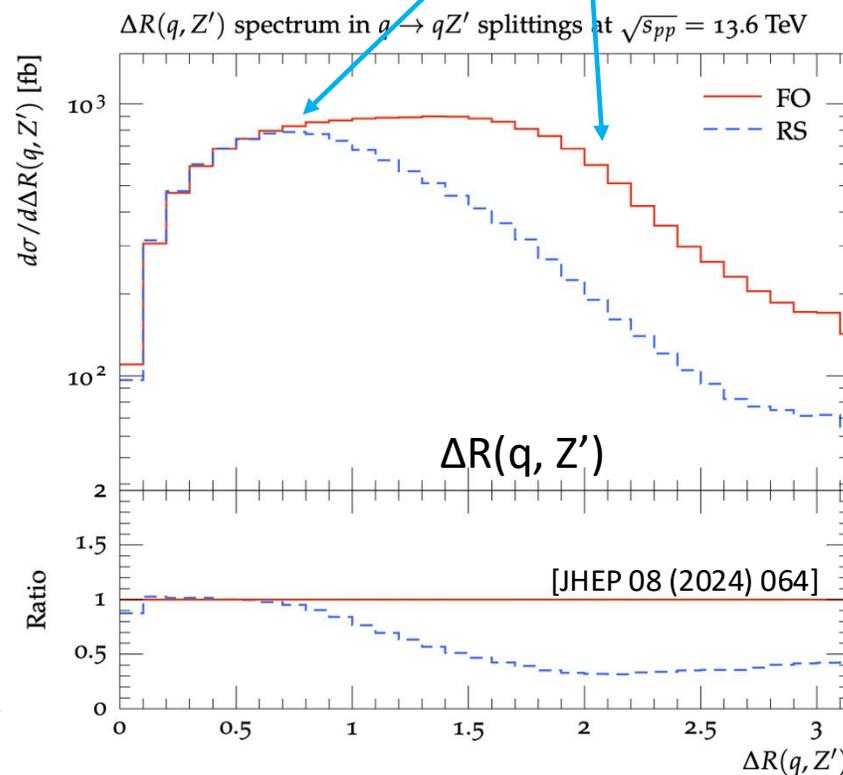
BSM Parton Shower
in Herwig7

Searching for New Physics Inside Jets with the Herwig 7 Generalised Parton Shower

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2 University of Manchester
3 IPPP, Durham University

Motivation

Direction
First look

- **Search Z' → μμ inside jets**

- **Model-independent**, but pick up one **example model (B-L extension) for interpretation**

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times \boxed{U(1)_{B-L}}$$

- Signal samples are generated with HW BSM parton shower framework (previous work)

- **Search range: m(μμ) = [5, 50] GeV**, i.e. above B hadron & below Z mass

- **Provide kinematic features of BSM PS & significance** under the current LHC setup

Inclusive study is Key

Model Features

Gauge Symmetry

$$U(1)_{B\text{-}L}$$

Covariant Derivative

$$D_\mu = \partial_\mu + ig' \ Y_{B\text{-}L} \ Z'_\mu$$

Lagrangian

$$\mathcal{L}_f = \sum_k i\, \bar{\psi}_k \gamma^\mu D_\mu \psi_k$$

$$\mathcal{L}_{\text{int}} \supset g'_1 \, Z'_\mu \sum_f \left(Y^f_{B-L} \, \bar{f} \gamma^\mu f \right)$$

Properties

Vector coupling only

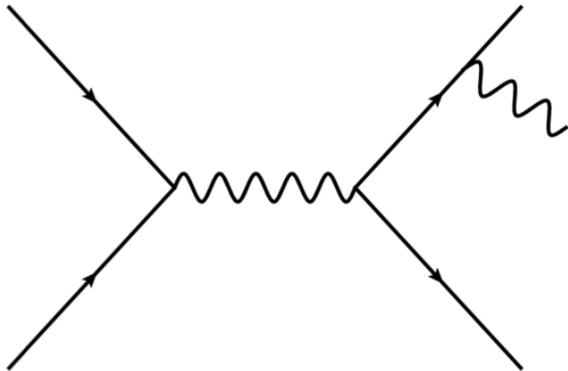Anomaly Free   Mass = Gauge Eigenstate   No mixing

Performance Test

Comparing Fixed-Order (FO) and Resummed Shower (RS) Approaches

Fixed-Order (FO)
`MadGraph5 Simulation`
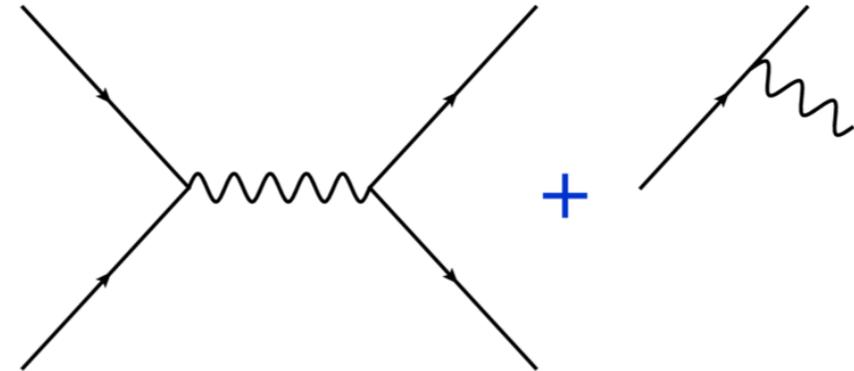

Sample References

`MG(Z')`   `MG(Z')+HW`

VS

Resummed Shower (RS)
`Herwig7 Parton Shower`

Sample References

`HW(only Z' PS)`   `HW(Z'+SM PS)`

✔ **Expected Agreement**

"HW(Z'+SM PS)" – "MG(Z')+HW" / "HW(only Z' PS)" – "MG(Z')" should show similar phenomena @ collinear regime

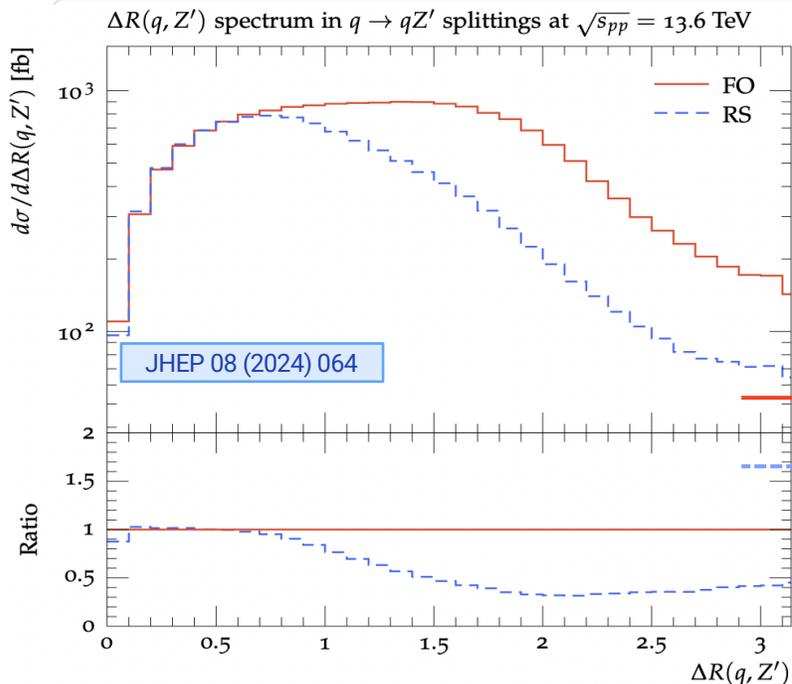Comparing "HW(Z'+SM PS)" – "HW(only Z' PS)" shows SM PS effect

Parton-level Validation Angular Separation ΔR(q, Z')

Previous Work

Only FSR-like diagrams considered in MG($u\bar{u} \to d\bar{d}\ Z'$) sample

No SM Parton Shower included, i.e. only Z' shower

Current Work

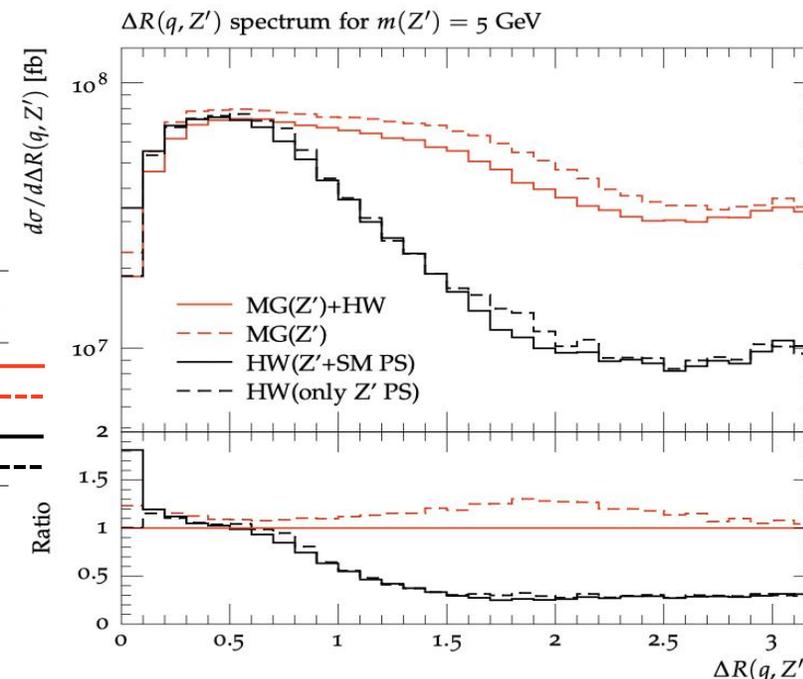Inclusive production of MG(pp → jj Z') events

Includes **full SM Shower + Z' shower** effects for **realistic** simulation

m(Z') = 10 GeV   **m(Z') = 5 GeV**

$\Delta R(q, Z')$ spectrum in $q \to qZ'$ splittings at $\sqrt{s_{pp}} = 13.6$ TeV

JHEP 08 (2024) 064

$\Delta R(q, Z')$ spectrum for $m(Z') = 5$ GeV

Sample	MadGraph 5 (ME)	Herwig 7 (shower)	
	Hard process	Z' shower	SM shower
MG(Z')+HW	$pp \to Z'jj$	off	on
MG(Z')	$pp \to Z'jj$	off	off
HW(Z'+SM PS)	$pp \to jj$	on	on
HW(only Z' PS)	$pp \to jj$	first-emission only	off

Key Findings & Improvements

✓ **Good agreement** observed in collinear region (ΔR < 1)

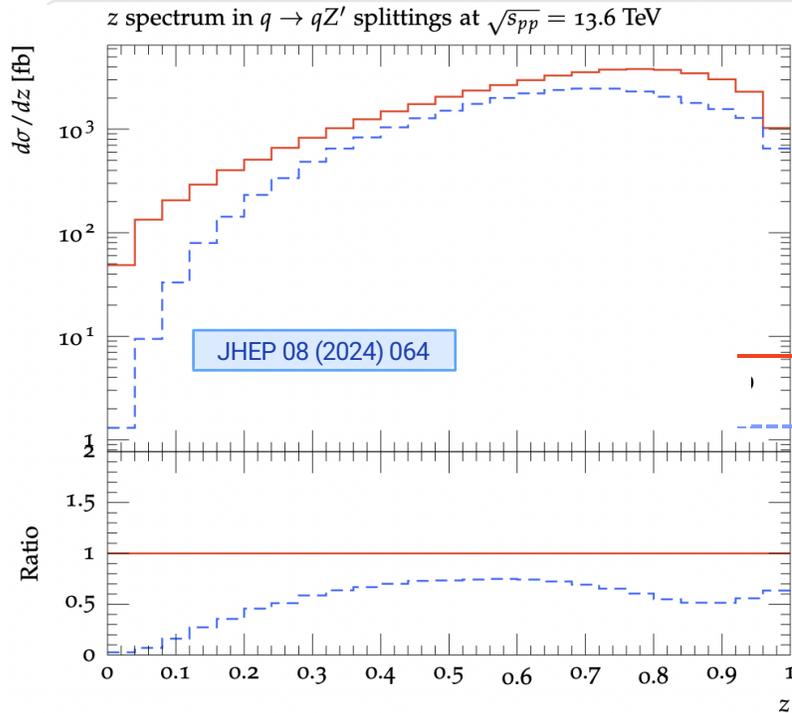↑ HW(Z'+SM PS) > HW(only Z' PS) as ΔR → 0

Enhancement driven by cascade radiation effects

Parton-level Validation   Energy Spectrum z (with ΔR < 1 cut)

Previous Work

Only FSR-like diagrams considered in MG(pp → Z' jj) sample
No SM Parton Shower included, i.e. only Z' shower

Current Work

Inclusive production of MG(pp → Z' jj) events

Includes **full SM Shower + Z' shower** effects for realistic simulation

z spectrum in $q \to qZ'$ splittings at $\sqrt{s_{pp}} = 13.6$ TeV

m(Z') = 10 GeV

JHEP 08 (2024) 064

m(Z') = 5 GeV

z spectrum for $m(Z') = 5$ GeV

Sample	MadGraph 5 (ME)		Herwig 7 (shower)	
	Hard process	Z' shower	SM shower	
MG(Z')+HW	$pp \to Z'jj$	off	on	
MG(Z')	$pp \to Z'jj$	off	off	
HW(Z'+SM PS)	$pp \to jj$	on	on	
HW(only Z' PS)	$pp \to jj$	first-emission only	off	

Legend (right plot):
- MG(Z')+HW
- MG(Z')
- HW(Z'+SM PS)
- HW(only Z' PS)

Key Findings & Improvements

👍 **Better agreement** due to the ΔR(q, Z') < 1 cut

Analysis Object-level Validation

Variable Transition   ΔR(q, Z') → ΔR(j, μμ)   z (Energy Fraction) → Muon Energy Fraction (MEF)

Quark-Z' Separation: ΔR(q, Z')

Jet-Dimuon Separation: ΔR(j, μμ)

jet criteria: $p_T > 30$ GeV & ΔR(j, q) < 0.4

Sample	MadGraph 5 (ME)	Herwig 7 (shower)	
	Hard process	Z' shower	SM shower
MG(Z')+HW	$pp \to Z'jj$	off	on
MG(Z')	$pp \to Z'jj$	off	off
HW(Z'+SM PS)	$pp \to jj$	on	on
HW(only Z' PS)	$pp \to jj$	first-emission only	off

🔍 **Observation**

More events observed as **ΔR(j, μμ) → 0,** because **anti-kt algorithm** clusters jets around the collinear Z'

Analysis Object-level Validation

Variable Transition | z (Energy Fraction) → Muon Energy Fraction (MEF) | based on "MEF $\approx 1 - z$" relation

Energy fraction, z
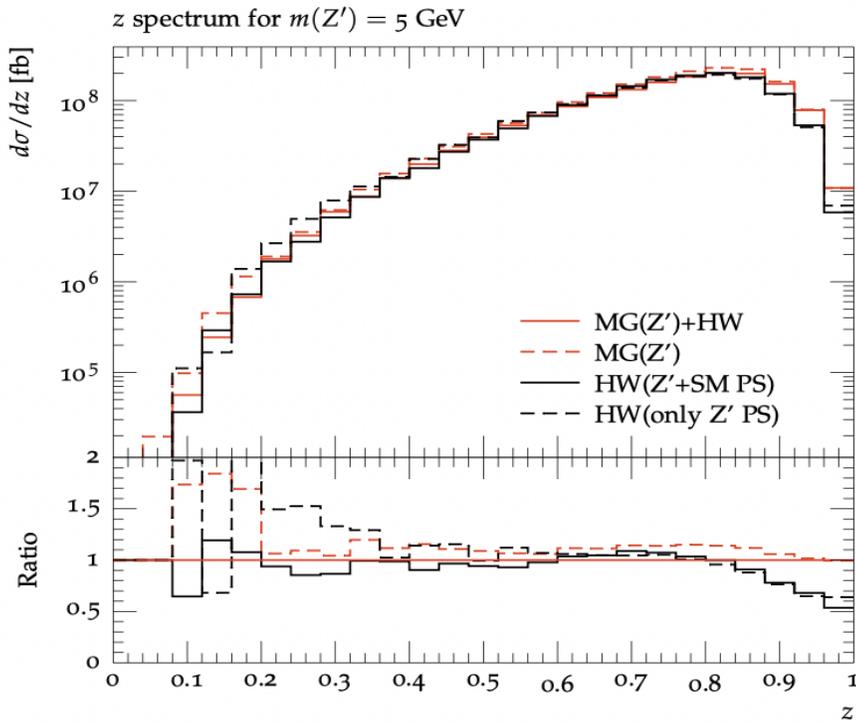
Muon Energy Fraction in a jet

	MadGraph 5 (ME)	Herwig 7 (shower)	
Sample	Hard process	Z' shower	SM shower
MG(Z')+HW	$pp \to Z'jj$	off	on
MG(Z')	$pp \to Z'jj$	off	off
HW(Z'+SM PS)	$pp \to jj$	on	on
HW(only Z' PS)	$pp \to jj$	first-emission only	off
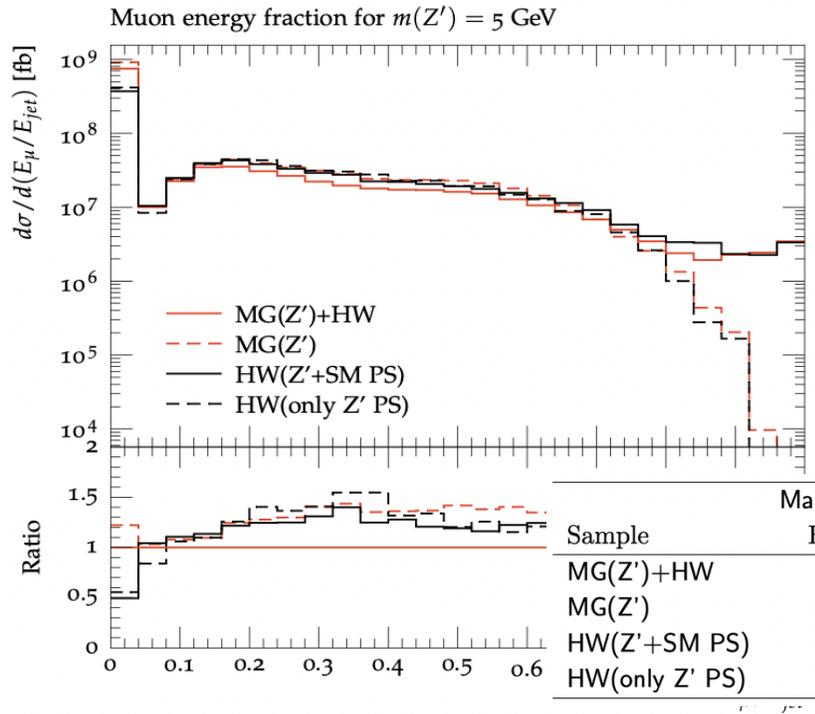
🔍 **Observation**

MEF → 0: Z' has large ΔR with the quark; MEF → 1: SM shower makes the final partons softer & non-collinear

Kinematics of jets and muons Event Selection & Background Estimation

Event selection: OS dimuon pair with pT > 52, 5 GeV (for standrad trigger) & 5, 5 GeV (for scouting trigger) inside jets (ΔR < 0.3)

Background estimation: Due to the large stat uncertainty, fit $f(m_{\mu\mu}) = A\, m_{\mu\mu}^{-n} \times \dfrac{1}{2}\left[1 + \mathrm{erf}\left(\dfrac{m_{\mu\mu} - \bar{m}}{\sqrt{2}\,\sigma}\right)\right]$

~ QCD cross section (power law) p_T turn-on
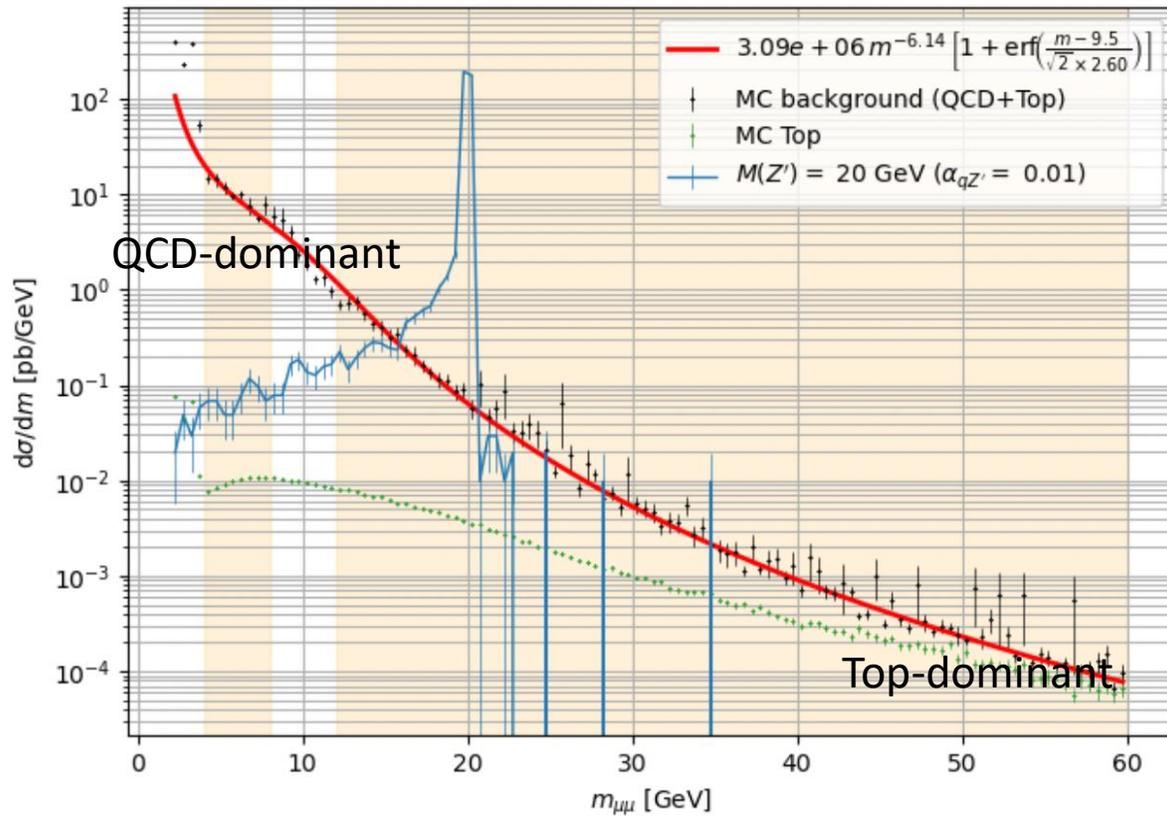
Standard Trigger   **Scouting trigger**
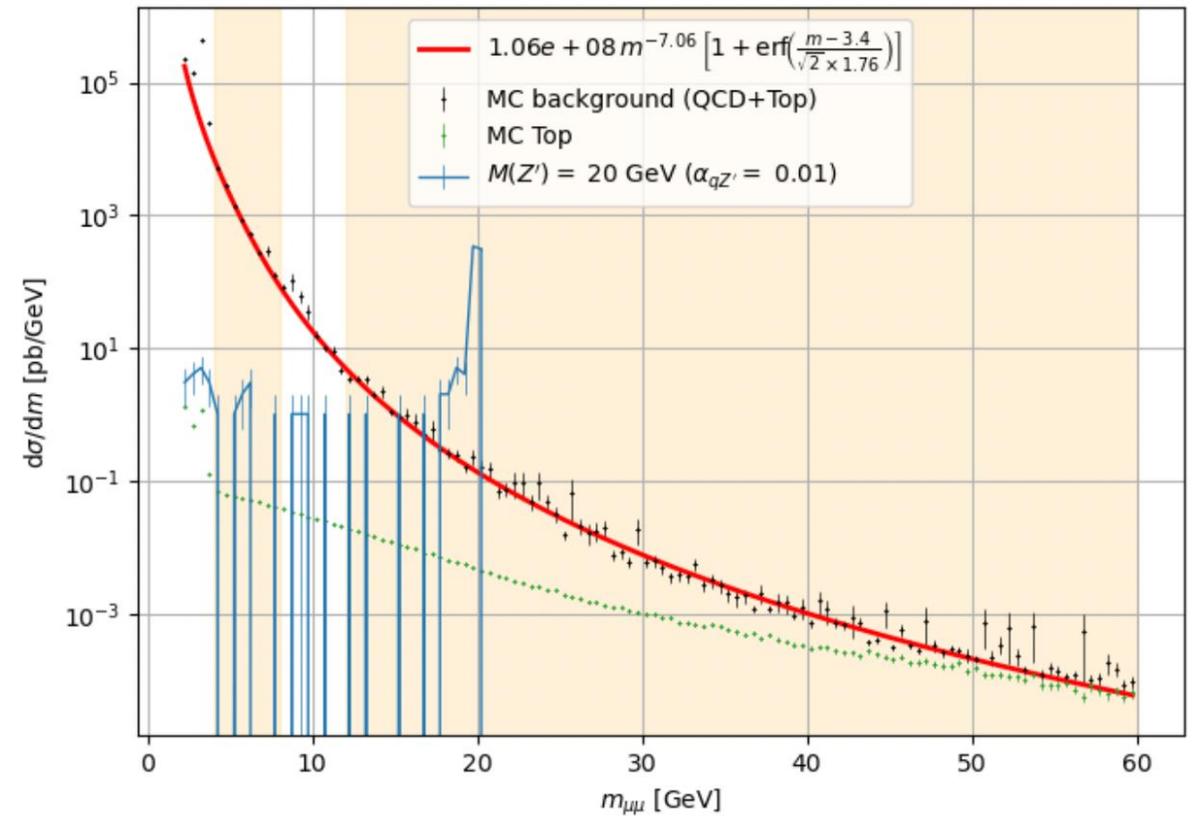
💡 Key Insight: Scouting trigger introduces no turn-on curve, improving limits @ low mass region

Significance & Expected Limit

* First-look utilizing Asimov significance without systematics consideration yet.

Significance ($\alpha_{qZ'} = 10^{-7}$, BR($Z' \to \mu^+\mu^-$)=1)

(Preliminary)

$Z_{Asimov} = \sqrt{2[(S+B)\ln(1+S/B) - S]}$

Standard, Run-2+3 (500 fb^{-1})
Standard, HL-LHC (3 ab^{-1})
Scouting, Run-2+3 (500 fb^{-1})
Scouting, HL-LHC (3 ab^{-1})

$M_{Z'}$ [GeV]

Expected 95% CL exclusion (BR($Z' \to \mu^+\mu^-$)=1)

Standard, Run-2+3 (500 fb^{-1})
Standard, HL-LHC (3 ab^{-1})
Scouting, Run-2+3 (500 fb^{-1})
Scouting, HL-LHC (3 ab^{-1})

$\alpha_{qZ'}$ (95% CL, stat-only)

$M_{Z'}$ [GeV]
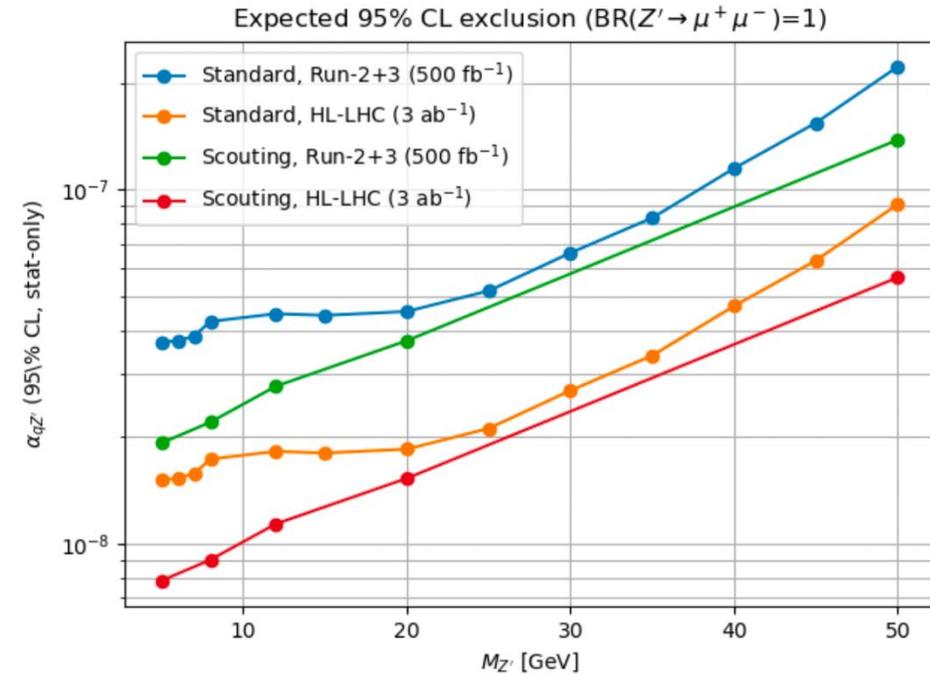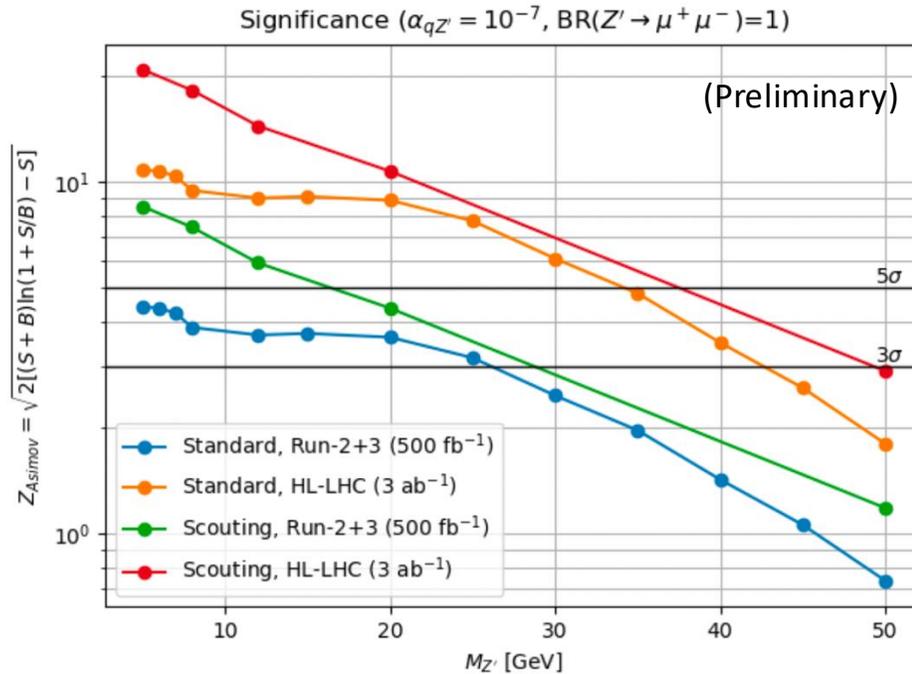
🧮 Conclusion remarks

📈 Can get 3σ @ m(Z') < 30 GeV w/ Run-2+3 & 5σ across the full search region with HL-LHC data

🚀 Because this study is the first look, we utilise the Aimov significance w/o consideration of systematics

Systematics

from the paper

A detailed study of systematic uncertainties is beyond the scope of the present first-look analysis. Nevertheless, if the observable of interest is defined as a ratio of cross sections,

$$R(j \to Z') = \frac{\sigma(pp \to jj,\ j \to Z' \to \mu^+\mu^-)}{\sigma(pp \to jj)},$$

the dominant uncertainties associated with QCD scale variations and parton distribution functions are expected to be significantly suppressed due to their substantial cancellation in the ratio. The remaining theoretical uncertainties are anticipated to originate primarily from EW Sudakov logarithms associated with Z' radiation and from the treatment of the bottom-quark mass scheme and fragmentation. These effects are expected to be moderate and, in principle, amenable to systematic control in more refined future studies.

Summary & Outlook

Achievements and Future Directions

Achievements
Current Status

Completed

- ✓ First study using **Generalised BSM Shower** in Herwig7 and validate it against fixed-order calculations.

- ✓ Proposed novel search for **Z' → μμ inside jets** using non-isolated leptons.

- ✓ Demonstrated robust modeling of BSM radiation and **promising sensitivity** in 5–50 GeV range.

- ✓ Main feature of Herwig 7.4

Future Work
Upcoming Tasks

Planned

> **Systematics Study & Optimization of event selection**
> Include full systematic uncertainties and optimize event selection (b-tagging, vertexing).

> **Model Interpretations**
> Extend analysis to other models: 2HDM+CS, hypercharge models, 3R, X models.

> **Experimental Implementation**
> Collaborate with experimental groups (CMS/ATLAS) to implement search with real data.

BSM Parton Shower
in Herwig7

END

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MCnet project

Marie Curie Actions

Event Generator = Bridge b/w Theory and Expeirment

Connecting Experimental Reality with Theoretical Calculations

Experiments
Real-world Data

- **Detector-level objects (tracks, clusters)**
- Complex environments: Pileup, electronic noise
- Trigger constraints & selection bias
- Complex final states with hadronization effects

CMS / ATLAS / LHCb

Event Generators

~1,000 particles in a single event
= **Ultra-high dimension integration**

Analysis-Ready Events

Theory
Fundamental Physics

- **Lagrangians** & Feynman Rules
- Hard scattering Matrix Elements (ME)
- Parton Distribution Functions (PDFs)
- Resummation & perturbative calculations

SM / BSM / EFT

Non-isolated lepton study

How to examine this collinear region?

2. Displaced muons
CMS-EXO-17-004: delayed μ's
CMS-EXO-16-022: eμ

CMS detector

1. Nominal muon
CMS-EXO-19-002: multilepton
CMS-SMP-17-001: DY

3. High pT muon
CMS-EXO-19-019: Z'→ll
CMS-MUO-17-001: Reco & ID

?

What's next?

4. Boosted muon pair
CMS-EXO-14-006: Z'→ϕϕ→4l

Non-isolated lepton study

How to examine this collinear region?

2. Displaced muons
CMS-EXO-17-004: delayed μ's
CMS-EXO-16-022: eμ

CMS detector

1. Nominal muon
CMS-EXO-19-002: multilepton
CMS-SMP-17-001: DY

3. High pT muon
CMS-EXO-19-019: Z'→ll
CMS-MUO-17-001: Reco & ID

"Non-isolated muon"

leptons inside a jet
→ large lepton isolation

4. Boosted muon pair
CMS-EXO-14-006: Z'→ϕϕ→4l
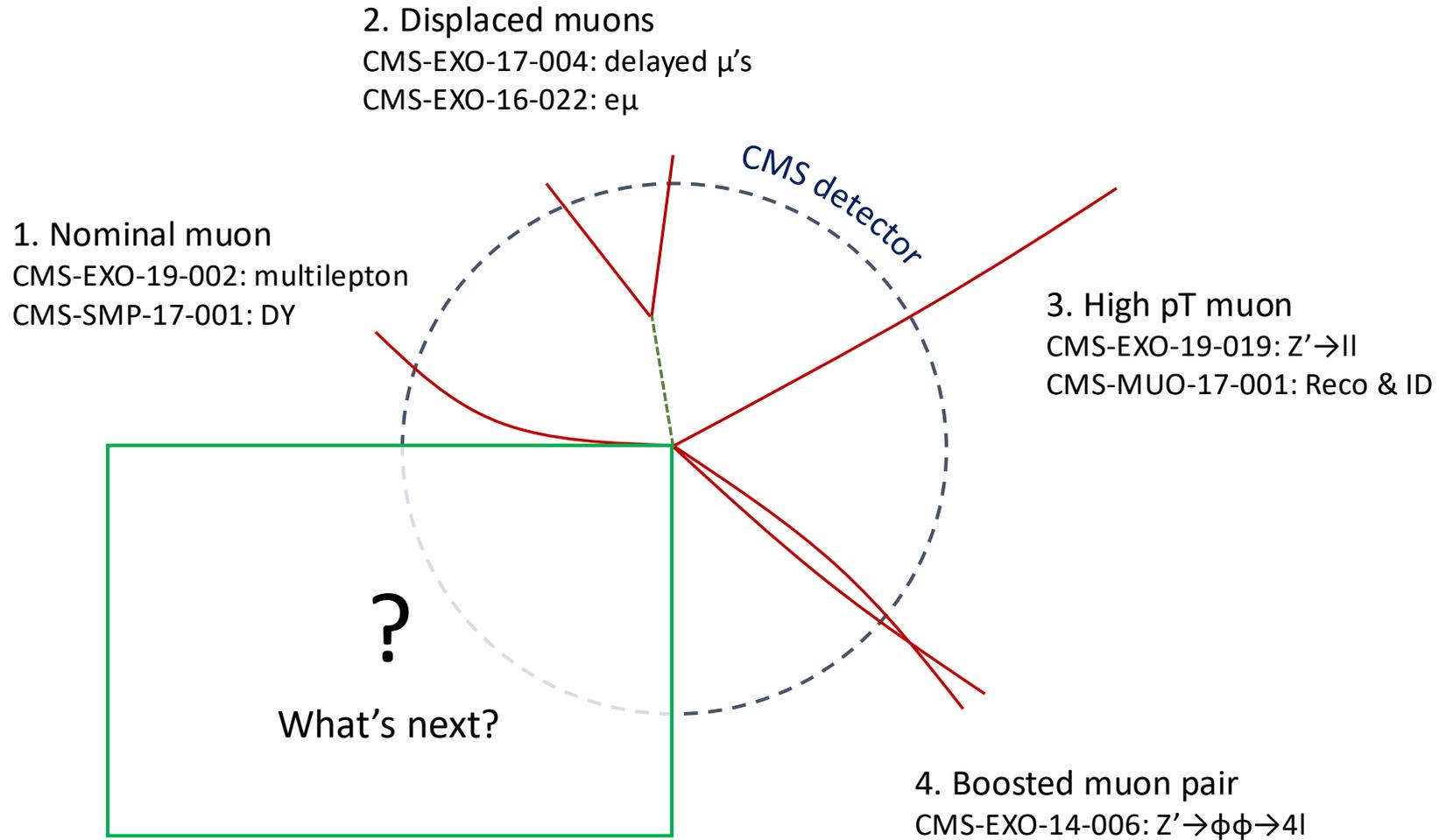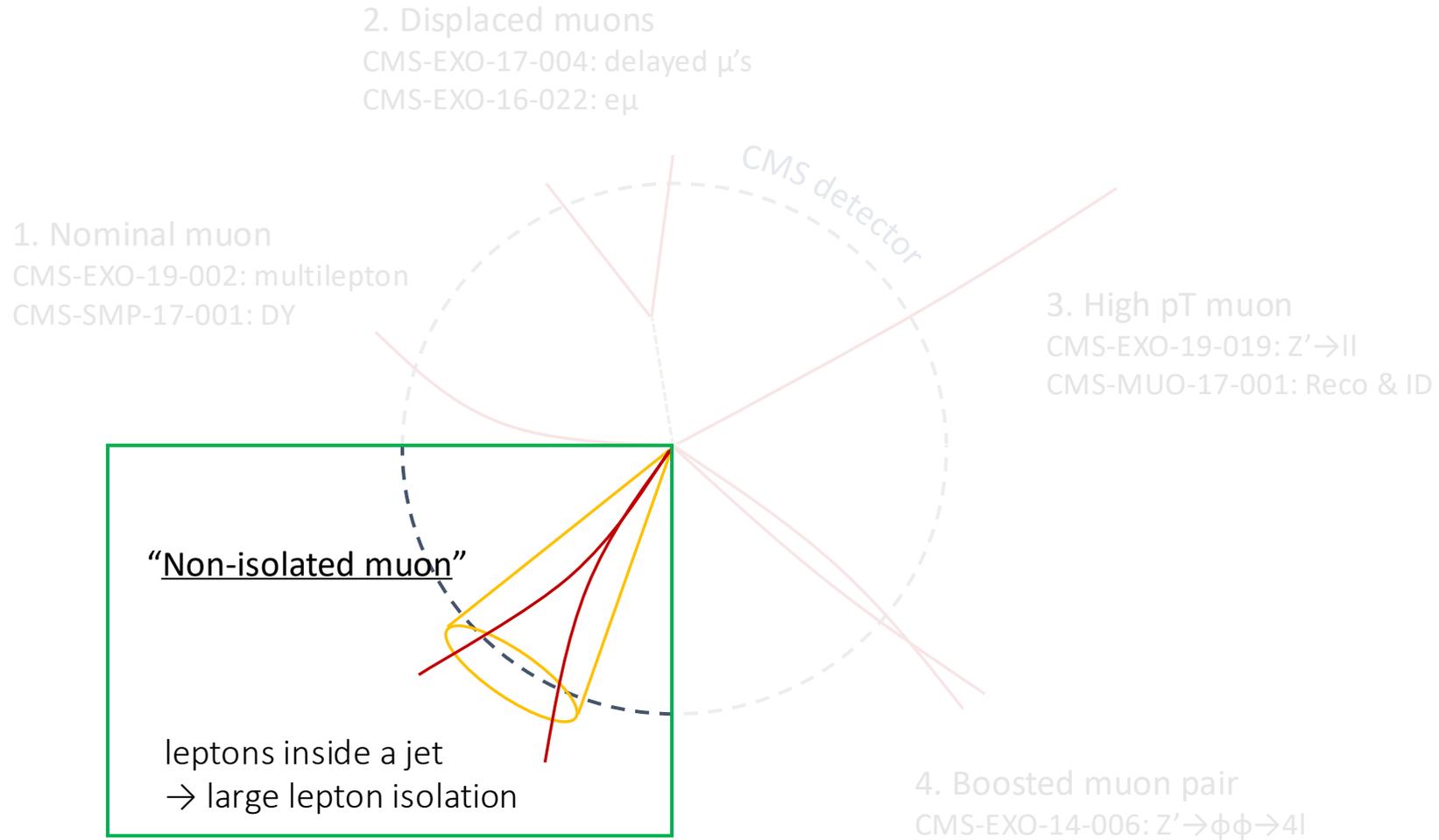
Non-Isolated Leptons Inside Jets

Signal Characteristics & Physics Opportunity

Definition

Leptons contained physically within jet cones, characterized by **large isolation values** (sum of pT in cone > lepton pT). Distinct from standard isolated leptons used in SM precision measurements.

Model Agnostic study

Can arise from the **parton shower process**, but this is just a single example w/o consideration of specific model. They are produced collinearly with other partons during the evolution of the jet.

Motivation

1. Experimentally new observables
2. Complements existing searches @ low mass

Physics Opportunity

Enables identification of $Z' \rightarrow \mu\mu$ signals produced within jets. A previously unexplored phase space for light dark sector mediators.

Signal Samples and Coupling Choice

Balancing Production Efficiency with Physics Accuracy
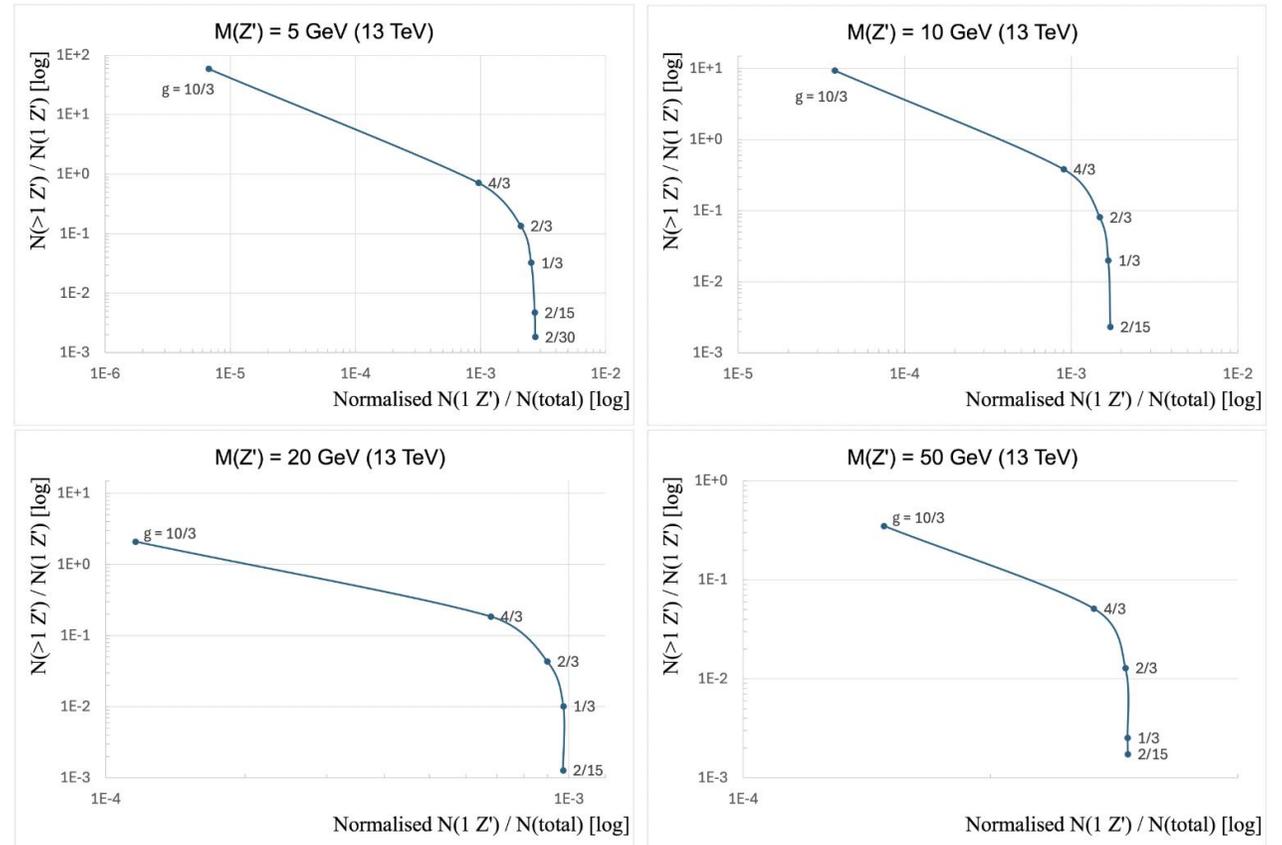
Optimization Strategy
`Coupling Trade-offs`

- **Goal:**

  Maximize statistics while keeping multi-emission rate low.

  $$N(1\ Z') \propto \alpha_{Z'}$$

- **Too Large Coupling:**

  Breaks down the $\sigma \sim \alpha_{Z'}$ relation due to multiple emissions.

- **Too Small Coupling:**

  Inefficient production requires enormous computing resources.

- ✓ **Final Choice:** N(>1 Z') / N(1 Z') ≈ 0.01

$$p_T(q) = 200\text{--}300 \text{ GeV}$$


Figure 1. Coupling-dependence study of Z' radiation in the parton shower for $M(Z') = 5, 10, 20,$ and 50 GeV. Each panel shows the ratio of events containing more than one Z' boson to those containing exactly one Z' boson, $N(> 1\ Z')/N(1\ Z')$, as a function of the fraction of di-jet events with exactly one Z' boson, $N(1\ Z')/N(\text{total})$ normalised by $1/g_{qZ'}^2$.

Parton-level validation

- Good agreement @ ΔR(q, Z') < 1

- HW(Z'+SM PS) > HW(only Z' PS) @ ΔR → 0
  - ✓ enhanced by cascade radiation

- ΔR(q, Z') < 1 cut is applied to z spectrum
  - ✓ Better agreement is achieved then the previous one

Previous work (only FSR-like diagrams are considered)
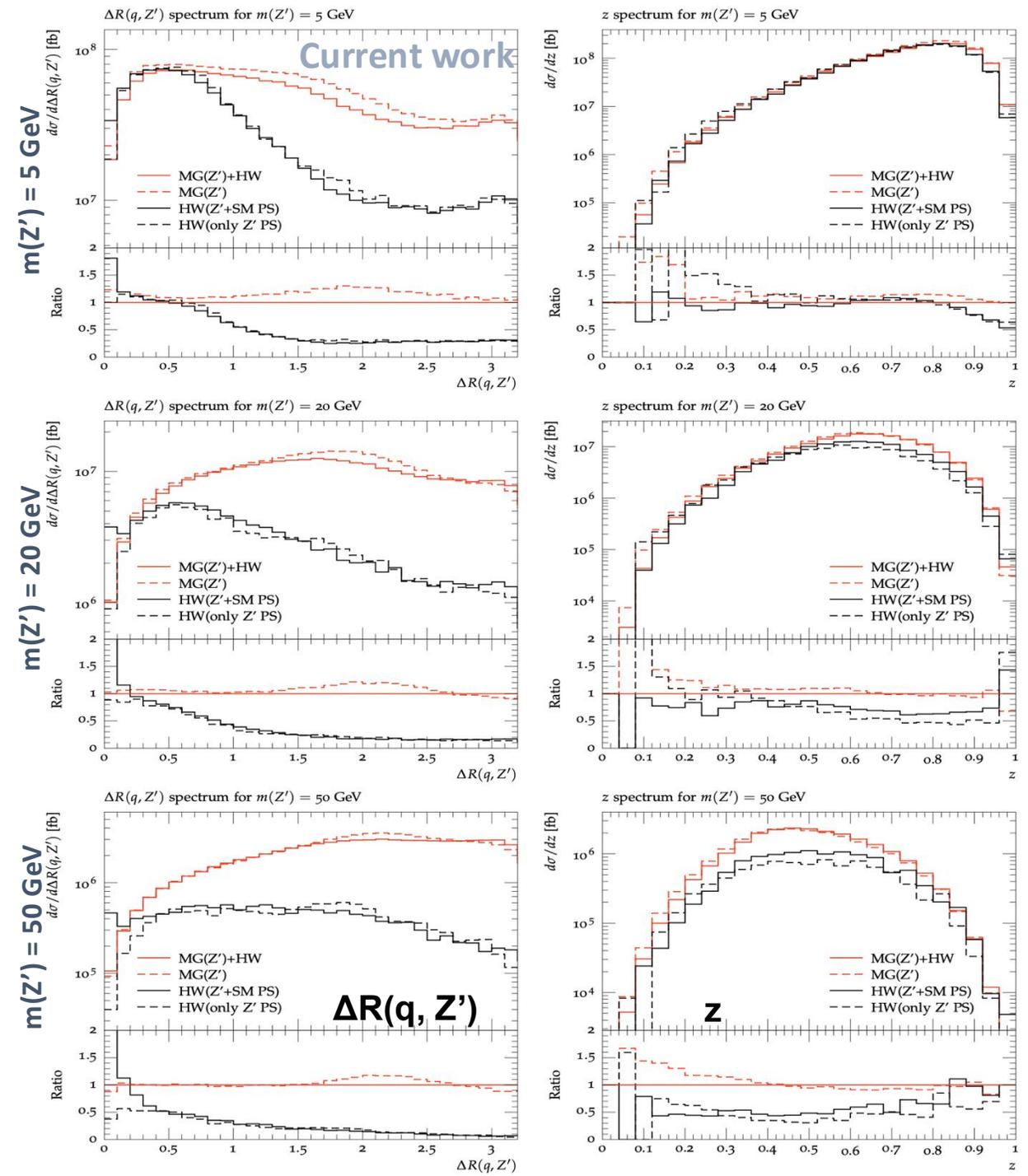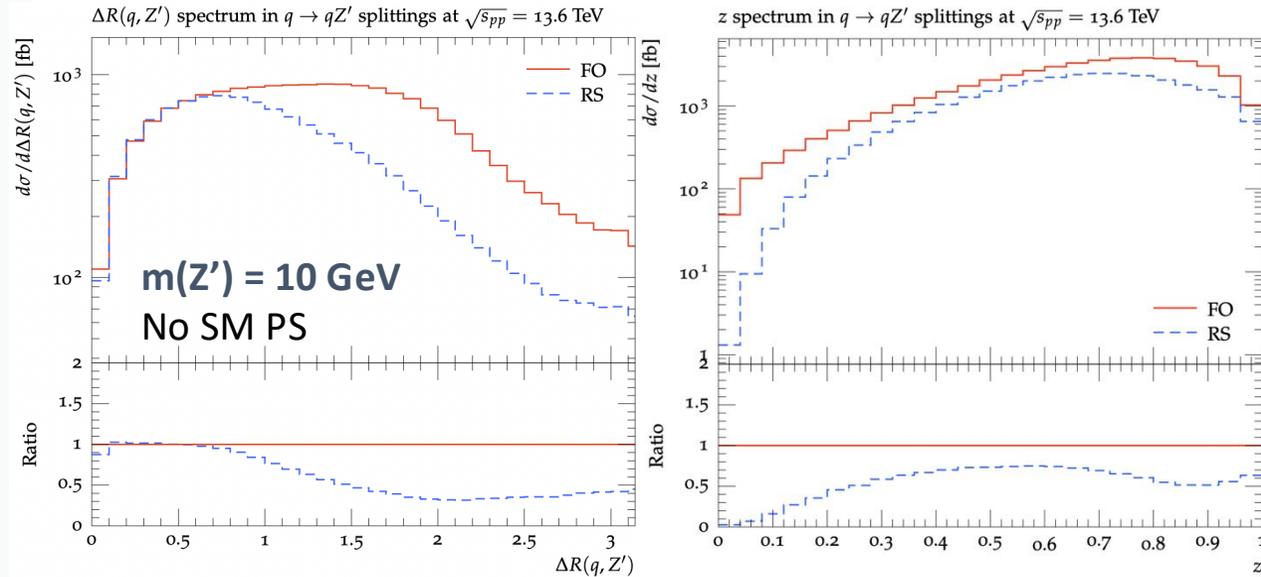
Analysis object-level validation

- Variables similar to those used in the parton-level validation are selected

- $\Delta R(q, Z') \rightarrow \Delta R(j, \mu\mu)$
  - ✓ Good agreement
  - ✓ More events @ $\Delta R(j, \mu\mu) \rightarrow 0$, because jets are clustered by the anti-kt algorithm

- $z \rightarrow$ Muon Energy Fraction
  - ✓ Equivalent to 1-z spectrum
  - ✓ MEF $\rightarrow$ 0: Z' has large ΔR with the quark
  - ✓ MEF $\rightarrow$ 1: SM shower makes the final partons softer & non-collinear
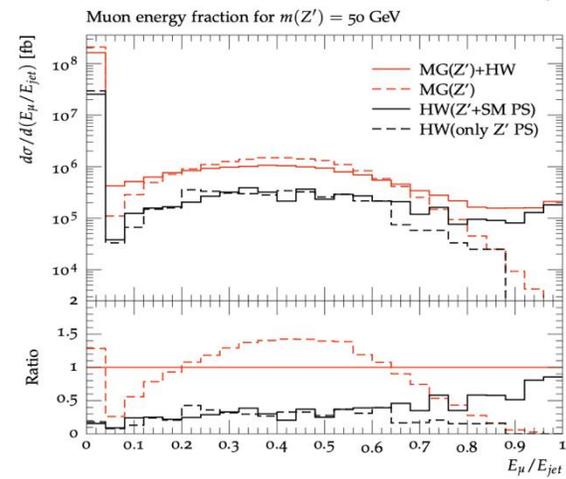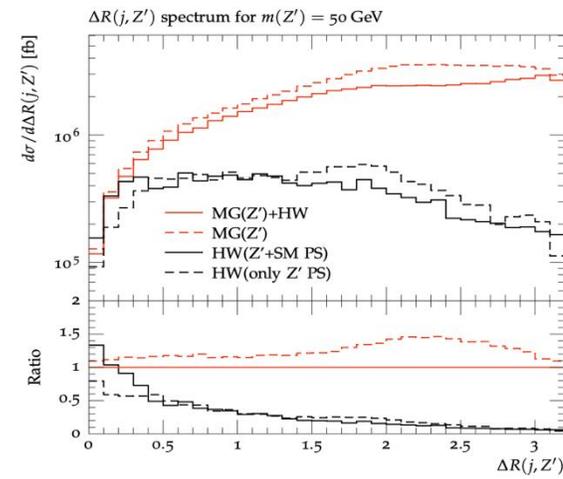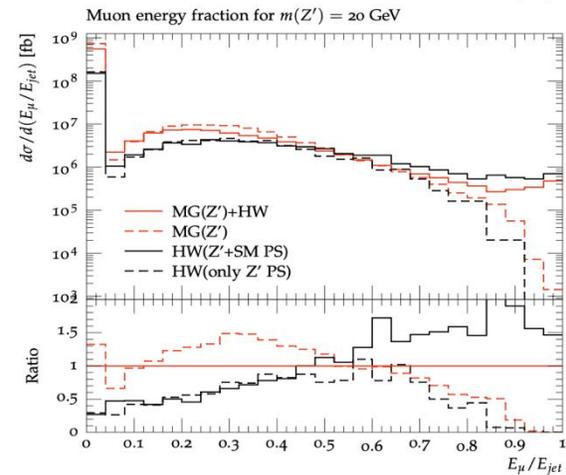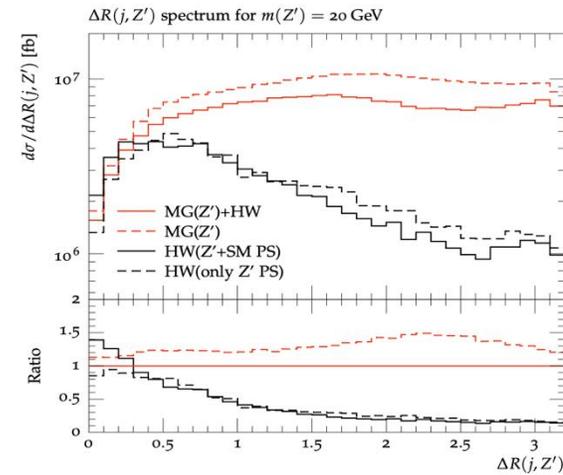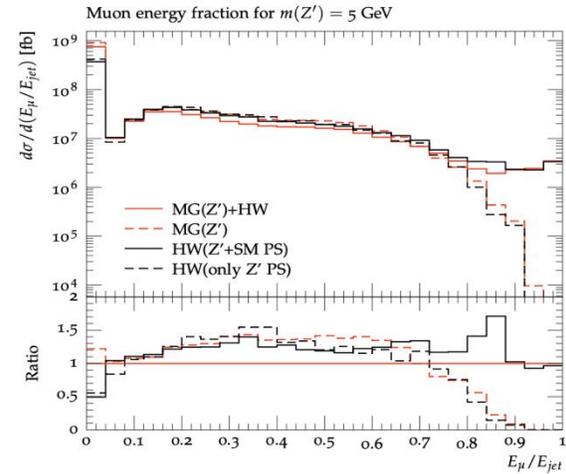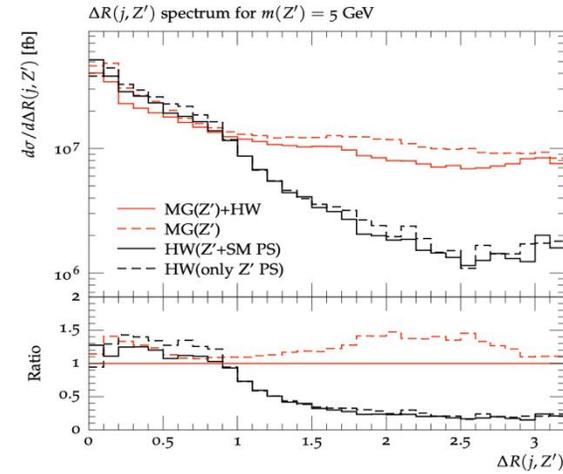
Analysis object-level validation

- ΔR(j, leading/sub-leading μ)

- Dip @ ΔR → 0.4 due to the jet reco algorithm

- In the later section, only muons with ΔR < 0.3 (conservative choice) are used to study those clustered as jets
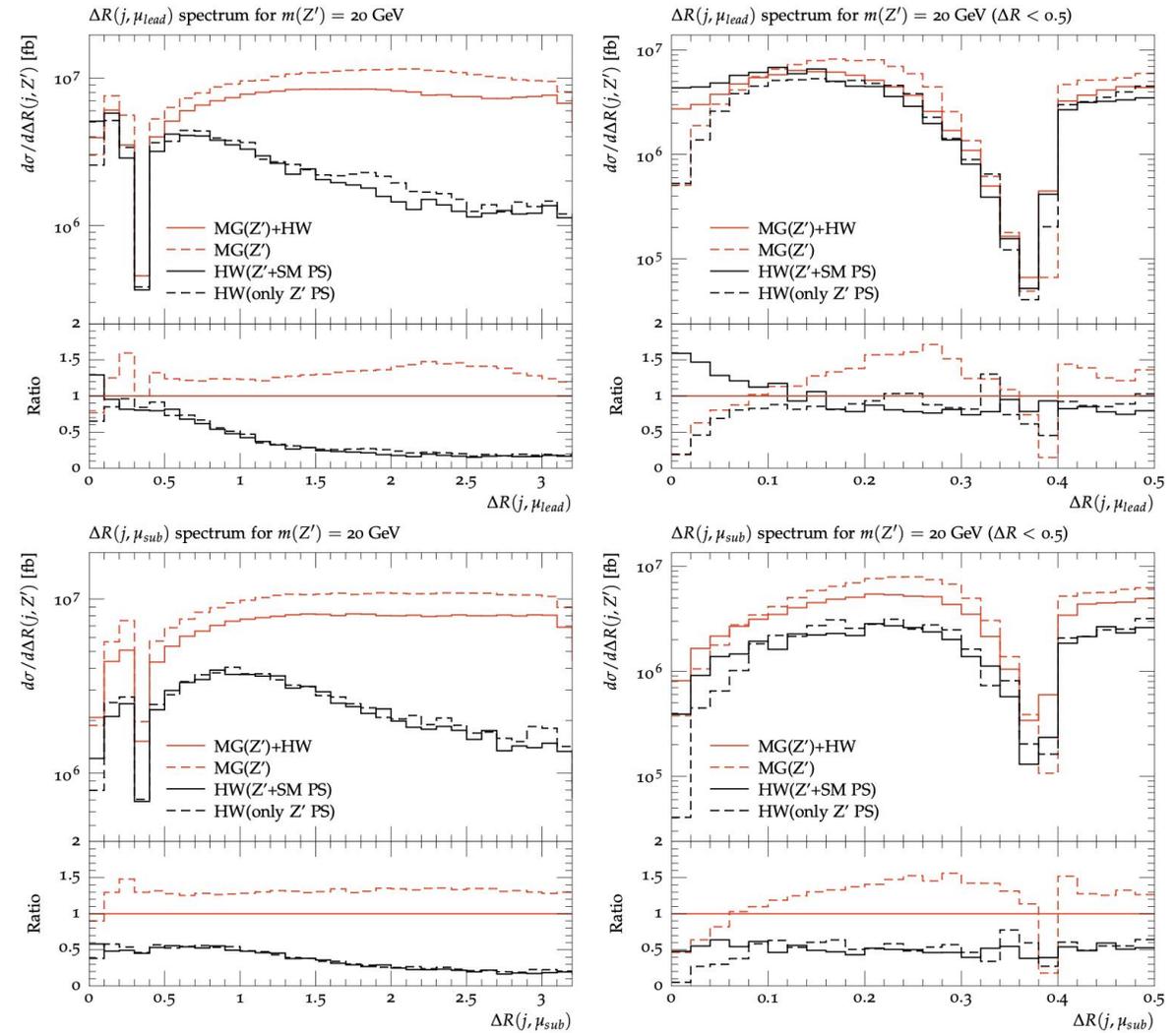
Figure 5. $\Delta R(\mu, \text{jet})$ distributions for $M(Z') = 20$ GeV. The top (bottom) panels show the separation between the jet and the leading (subleading) muon. The left column covers the full range, $\Delta R < 3.2$, while the right column provides a zoomed view of the near-jet region, $\Delta R < 0.5$.

$\Delta R(j, \mu_{sub})$ spectrum for $m(Z') = 20$ GeV

$\Delta R(j, \mu_{sub})$ spectrum for $m(Z') = 20$ GeV ($\Delta R < 0.5$)

Legend (both plots):
- MG(Z')+HW
- MG(Z')
- HW(Z'+SM PS)
- HW(only Z' PS)
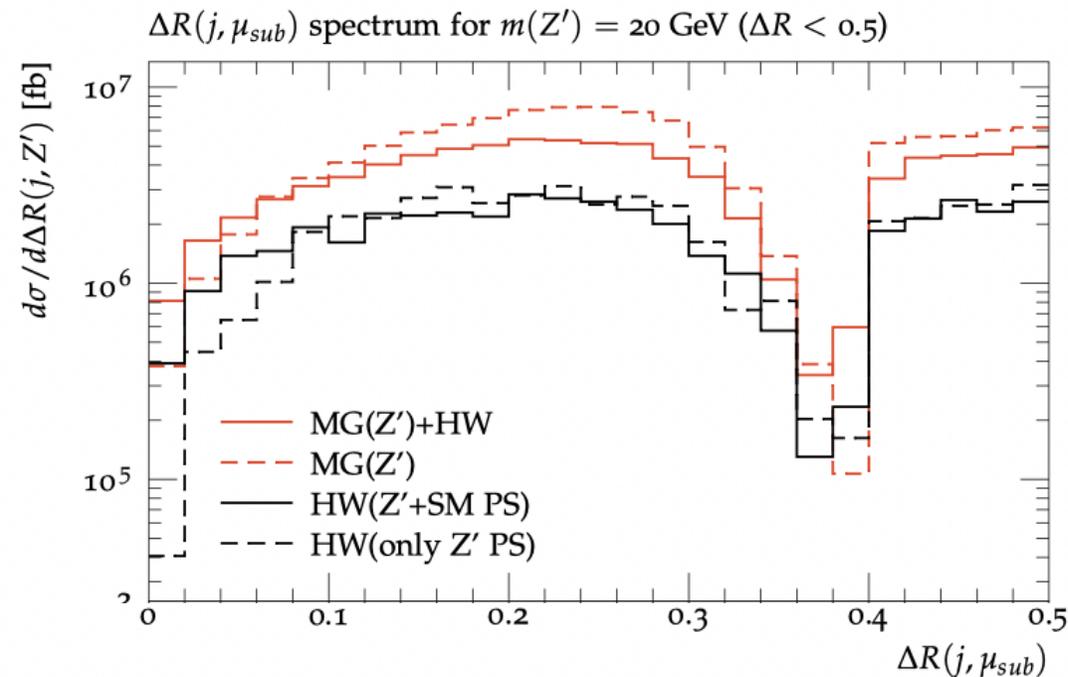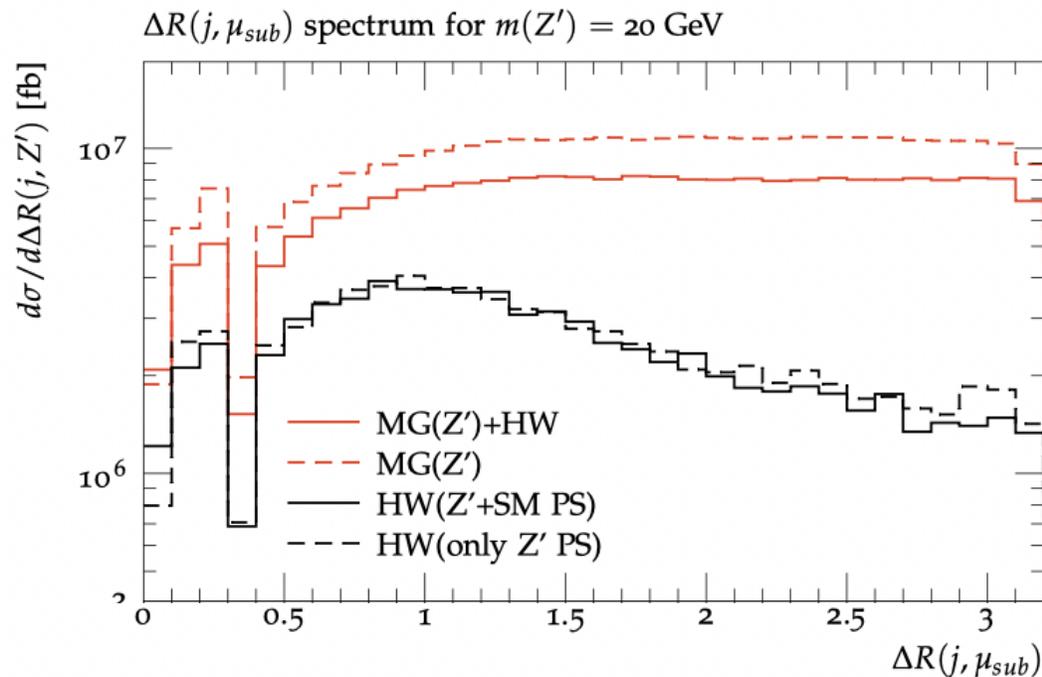
⚠ **Reconstruction Artifact**

ⓘ **Dip at ΔR ≈ 0.4** → boundary effects: **Jet Reconstruction Algorithm** (Anti-kt, R=0.4)

🔍 Muons near the jet boundary are less likely to be clustered or pass selection.

✓ **Analysis Choice**

To avoid this reconstruction artifact and ensure robust signal selection:

Only muons with ΔR < 0.3 **are used to study those clustered as jets.**   *(Conservative choice)*

Z' → μμ Inside Jets Search Strategy

Identifying Non-Isolated Leptons from BSM Showers

01 — Event Generation

Simulate dijet events with Herwig7 BSM parton shower framework.

HW(Z'+SM PS)

02 — Trigger Selection

Select Opposite Sign (OS) dimuon pairs based on pT thresholds.

Standard & Scouting

03 — Isolation Cut

Require muons to be inside jets within a tight cone.

$\Delta R(j, \mu) < 0.3$

04 — Reconstruction

Reconstruct invariant mass in the low-mass window.

$m(\mu\mu) \in [5, 50]$ GeV

05 — Backgrounds

Estimate QCD and Top processes; fit shapes using power law.

Shape Analysis

Background Samples

QCD (pT-binned with PY8) and Top (ttbar + tW with POWHEG+PY8) are the dominant backgrounds.

QCD Top

The B−L Model Extension

Simplest Gauge Extension

Anomaly-free model with conserved **B−L** (Baryon minus Lepton number).

No Mixing with SM Bosons

Zero mixing in both mass & kinetic terms. No tree-level interaction betwe
z' and SM bosons.

Pure Vector Coupling

The **z'** boson is its own mass eigenstate with only vector couplings to fermions.

Interpretation Role

Used as a benchmark for interpretation; our shower formalism remains **model-agnostic**.

Lagrangian Features

Gauge Symmetry

$$U(1)_{B-L}$$

Covariant Derivative

$$D_\mu = \partial_\mu + ig' \, Y_{B-L} \, Z'_\mu$$

Properties

| Anomaly Free | Mass = Gauge Eigenstate |

Significance & Expected Limit

*First-look study utilizing Asimov significance without systematics consideration yet.

- Because this study is the first look, we utilise the Aimov significance w/o consideration of systematics
- We can get evidence-level significance @ m(Z') < 30 GeV with Run-2+3 data & discovery-level significance across the full search region with HL-LHC data

50

Current Era

Run-2 + Run-3 Potential

Future Era

HL-LHC Discovery Reach

Next Steps

Refinement Plan

Future iterations will include systematic uncertainties, optimized b-tagging, and improved dimuon vertex reconstruction.

📖 **Conclusion remarks**

*First-look study utilizing Asimov significance without systematics consideration yet.

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- **Too Small Coupling:**
  Inefficient production requires enormous computing resources.

✅ **Final Choice:** $N(>1\ Z') / N(1\ Z') \approx 0.01$

Generated Samples
Simulation Datasets

- **HW(Z'+SM PS)**
  Main signal sample with full BSM shower and SM shower effects.

- **HW(only Z' PS)**
  Validation sample without SM shower (isolates BSM splitting).

- **MG(Z') + HW**
  Matrix Element generation of Z' interfaced to Herwig.

- **HW(Z'+SM PS)**
  Main signal sample with full BSM shower and SM shower effects.

`Herwig 7.2`   `MadGraph5_aMC`   `UFO Model`

Presentation **Overview**

Fundamentals of Event Generators

How do we simulate proton-proton collision events?

Parton Shower Algorithms

Understanding the role of parton shower & difference b/w PY8 and HW7.

BSM extensions

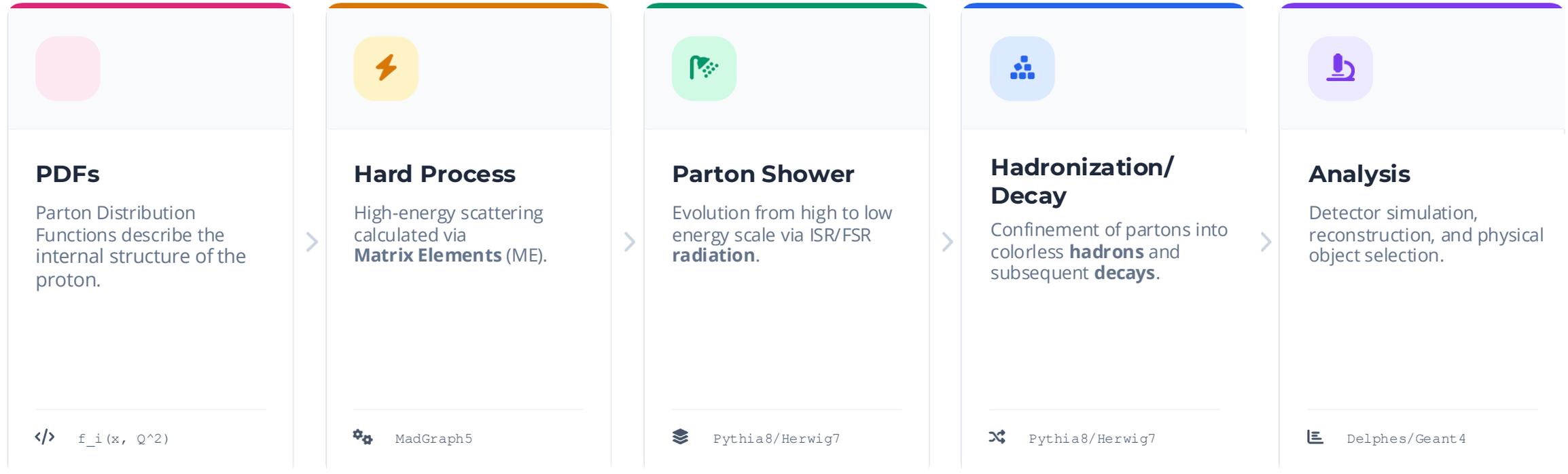Extending showers to BSM physics and why are a crucial signal.

What is the non-isolated lepton study?

Why should we study NIL? What we can observe?

Event Simulation Workflow

From Proton-Proton Collision to Final-State Objects

PDFs

Parton Distribution Functions describe the internal structure of the proton.

`</>` `f_i(x, Q^2)`

Hard Process

High-energy scattering calculated via **Matrix Elements** (ME).

⚙ `MadGraph5`

Parton Shower

Evolution from high to low energy scale via ISR/FSR **radiation**.

≋ `Pythia8/Herwig7`

Hadronization/ Decay

Confinement of partons into colorless **hadrons** and subsequent **decays**.

⤬ `Pythia8/Herwig7`

Analysis

Detector simulation, reconstruction, and physical object selection.

📊 `Delphes/Geant4`

ℹ **Factorization Theorem**

Allows separating long-distance (low energy) physics from short-distance (high energy) interactions. Integrating all interactions at once is inefficient Calculate each part individually.

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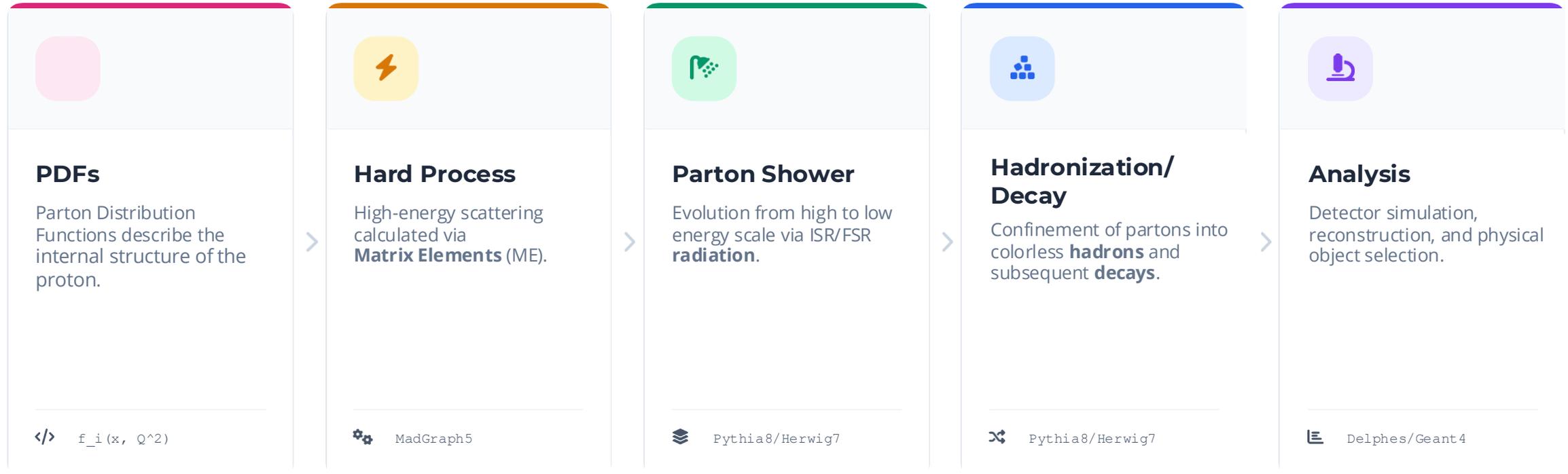
⊫ Delphes/Geant4

What Event Generators do

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