CTPU-PTC Seminar @ 10.Jun.2026

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Search New Physics with
BSM Parton Shower in Herwig7

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[4] University of Manchester
[5] CERN Theoretical Physics

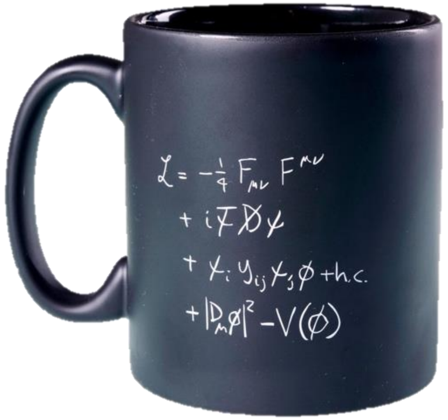
as a part of the MCnet project

funded by Marie Curie Actions

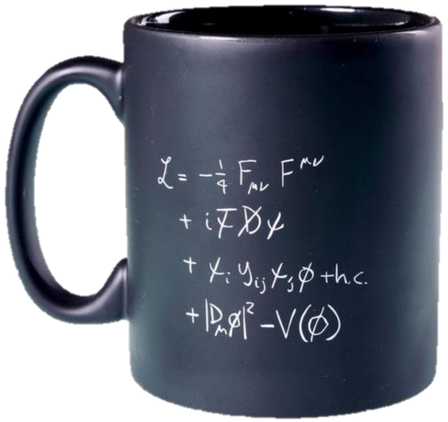
photo from [키맨의 추억노트 사진 갤러리]

The 2nd EXPO bridge, 과학의 다리

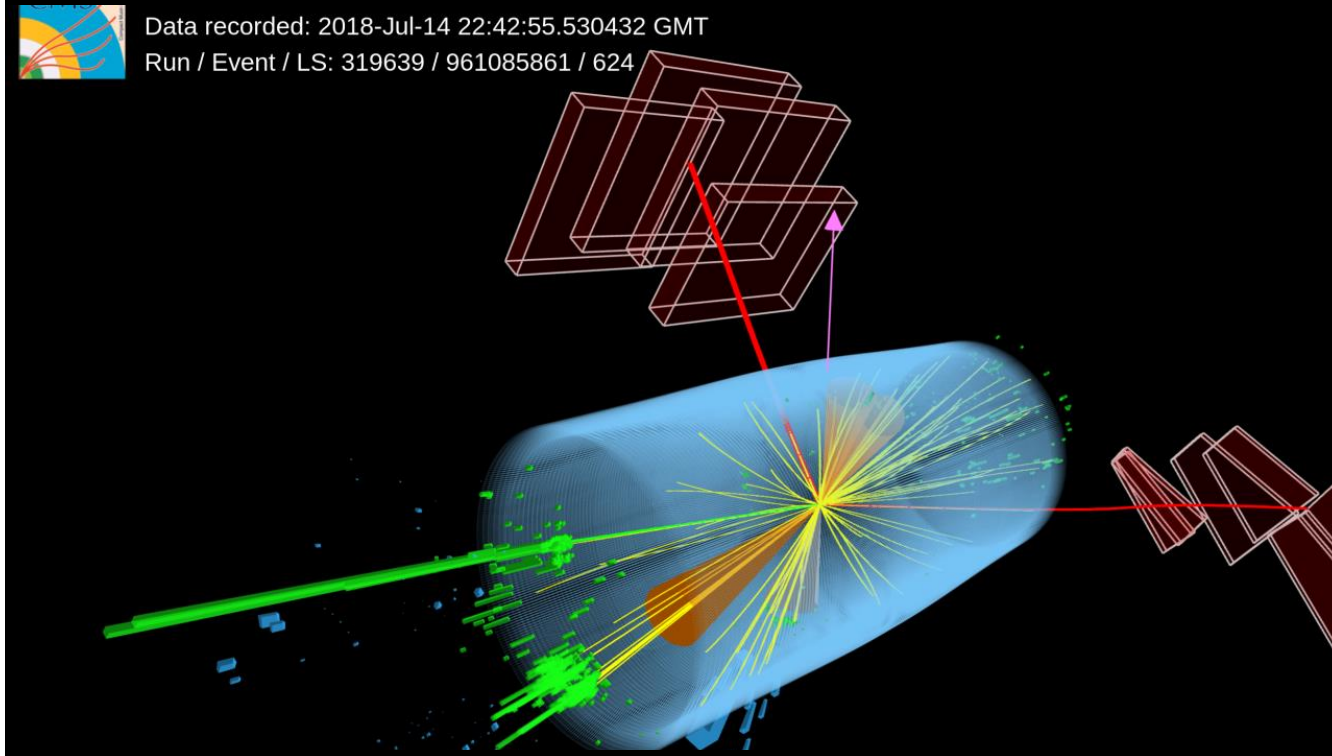
Equation of Motion



Equation of Motion

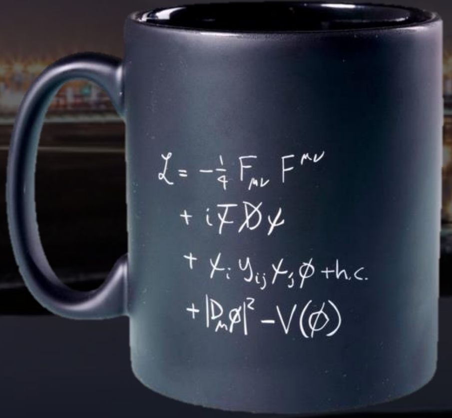


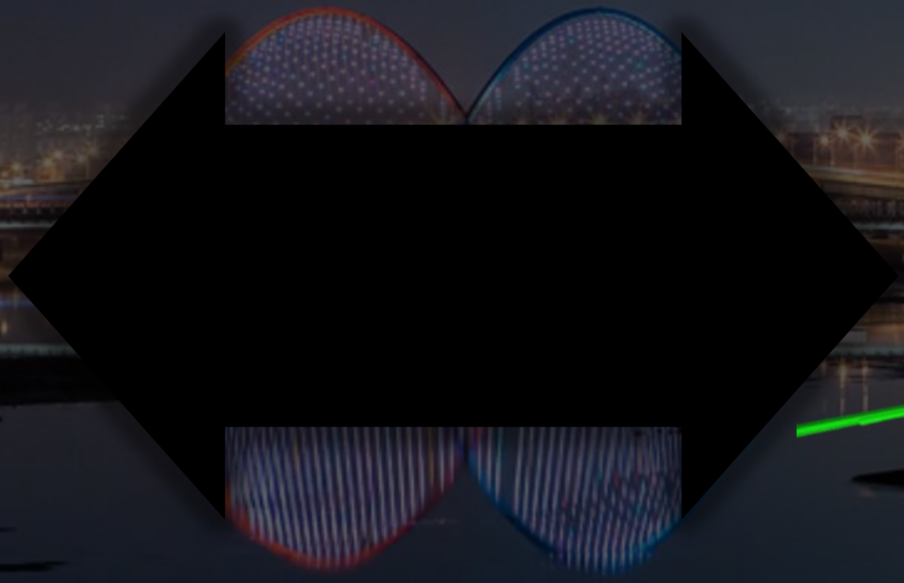
CMS ttH event display



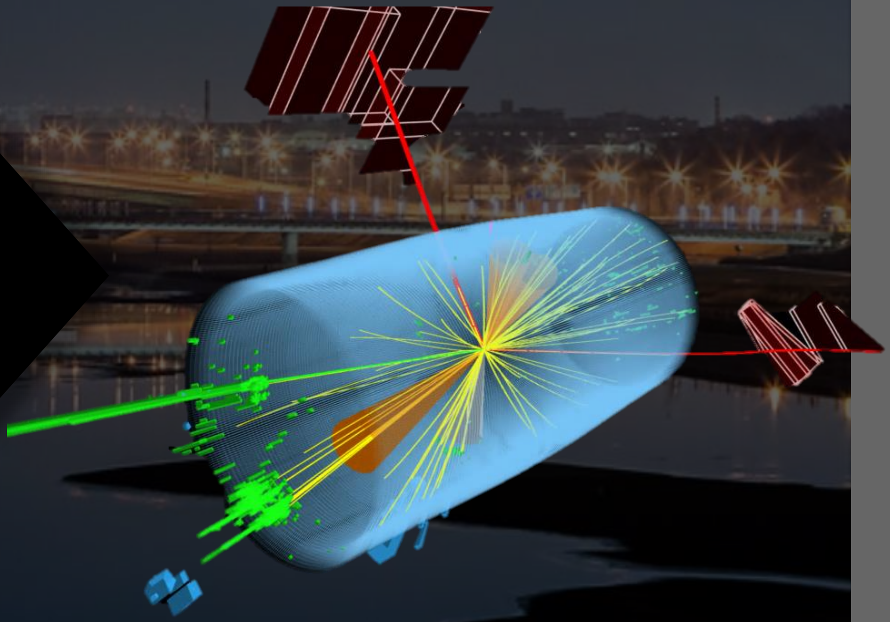
Huge gap between

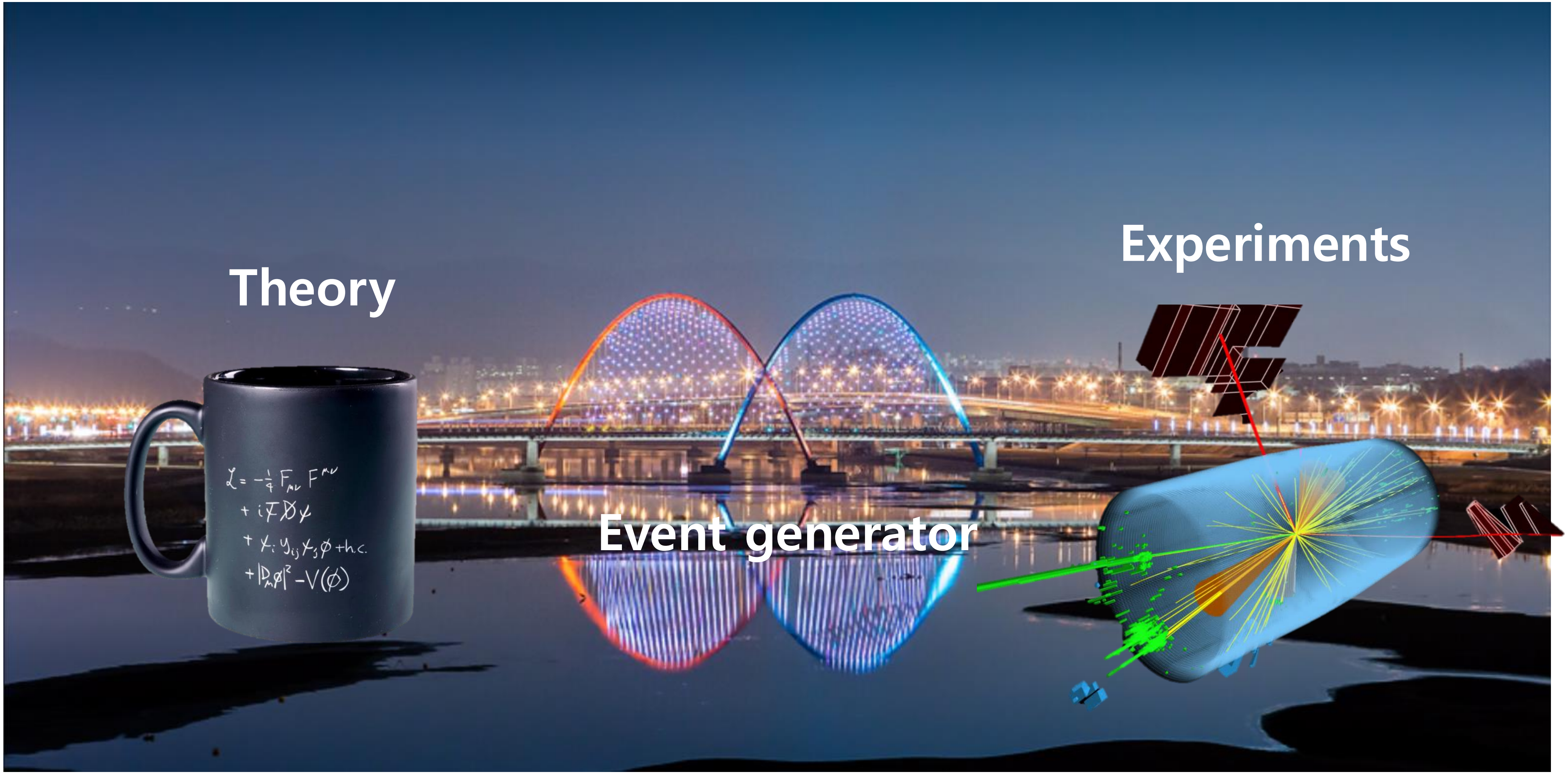
Theory





Experiments



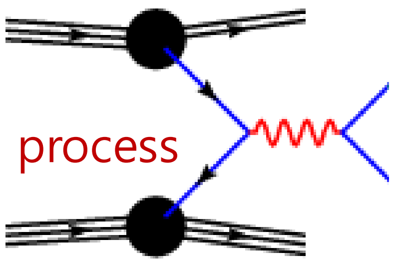


Theory
Experiments
Event generator
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

What are Event Generators?

- They translate theoretical models into quantities directly measurable by detectors
  - dictate real events as close as possible

[proton-proton collision event]



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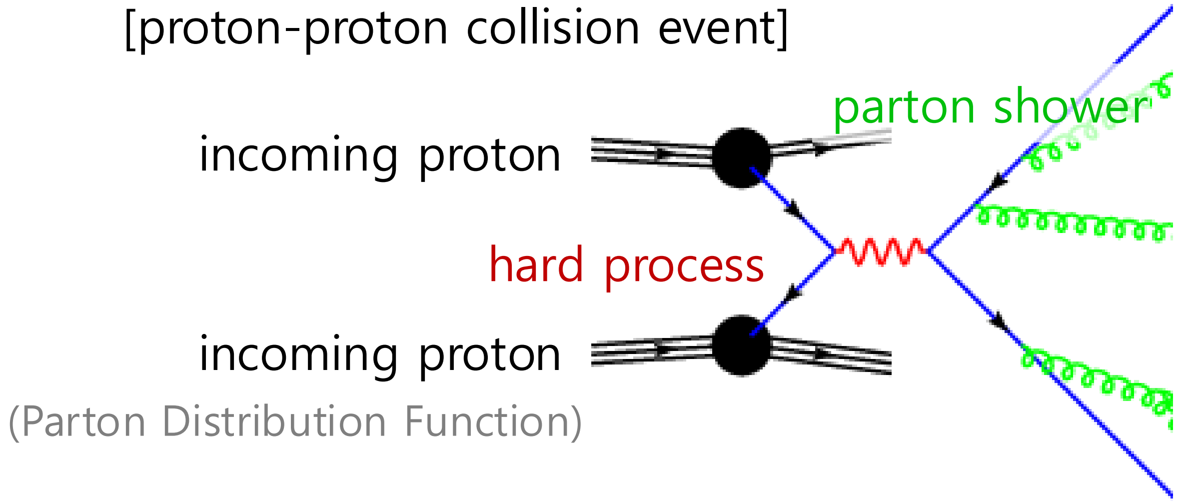

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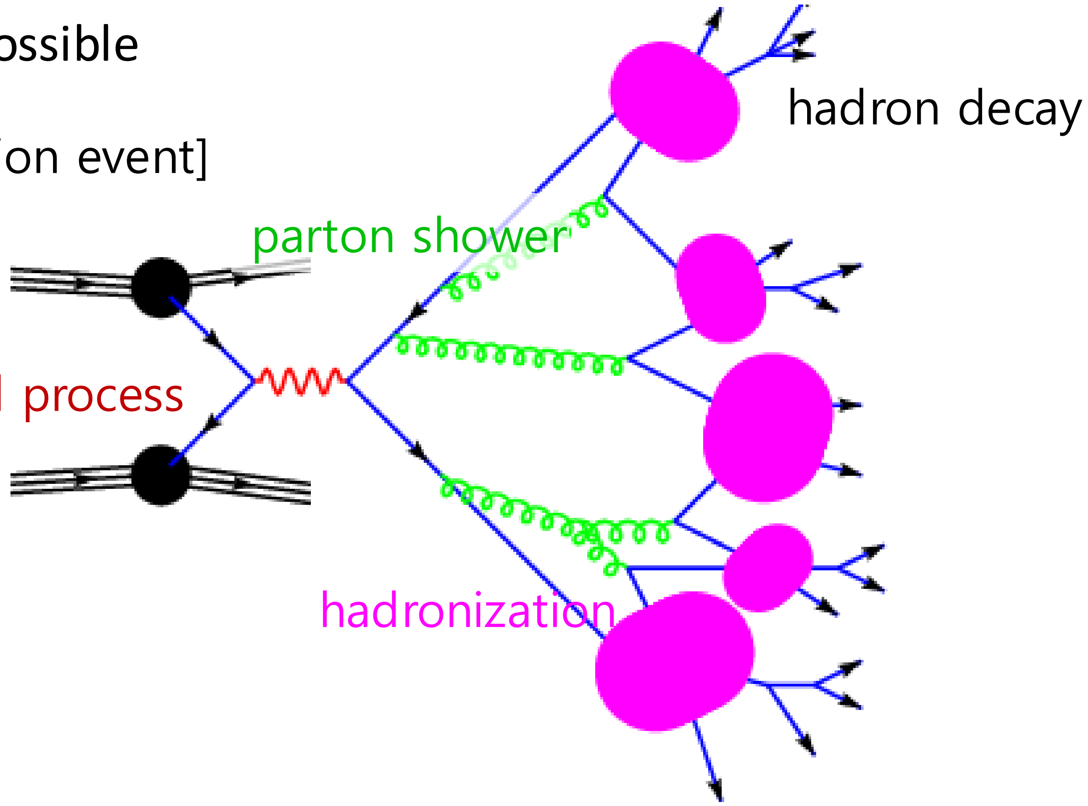

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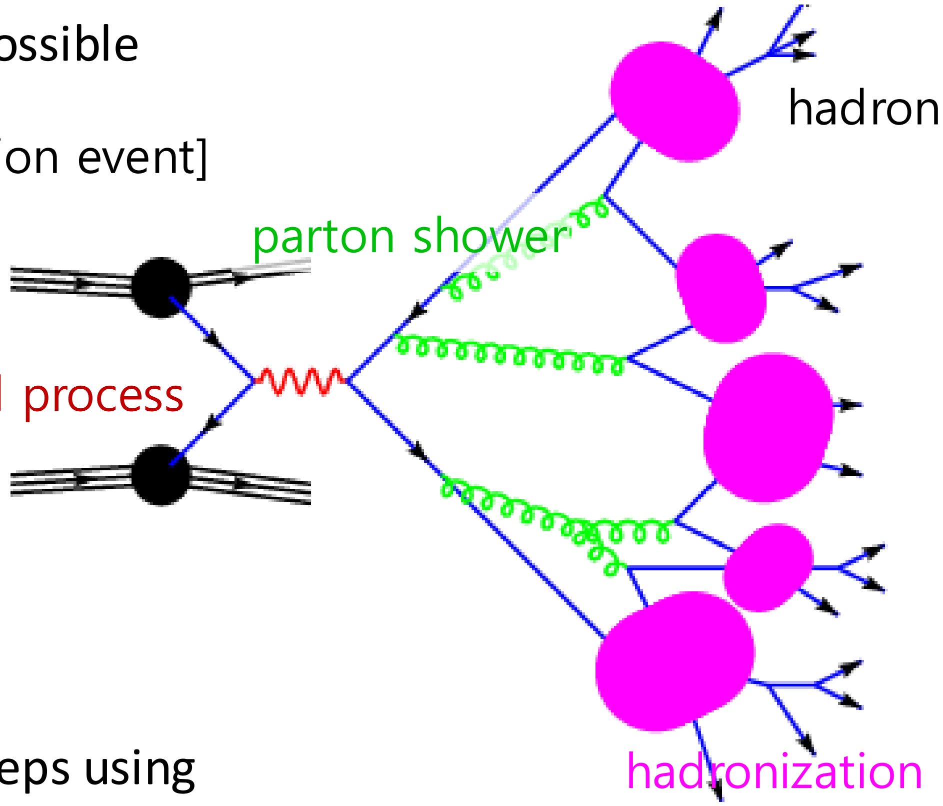

  - Generators simulate all these steps using Monte Carlo (MC) techniques

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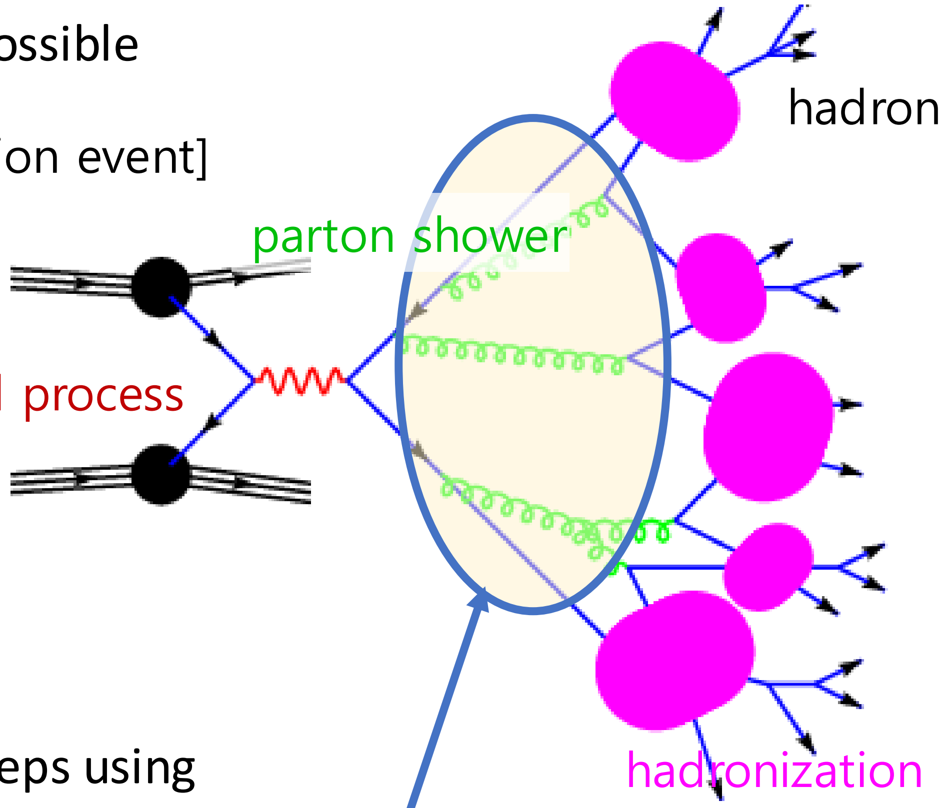


- Generators simulate all these steps using Monte Carlo (MC) techniques

This presentation concentrates on this part (parton shower)!

Why Monte Carlo integration?

- **LHC gives ~50 charged tracks** for each event

  → ~200-dim integration

- Traditional integration algorithms necessitates regular n^d grids
  - n: integration points, d: dimension of the integration
  - e.g. Trapezoidal Rule

$$\int_a^b f(x)dx \approx \sum_{k=1}^{N} \frac{f(x_{k-1}) + f(x_k)}{2} \Delta x_k$$

- **MC integration**
  - Law of large numbers (LLN) – a huge number of independent and identical random samplings make its average value converge to the true value

  → It makes the **accuracy only depends on the number of random points** independent to the dimension

[Relative uncertainty of each integration method]

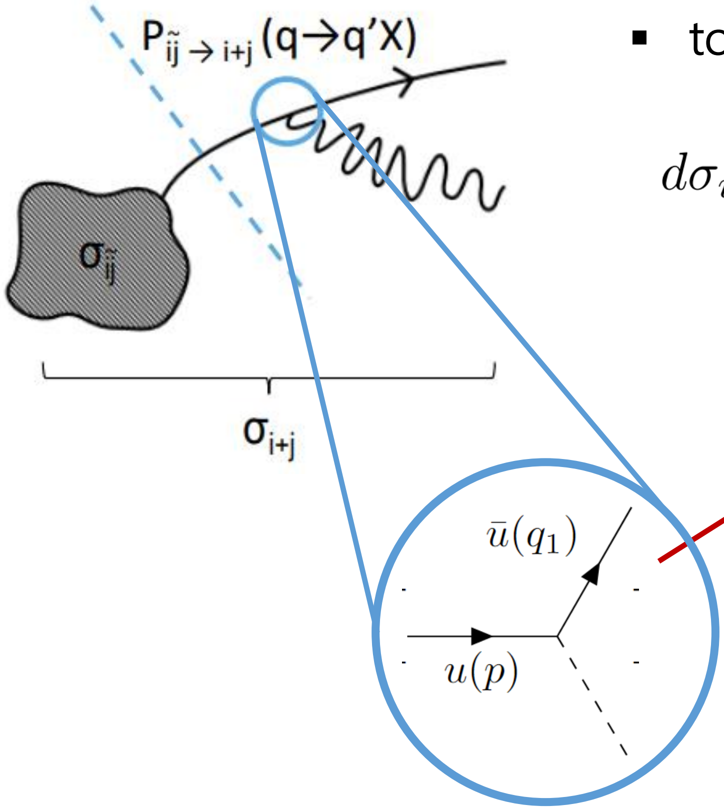
Convergence Rate	1-dim	d-dim
Trapezoidal Rule	$1/n^2$	$1/n^{2/d}$
Simpson's Rule	$1/n^4$	$1/n^{4/d}$
Monte Carlo Method	$1/\sqrt{n}$	$1/\sqrt{n}$

traditional methods depending on d

independent to d

Parton Shower Algorithm

- What is a parton shower process and how does it work?
  - Every coloured particles do QCD showers **to make colour singlet** final states
  - When initial partons radiate soft & collinear partons, these final-state partons can be treated separately from the matrix element calculation ➡ *“ Factorization Theorem ”*



- total cross section

$$d\sigma_{i+j} \simeq \frac{\alpha_{\rm int}(\tilde{q}^2)}{2\pi}\frac{d\tilde{q}^2}{\tilde{q}^2}dz\, P_{\tilde{ij}\rightarrow i+j}(z,\tilde{q})\, d\sigma_{\tilde{ij}}$$

“splitting function”

! The splitting function contains kinematic properties of radiations **!**

z : energy fraction ~ E_{in}/E_{out}

$\tilde{q}$: ordering variable

(in Herwig 7, angular variable ~ $\theta \cdot E$)

Parton Shower Algorithm

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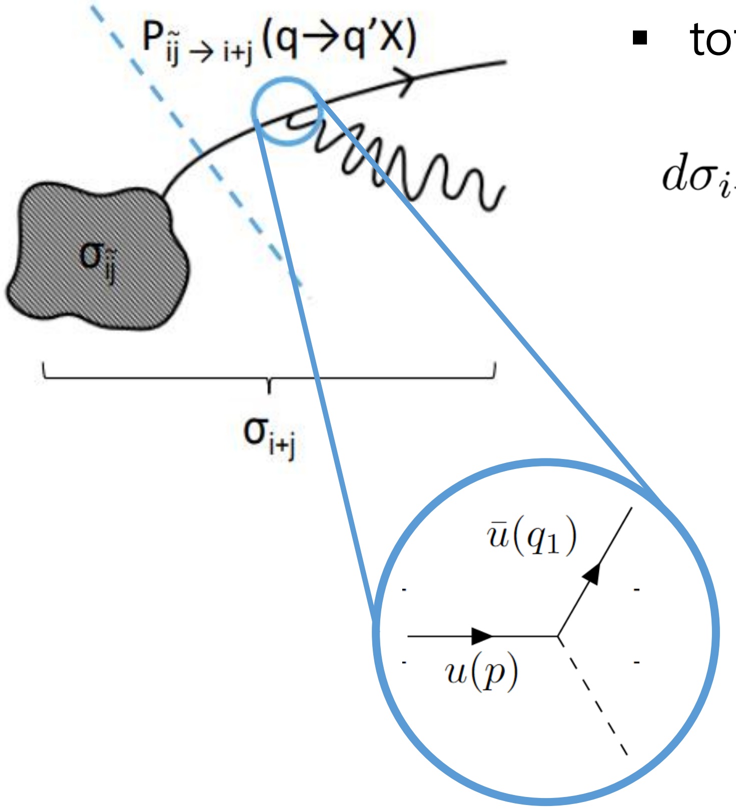


- total cross section

! <u>simple multiplication</u> !

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

"splitting function"

In the soft limit, this splitting function becomes

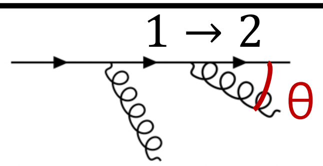
$$P_{\tilde{ij}\to ij}(z) \sim \frac{1}{z} \qquad \sigma \sim exp\left(-\log\frac{Q^2_{hard}}{Q^2_{\Lambda_{QCD}}}\right)^2$$

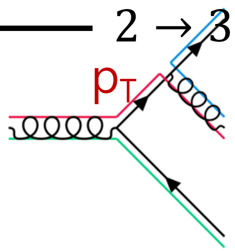
"logarithmic accuracy"

Parton Shower Programs

- Shower algorithms

	Herwig7	PYTHIA8
shower algorithm	angular-order	p_T-ordered dipole shower

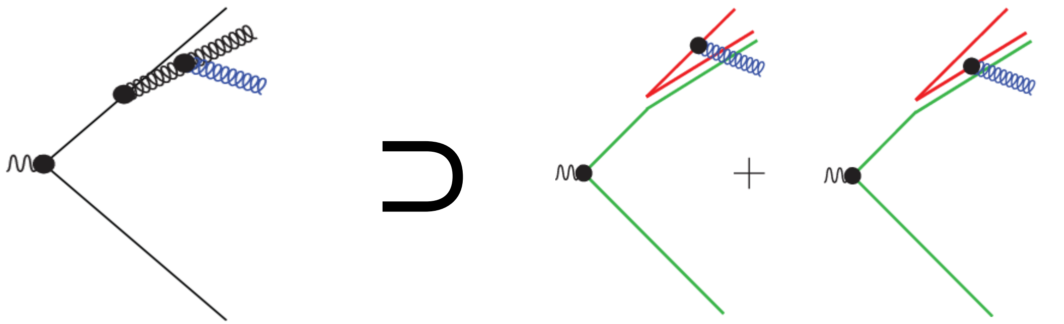




- When we consider parton showers, colour coherence is a great issue

(Most of old generators (PYTHIA6 …) cannot treat this effect correctly)

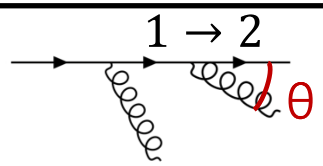
interference → colour coherence

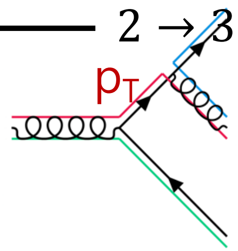


Herwig7: angular-order parton shower

- Shower algorithms

	Herwig7	PYTHIA8
shower algorithm	angular-order	p_T-ordered dipole shower



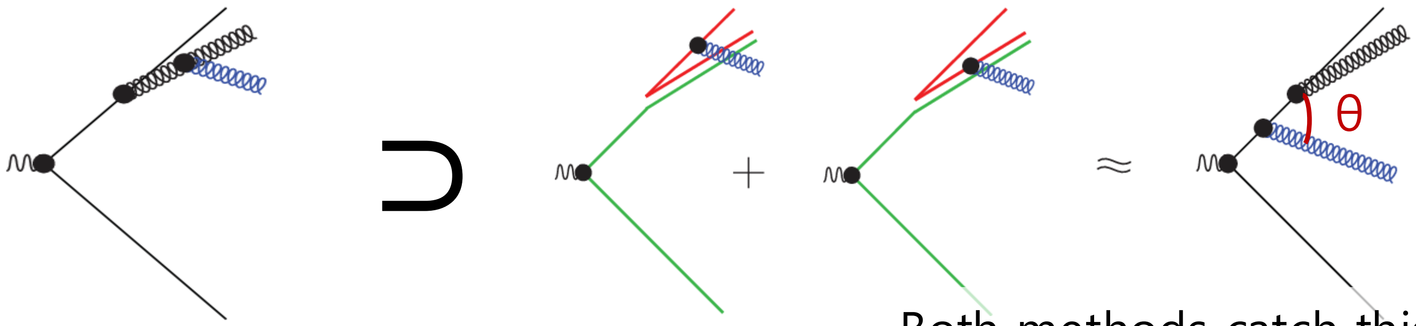


- When we consider parton showers, colour coherence is a great issue

(Most of old generators (PYTHIA6 …) cannot treat this effect correctly)

[Chudakov effect]
A radiating parton (blue gluon) only sees the charge of the initial parton (green) = total charge of the final partons

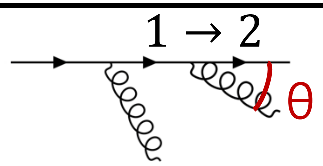
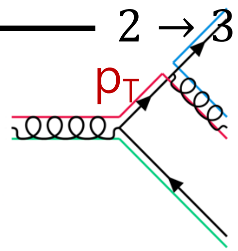
interference → colour coherence



Both methods catch this effect completely!

Herwig7: angular-order parton shower

- Shower algorithms

	Herwig7	PYTHIA8
shower algorithm	angular-order 	p_T-ordered dipole shower 

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

Shower history reconstruction can be more complex.

Parton Shower in Event Generators

1. Find out an evolution variable, q^2, at the point when a radiation occurrs

   Select a random number, $\rho \in [0, 1]$, and solve

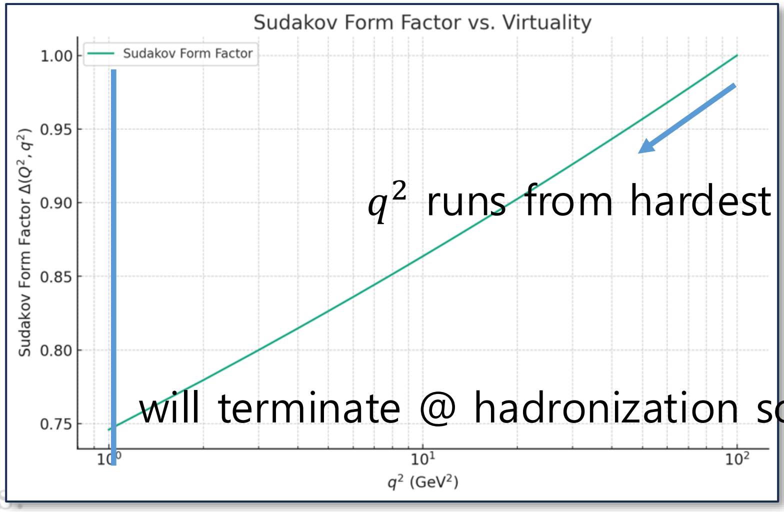
   - No emission probability: $\Delta_i(Q^2, q^2) = \rho$

   to find a q^2. Finally, if

   (a) $q^2 > Q_0^2$: New branching is generated.

   (b) $q^2 < Q_0^2$: Evolution is terminated.

[ChatGPT4.0 – Sudakov Form Factor]



q^2 runs from hardest scale, e.g. m_Z^2

will terminate @ hadronization scale (Q_0^2) ~ GeV

2. Fix a branching type

   Normalize the integrated emission probabilities as follows:

   - Splitting probability: $\mathcal{P}_{ji} = \dfrac{\int_{z_{min}}^{z_{max}} P_{ji}(z)dz}{\int_{z_{min}}^{z_{max}} \sum_k P_{ki}(z)dz}$. (2.18)

   (integrated & normalized splitting function)

   Select a random number, $\lambda \in [0, 1]$.

   (a) If $\lambda < \mathcal{P}(g \to q\bar{q})$, choose $q\bar{q}$ splitting.

   (b) If $\mathcal{P}(g \to q\bar{q}) < \lambda < \mathcal{P}(g \to q\bar{q}) + \mathcal{P}(g \to gg)(= 1$, in this case$)$, choose gg splitting.

Parton Shower in Event Generators

1. Find out an evolution variable, q^2, at the point when a radiation occurrs

   Select a random number, $\rho \in [0,1]$, and solve

   - No emission probability: $\Delta_i(Q^2, q^2) = \rho$ (2.17)

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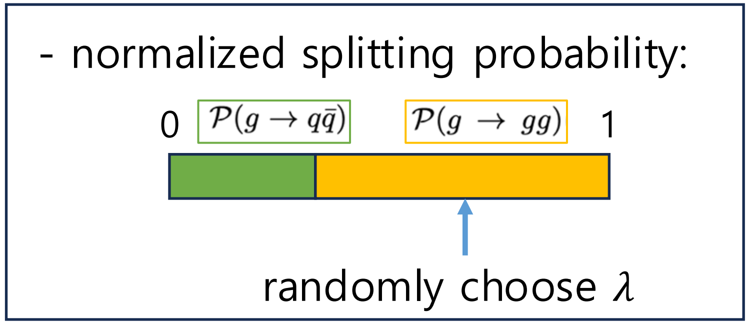

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Parton Shower in Event Generators

3. Find out z

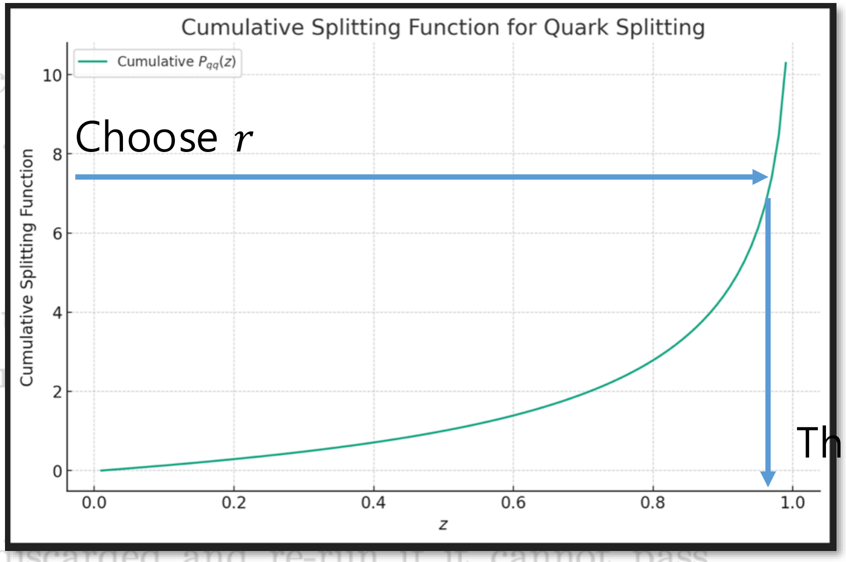
   Again choose a random number, $r \in [0, 1]$. Solve the following equation:

$$r \int_{z_{min}}^{z_{max}} P(z)dz = \int_{z_{min}}^{z} P(z')dz', \qquad (2.19)$$

   where $P(z)$ is a splitting function, showing a likelihood of the variable, z.

   * Rejection sampling

[ChatGPT4.0 - cumulative q→qg splitting function]



4. Fix kinematics

   Choose all the other dependent variables, suc
   q^2 and z, where ϕ is almost randomly chosen

5. Kinematic mapping

   All variables have been calculated in the S
   shower coordinates. Apply boostings, rotatio

6. Apply phase space constraints

   To avoid the divergence issues, events are discarded and re-run if it cannot pass virtuality or p_T cutoffs.

Parton Shower in Event Generators

3. Find out z

   Again choose a random number, $r \in [0, 1]$. Solve the following equation:

   $$r \int_{z_{min}}^{z_{max}} P(z)dz = \int_{z_{min}}^{z} P(z')dz', \tag{2.19}$$

   where $P(z)$ is a splitting function, showing a likelihood of the variable, z.

   * Rejection sampling

4. Fix kinematics

   Choose all the other dependent variables, such as p_T, ϕ, and 4-momentum based on q^2 and z, where ϕ is almost randomly chosen.

5. Kinematic mapping

   All variables have been calculated in the Sudakov basis or corresponding parton shower coordinates. Apply boostings, rotations and so on to make the lab frame.

6. Apply phase space constraints

   To avoid the divergence issues, events are discarded and re-run if it cannot pass virtuality or p_T cutoffs.

INTRODUCTION

- Goal: Implement BSM showers as general as possible in Herwig7

- Step by step guidelines
  1) Calculate matrix elements of each process from Feynman rules

     → only depends on their spin and mass

  2) Calculate new splitting functions (NPB 126, 2 (1977) 298-318)
     - master formula by Altarelli and Parisi

$$P_{0\to12}(z,\tilde{q}) = \frac{1}{2(q_0^2 - m_0^2)} \sum_{s_0,s_1,s_2} |\mathcal{M}_{s_0,s_1,s_2}|^2$$

  3) Herwig7 reads BSM model information and calculate all necessary ingredients automatically

model independent

No needs to calculate shower process for each BSM model/particle

- Important processes
  1. Splitting out of scalar bosons: $\phi \to \phi'\phi''$, $f \to f'\phi$, $V \to V'\phi$
  2. Splitting out of vector bosons: $\phi \to \phi' V$, $f \to f'V$, $V \to V'V''$
  3. All the other combinations can be calculated by symmetries

A cheating sheet for you

[JHEP 98 (2024) 064]

- upto $m^2(p_T^2)$ order in quasi-collinear limit(m, $p_T \to 0$)

1. Splitting out of spin-0 particles

$$P_{\phi\to\phi'\phi''}(z,\tilde{q}) = \frac{g^2}{2Sz(1-z)\tilde{q}^2}$$

$$P_{f\to f'\phi}(z,\ \tilde{q}) = \frac{1}{2(q_0^2-m_0^2)}\overline{\sum_{\text{pol}}}|\mathcal{M}|^2$$

$$= \frac{g^2}{2}\Big[\,\big(\rho_+|\kappa+\tilde{\kappa}|^2+\rho_-|\kappa-\tilde{\kappa}|^2\big)\,\big[(1-z)-m_{2,t}^2\big]+(\rho_++\rho_-)\big[|\kappa|^2(m_{0,t}+m_{1,t})^2 + |\tilde{\kappa}|^2(m_{0,t}-m_{1,t})^2\big]+2(\rho_+-\rho_-)\Re(\kappa\tilde{\kappa}^*)\big[(1-2z)m_{0,t}^2+m_{1,t}^2\big]\Big],$$

$$P_{V\to V'\phi}(z,\tilde{q}) = \frac{g_{BSM}^2}{2}\left[\frac{\rho_++\rho_-}{2m_1^2}\Big(z(1-z)+z(1-z)m_{0,t}^2+(1+z)m_{1,t}^2-zm_{2,t}^2\Big) + \frac{\rho_0}{z^2m_0^2}\Big(z(1-z)+z(1-z)m_{0,t}^2-(1-z)m_{1,t}^2-zm_{2,t}^2\Big)\right].$$

$$P_{V\to\phi\phi'}(z,\tilde{q}) = g^2\left[(\rho_++\rho_-)\,\big(z(1-z)(1+m_{0,t}^2)-(1-z)m_{1,t}^2-zm_{2,t}^2 + \rho_0\frac{(1-2z)^2}{2}m_{0,t}^2\right].$$

2. Splitting out of spin-1 particles

$$P_{f\to f'V}(z,\tilde{q}) = (|g_R|^2\rho_++|g_L|^2\rho_-)\left(\frac{1+z^2}{1-z}(1+m_{0,t}^2)-\frac{1+z}{1-z}m_{1,t}^2-m_{2,t}^2\right) + (|g_R|^2\rho_-+|g_L|^2\rho_+)zm_{0,t}^2-2\Re(g_Lg_R^*)(\rho_++\rho_-)m_{0,t}m_{1,t}.$$

$$P_{V\to V'V''}(z,\tilde{q}) = 2g^2\left[\frac{(1-z(1-z))^2}{z(1-z)}(\rho_++\rho_-)+2\rho_0(1-z)^2m_{0,t}^2 + \frac{(1-z(1-z))^2\,(m_{0,t}^2)-(1-z^2(1-z))m_{1,t}^2-(1-z(1-z)^2)m_{2,t}^2}{z(1-z)}(\rho_++\rho_-)\right]$$

$$P_{\phi\to\phi'V}(z,\tilde{q}) = g^2\left[\frac{2z}{1-z}(1+m_{0,t}^2)-\frac{2}{1-z}m_{1,t}^2+\frac{1}{2}m_{2,t}^2\right]$$

A cheating sheet for you

[JHEP 98 (2024) 064]

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1. Splitting out of spin-0 particles

$$P_{f\to f'\phi}(z,\ \tilde{q}) = \frac{1}{2(q_0^2 - m_0^2)}\overline{\sum_{\text{pol}}}|\mathcal{M}|^2$$

$$= \frac{g^2}{2}\Big[\left(\rho_+|\kappa+\tilde{\kappa}|^2 + \rho_-|\kappa-\tilde{\kappa}|^2\right)\left[(1-z) - m_{2,t}^2\right] + (\rho_+ + \rho_-)\left[|\kappa|^2(m_{0,t}+m_{1,t})^2 + |\tilde{\kappa}|^2(m_{0,t}-m_{1,t})^2\right] + 2(\rho_+ - \rho_-)\Re(\kappa\tilde{\kappa}^*)\left[(1-2z)m_{0,t}^2 + m_{1,t}^2\right]\Big],$$

$$P_{\phi\to\phi'\phi''}(z,\tilde{q}) = \frac{g^2}{2Sz(1-z)\tilde{q}^2}$$

$$P_{V\to V'\phi}(z,\tilde{q}) = \frac{g_{BSM}^2}{2}\left[\frac{\rho_+ + \rho_-}{2m_1^2}\left(z(1-z) + z(1-z)m_{0,t}^2 + (1+z)m_{1,t}^2 - zm_{2,t}^2\right) + \frac{\rho_0}{z^2 m_0^2}\left(z(1-z) + z(1-z)m_{0,t}^2 - (1-z)m_{1,t}^2 - zm_{2,t}^2\right)\right].$$

$$P_{V\to\phi\phi'}(z,\tilde{q}) = g^2\left[(\rho_+ + \rho_-)\left(z(1-z)(1+m_{0,t}^2) - (1-z)m_{1,t}^2 - zm_{2,t}^2\right) + \rho_0\frac{(1-2z)^2}{2}m_{0,t}^2\right].$$

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$$P_{f\to f'V}(z,\tilde{q}) = (|g_R|^2\rho_+ + |g_L|^2\rho_-)\left(\frac{1+z^2}{1-z}(1+m_{0,t}^2) - \frac{1+z}{1-z}m_{1,t}^2 - m_{2,t}^2\right) + (|g_R|^2\rho_- + |g_L|^2\rho_+)zm_{0,t}^2 - 2\Re(g_L g_R^*)(\rho_+ + \rho_-)m_{0,t}m_{1,t}.$$

$$P_{V\to V'V''}(z,\tilde{q}) = 2g^2\left[\frac{(1-z(1-z))^2}{z(1-z)}(\rho_+ + \rho_-) + 2\rho_0(1-z)^2 m_{0,t}^2 + \frac{(1-z(1-z))^2(m_{0,t}^2) - (1-z^2(1-z))m_{1,t}^2 - (1-z(1-z)^2)m_{2,t}^2}{z(1-z)}(\rho_+ + \rho_-)\right]$$

$$P_{\phi\to\phi'V}(z,\tilde{q}) = g^2\left[\frac{2z}{1-z}(1+m_{0,t}^2) - \frac{2}{1-z}m_{1,t}^2 + \frac{1}{2}m_{2,t}^2\right]$$

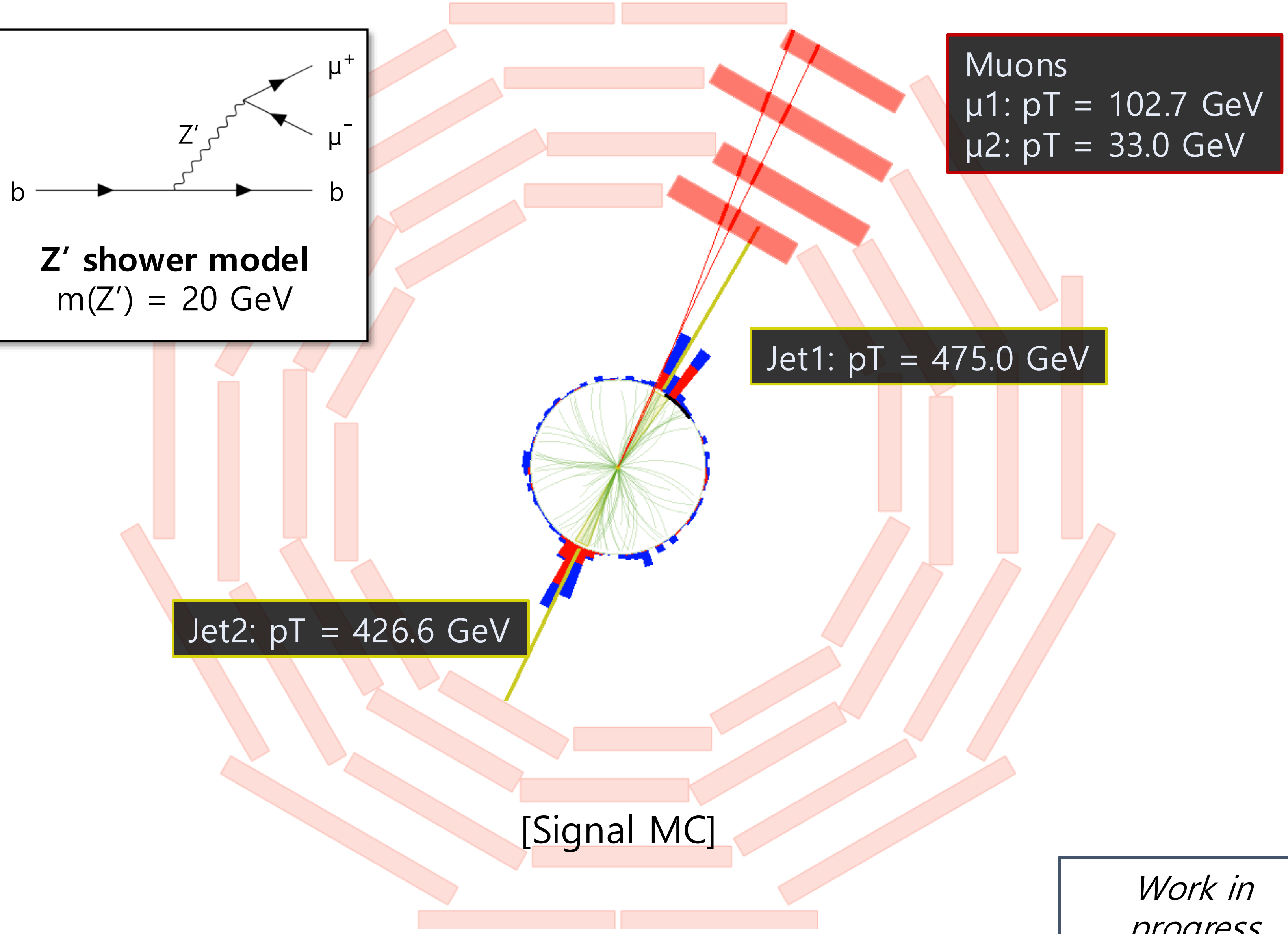
Event history ($gg \to bb$, $b \to bZ'$)

FO-like diagram, i.e. $pp \to jj+Z'$ & PS after Z' radiation

Event history (gg→bb, b→bg, b→bZ')

new signature, gluon splitting first followed by the Z′ radiation

Event display



Z′ shower model
m(Z′) = 20 GeV

[Signal MC]

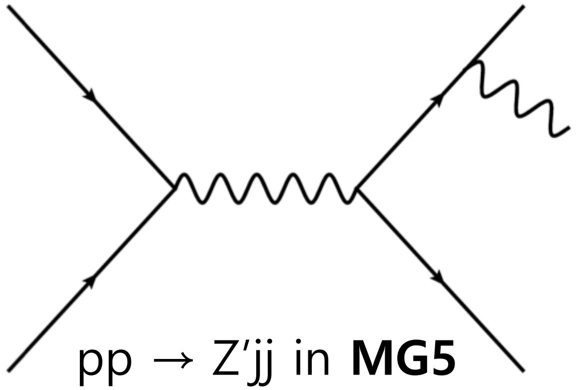
Work in progress

Performance Test

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

Fixed-Order (FO)

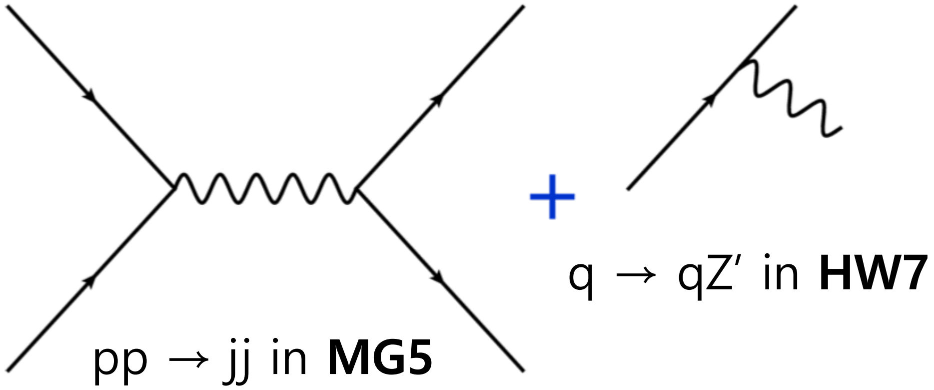
Full MadGraph5 Simulation



VS

Resummed Shower (RS)

Herwig7 Parton Shower



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

- Model Features

  Gauge Symmetry: ***U(1)**B-L*

  Covariant Derivative: Dμ = ∂μ + ig' YB-L Z'μ

  Lagrangian: $\mathcal{L}_f = \sum_k i\,\bar{\psi}_k \gamma^\mu D_\mu \psi_k$ $\quad \mathcal{L}_{\text{int}} \supset g_1'\, Z_\mu' \sum_f \left(Y_{B-L}^f\, \bar{f} \gamma^\mu f \right)$

- Advantages
  - Vector coupling only, $g_L = g_R = g_1'(B-L)$
  - No mixing, mass eigenstates = gauge eigenstates

- What happens in the splitting function?

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

➡

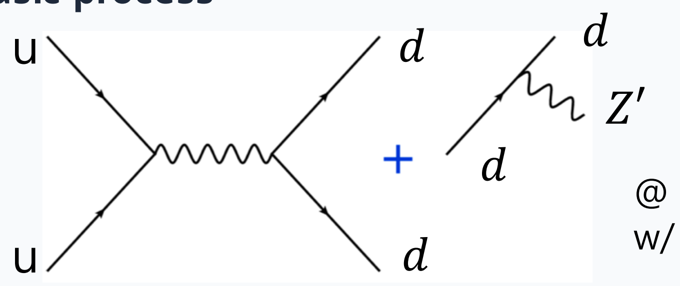
$$P_{f\to fV}(z,\tilde{q}) = \frac{g^2}{2}\left(\frac{1+z^2}{1-z} - 2m_{f,t}^2 - m_{V,t}^2\right)$$

Performance test: q → q V

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

Process: Fermion → Fermion + Vector

Basic process



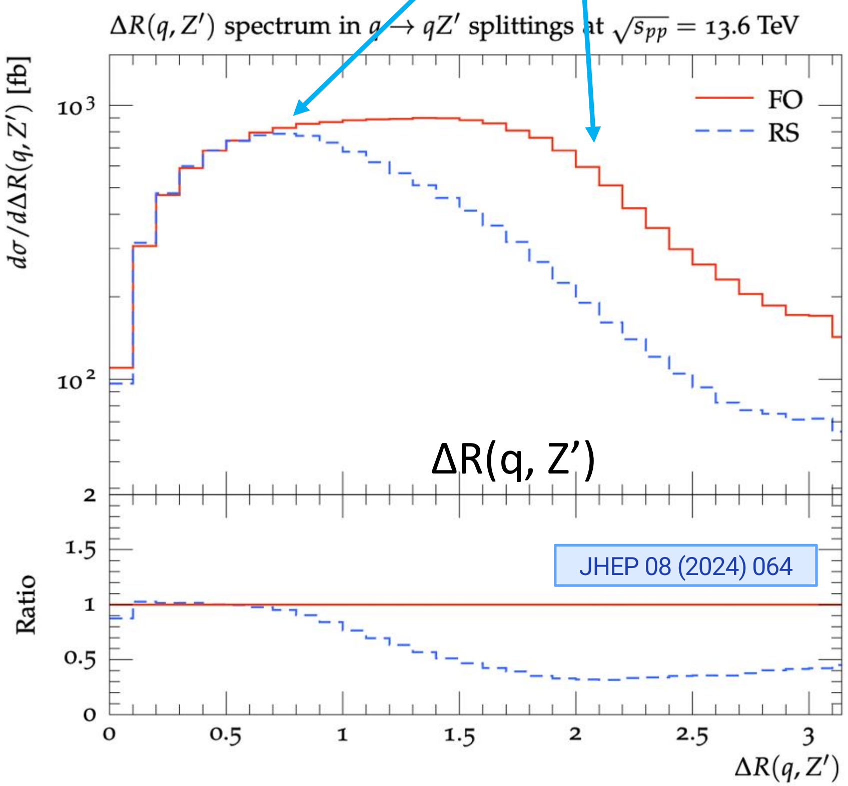
@ 13.6 TeV
w/ m(Z′) = 10 GeV

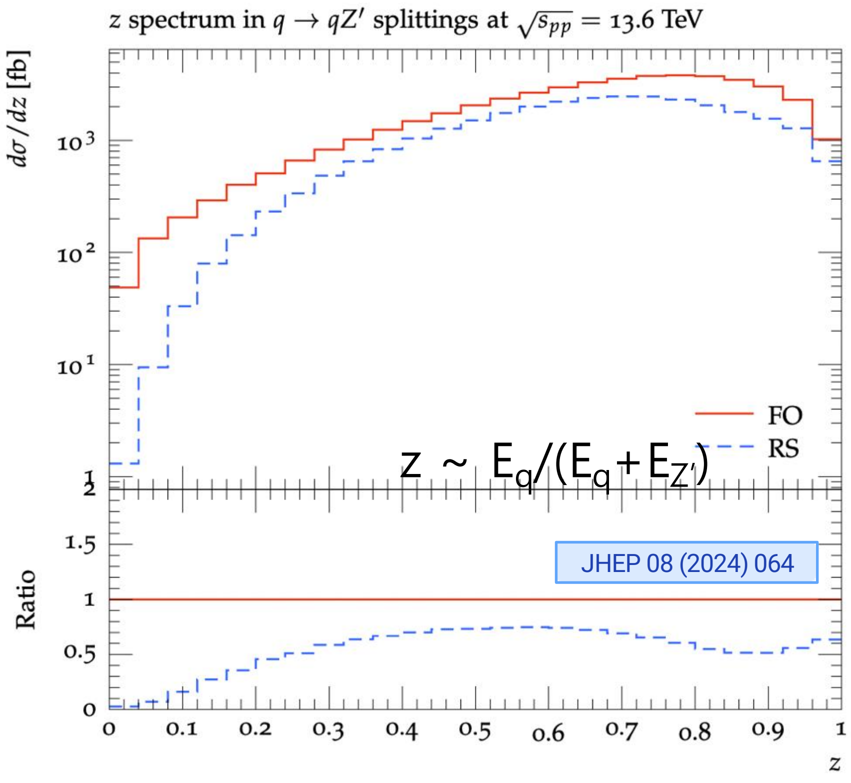
Validation results

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





Parton-level Validation

Angular Separation ΔR(q, Z')

Previous Work

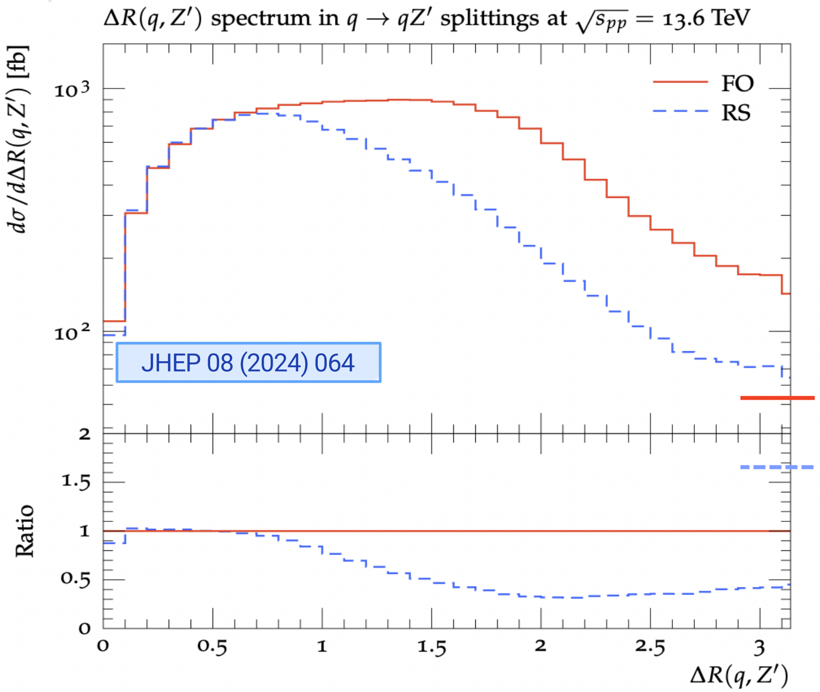
Only FSR-like diagrams considered in MG($u\bar{u} \to d\bar{d}\, Z'$) sample

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

Current Work

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

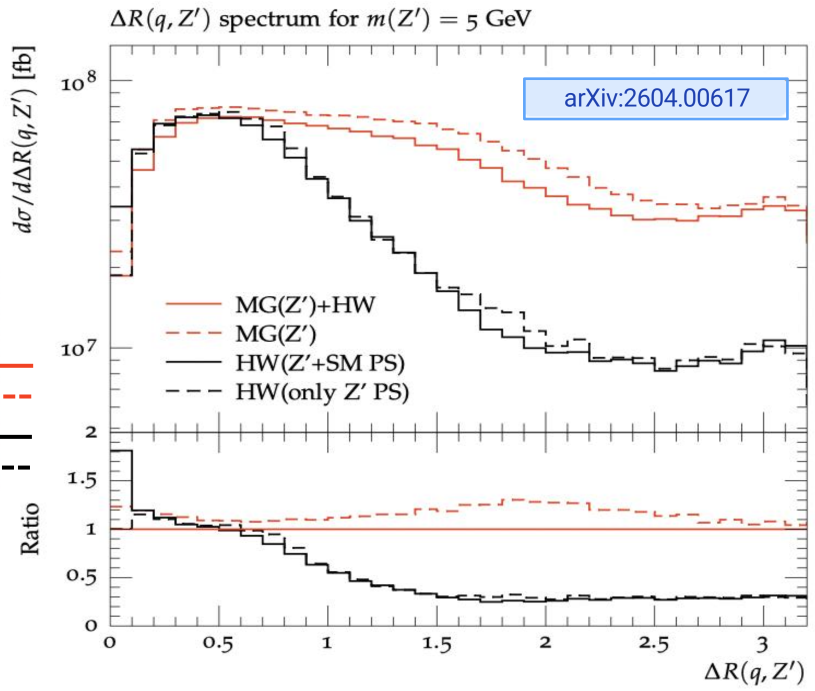
Includes **full SM Shower + Z' shower** effects for **realistic** simulation



m(Z') = 10 GeV

m(Z') = 5 GeV

Sample	MadGraph 5 (ME) Hard process	Herwig 7 (shower) 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

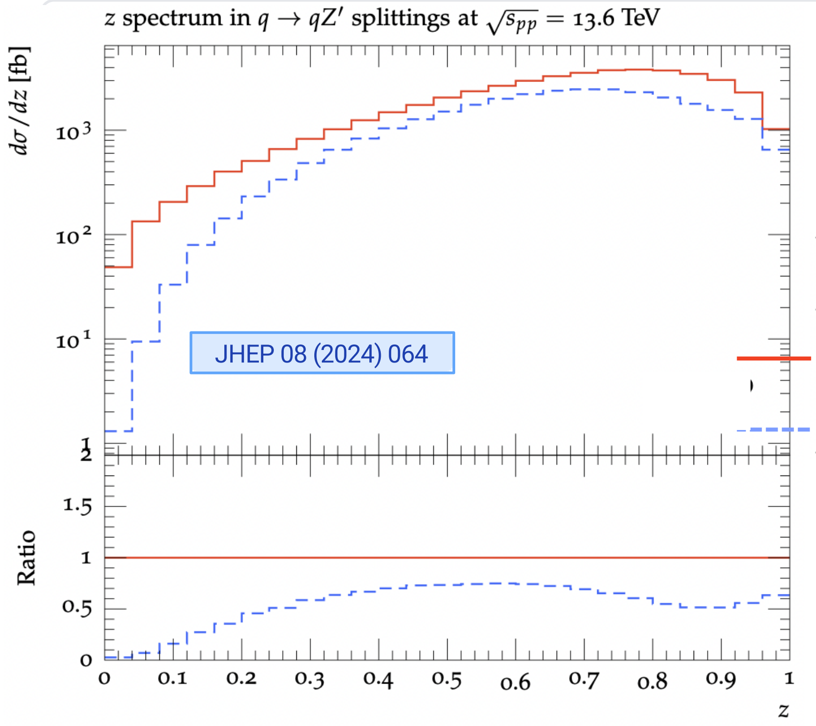
No SM Parton Shower included, i.e. only Z’ shower

Current Work

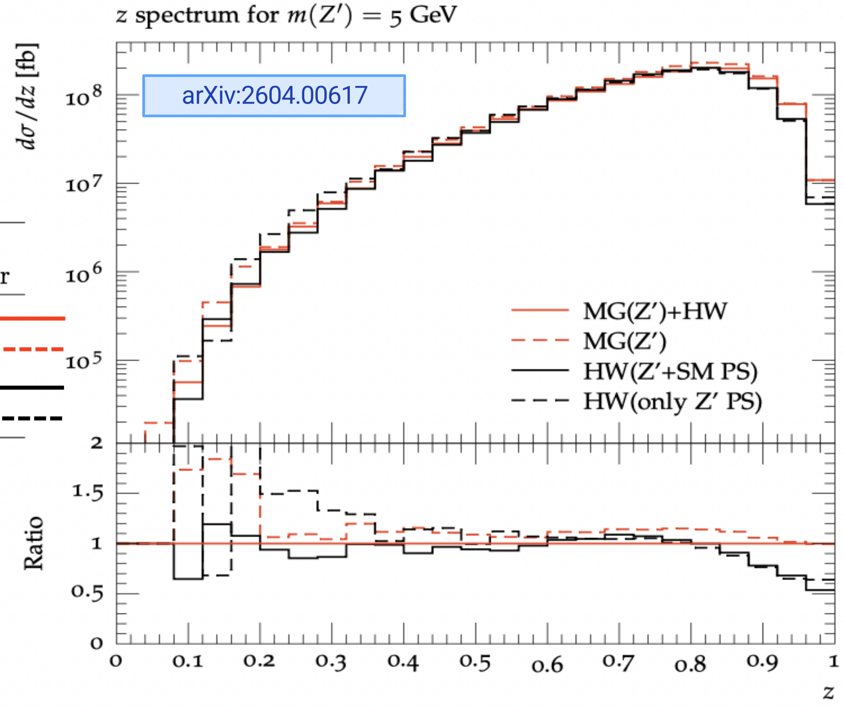
Inclusive production of MG(pp → Z’ jj) events

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

m(Z') = 10 GeV



m(Z') = 5 GeV



	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

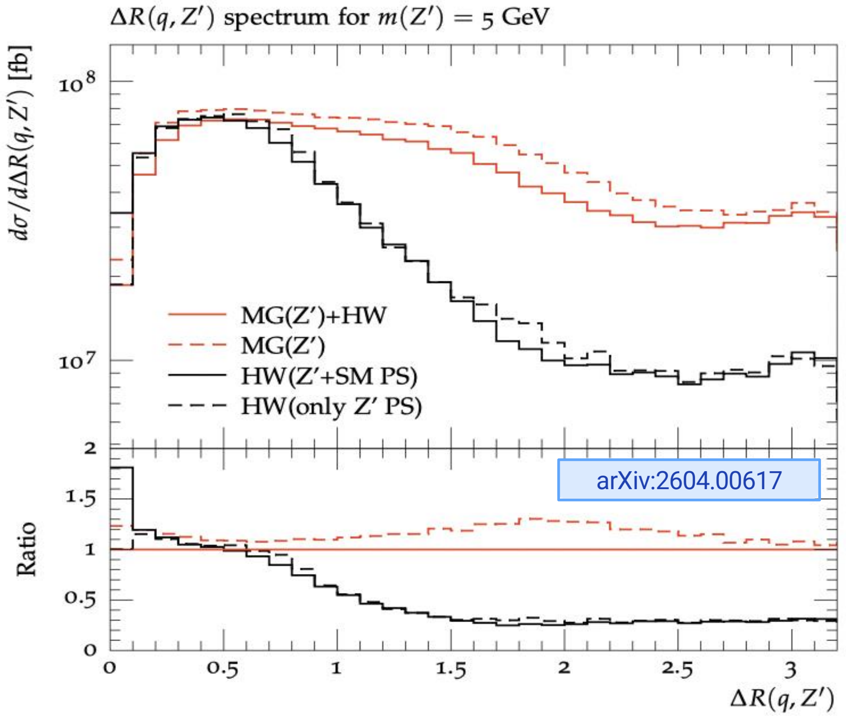
Key Findings & Improvements

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

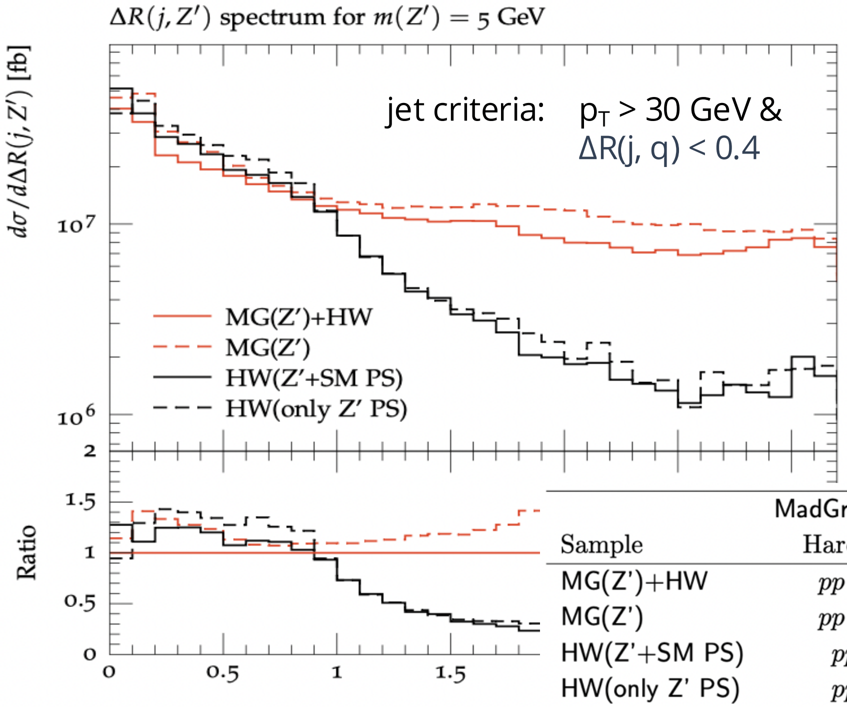
Analysis Object-level Validation

Variable Transition $\Delta R(q, Z')$ → $\Delta R(j, \mu\mu)$ z (Energy Fraction) → Muon Energy Fraction (MEF)

Quark-Z′ Separation: ΔR(q, Z′)



Jet-Dimuon Separation: ΔR(j, μμ)



Sample	MadGraph 5 (ME) Hard process	Herwig 7 (shower) 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

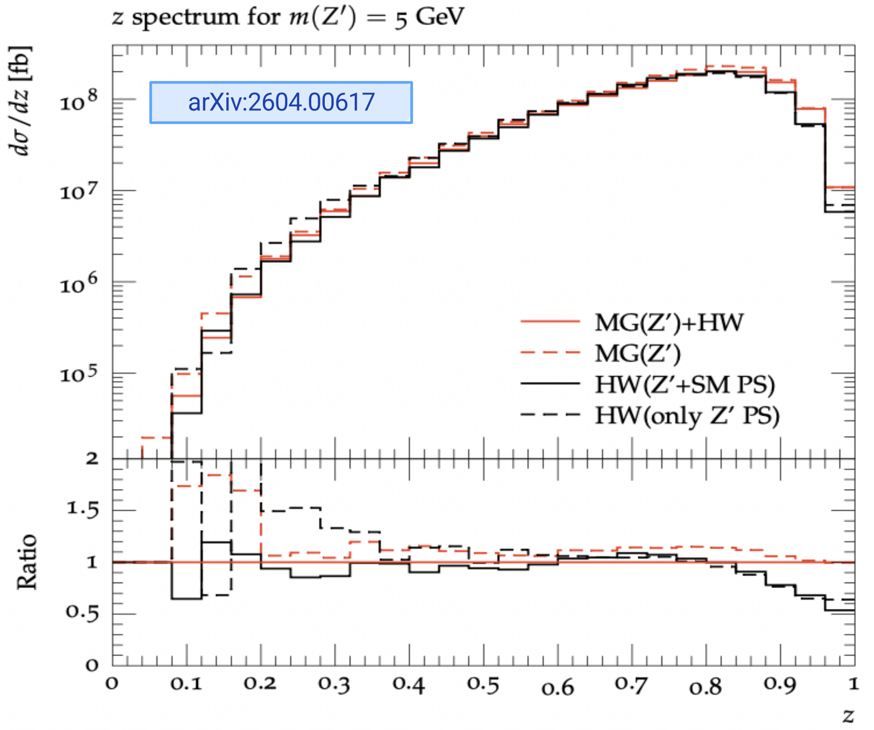
Observation

More events observed as **$\Delta R(j, \mu\mu) \to 0$,** because **anti-kt algorithm** clusters jets around the collinear Z′

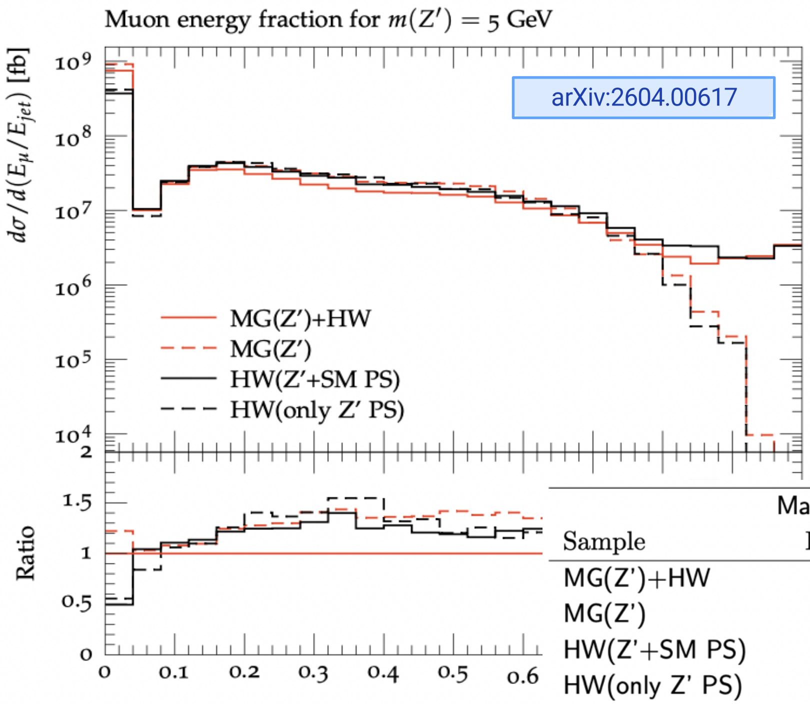
Analysis Object-level Validation

Variable Transition | z (Energy Fraction) → Muon Energy Fraction (MEF) | based on “MEF ≈ 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	red solid
MG(Z′)	$pp \to Z'jj$	off	off	red dashed
HW(Z′+SM PS)	$pp \to jj$	on	on	black solid
HW(only Z′ PS)	$pp \to jj$	first-emission only	off	black dashed

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

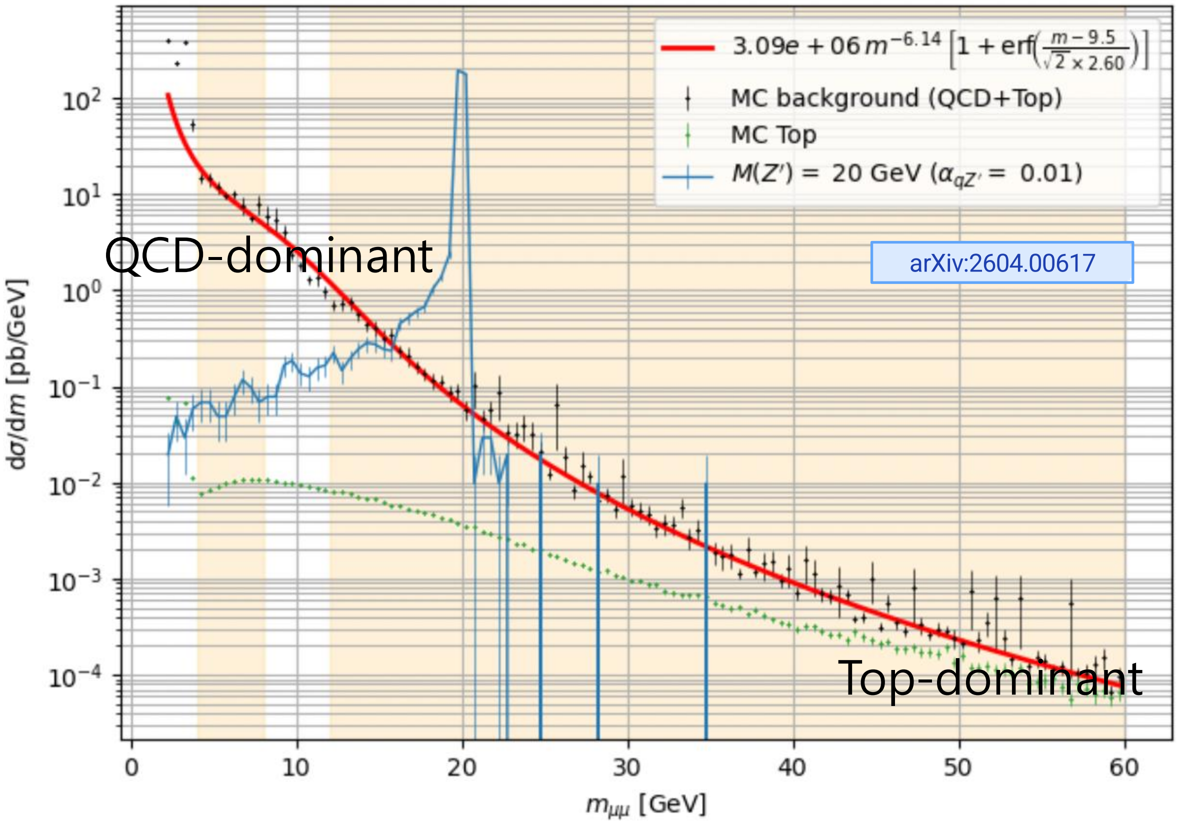
Event selection: OS dimuon pair with pT > 52, 5 GeV (for standrad trigger) & 5, 5 GeV (for scouting trigger) inside jets (ΔR < 0.3)

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

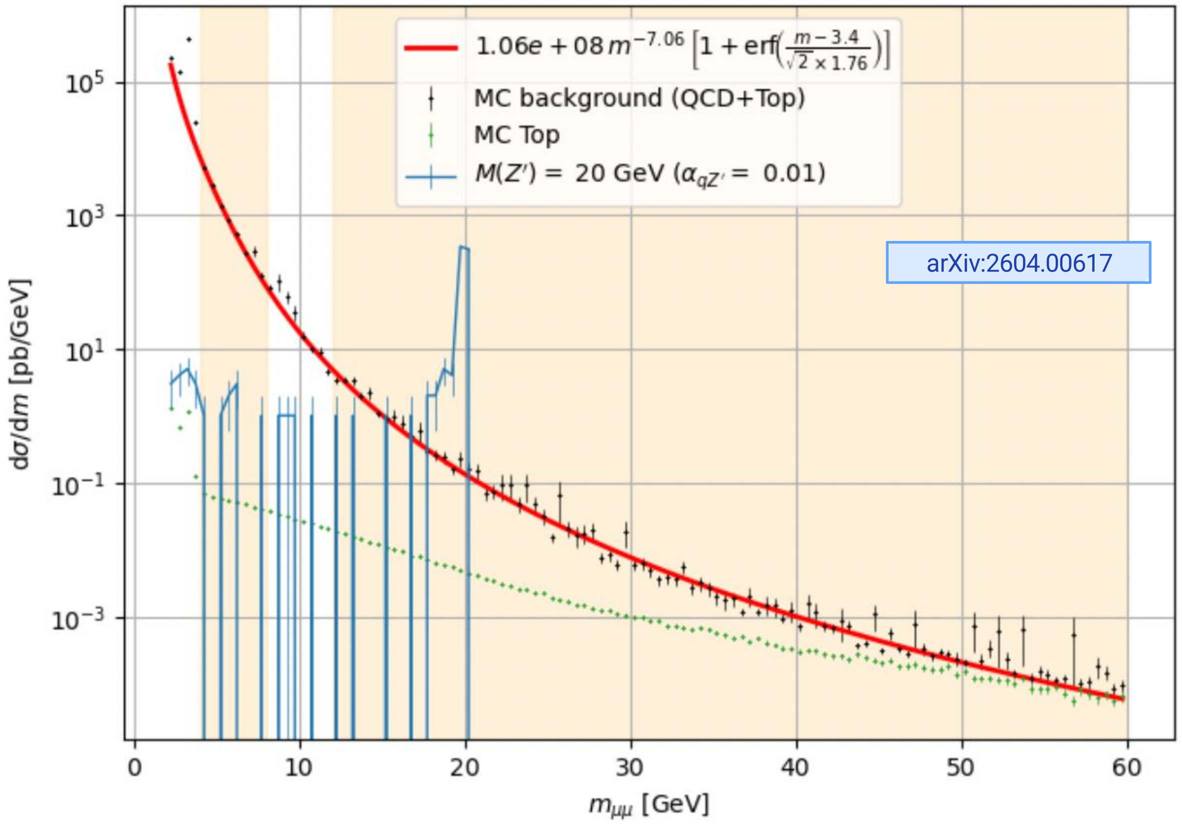
~ QCD cross section (power law)

p_T turn-on

Standard Trigger



Scouting trigger

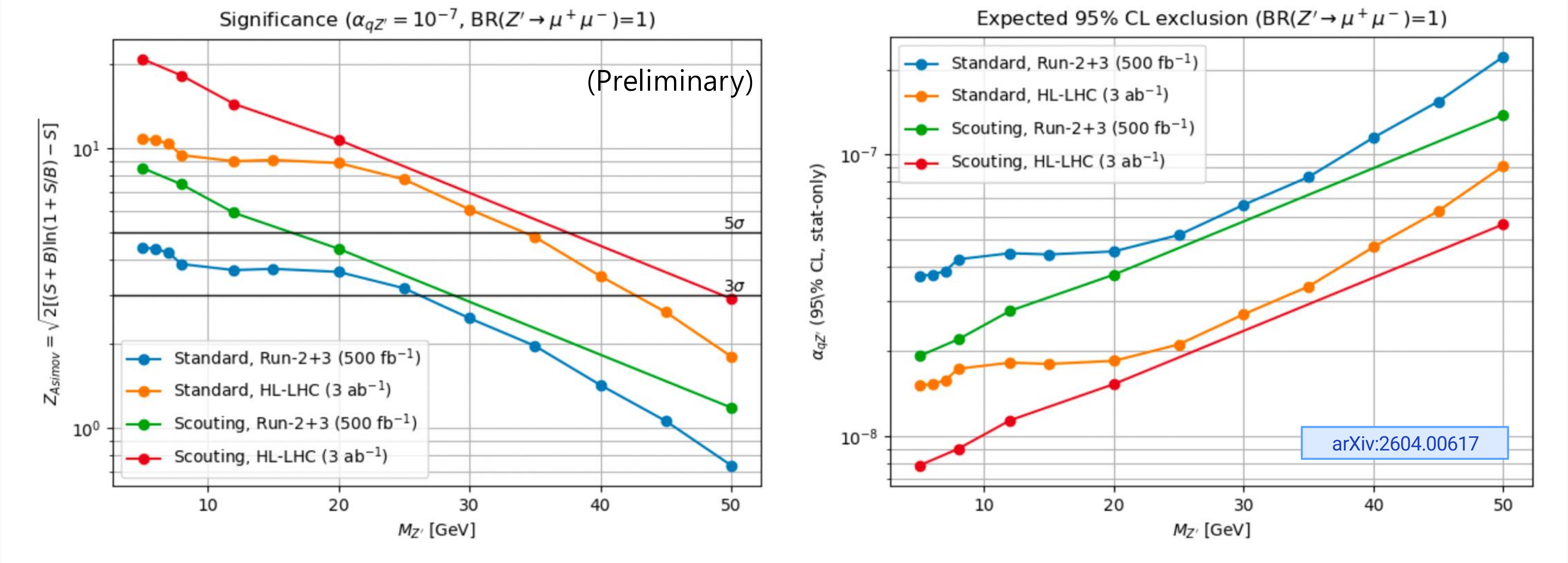


Key Insight: Scouting trigger introduces no turn-on curve, improving limits @ low mass region

Significance & Expected Limit

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

Method: Asimov (Stat. Only)



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

BSM PS & non-isolated signature collaboration

Phenomenology

- University of Manchester (Mike Seymour)
- University of South Dakota (Doojin Kim)
- IPPP, Durham University (Aidin Masouminia)
- University of London (Neda Darvishi)

Experiment

- CMS experiment

Joon-Bin Lee, Taehee Kim, Un-ki Y
ang, Hyungyong Kim
(Seoul National University)

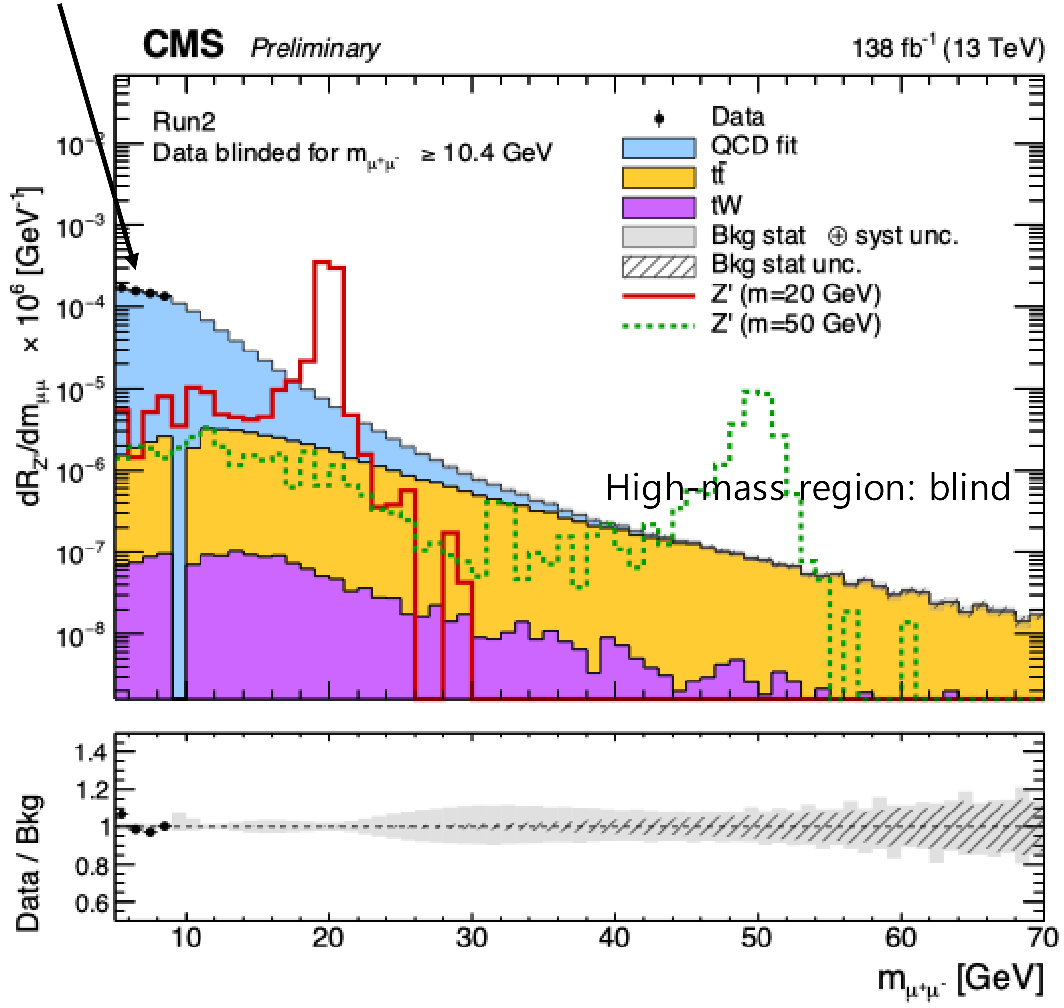
Search new physics using non-isolated dimuon inside a b-jet

- QUEST-DMC experiment

Light Bosons in Jets

In the CMS experiment…

- OS dimuon mass distribution inside jets
  - In the low mass control region, the data agree well with the expectation



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-iso lated leptons.
- Demonstrated robust modeling of BSM radiation and **promi sing sensitivity** in 5–50 GeV range.
- Main feature of Herwig 7.4

Future Work

Upcoming Tasks

Planned

Systematics Study & Optimization of event selection

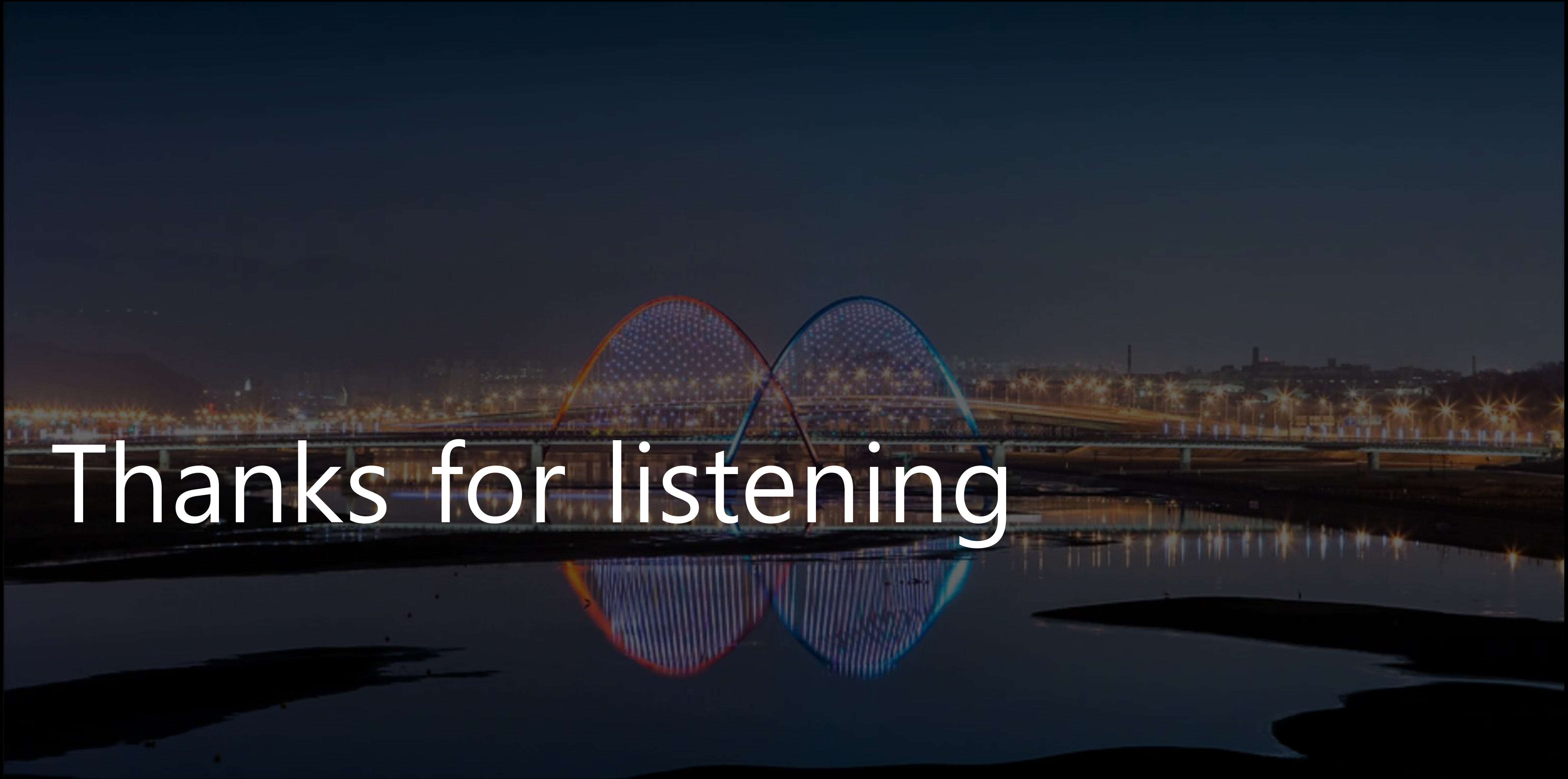
Include full systematic uncertainties and optimize event selection (b-taggi ng, vertexing).

Model Interpretations

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

Experimental Implementation

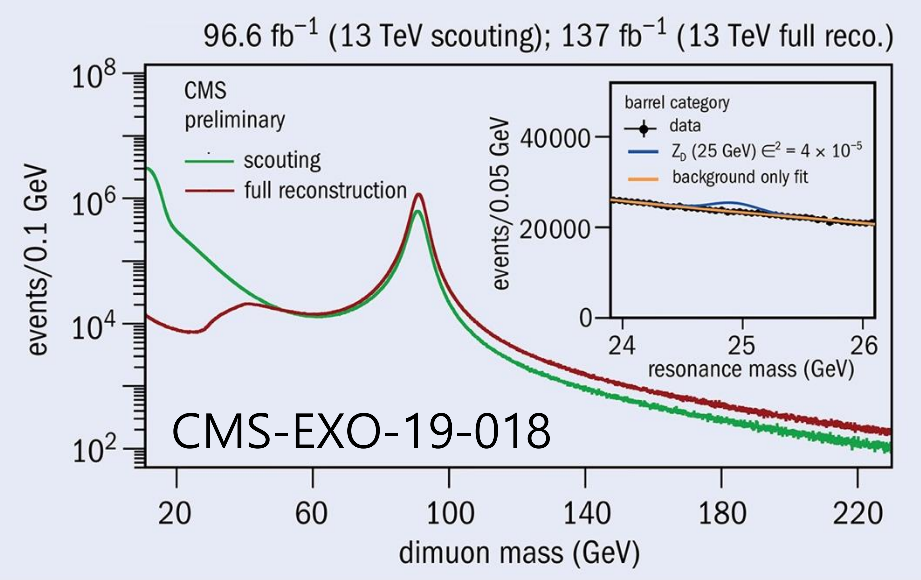
Collaborate with experimental groups (CMS/ATLAS) to implement search with real data.

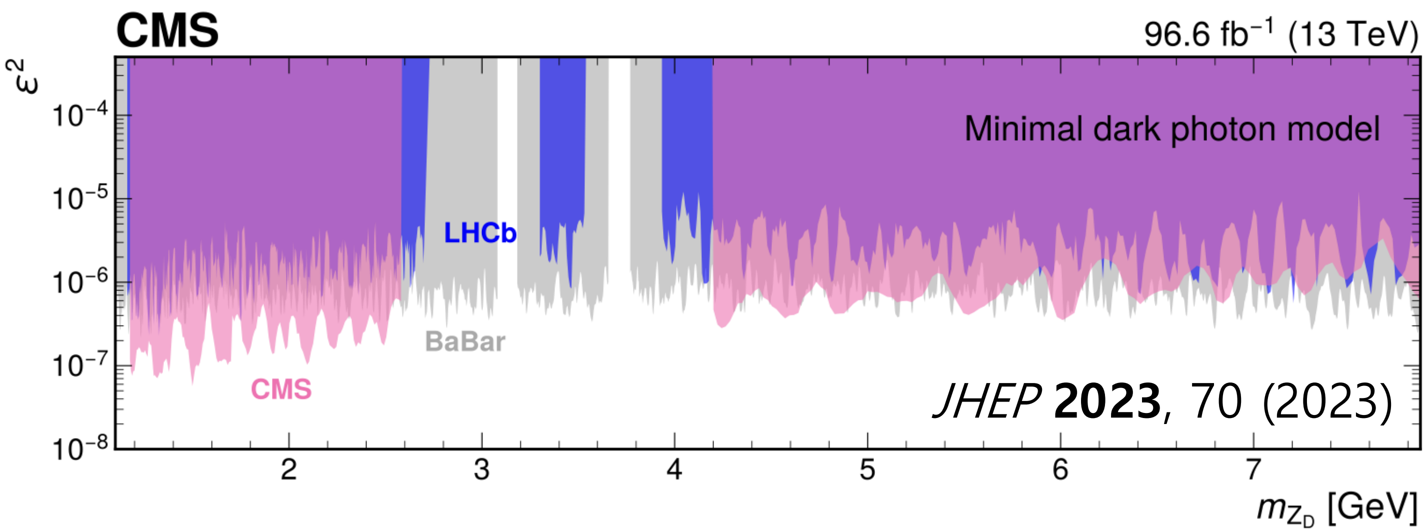


Thanks for listening

Why light BSM particles during PS?

- Low scale BSM searches in LHC



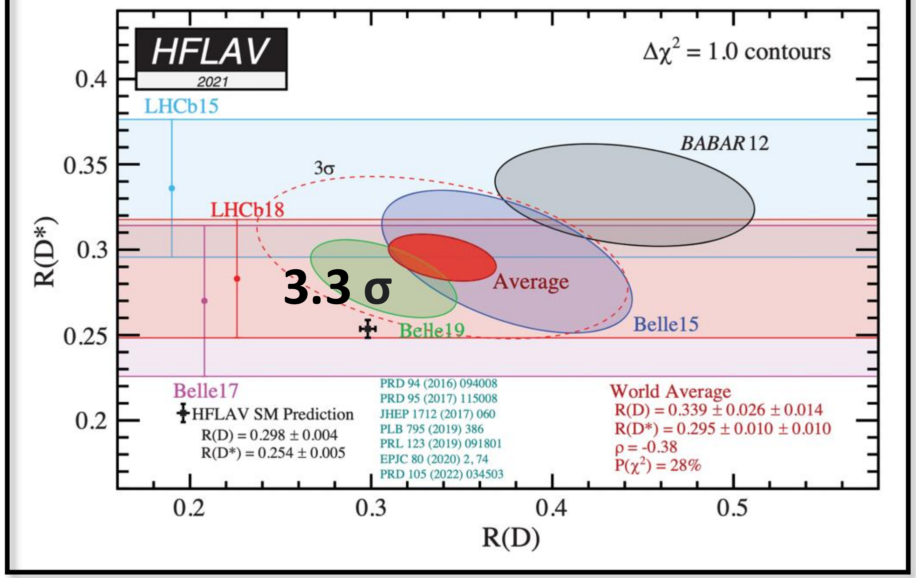


- Low mass BSM bosons can be produced during the PS process
  - tones of samples are necessitated over huge parameter spaces
  - hard to consider all higher order diagrams
- The additional time taken by adding BSM radiation grows slowly with the number of emitted particles
  - Practically we add only one or two BSM particles in common

Where should we go?

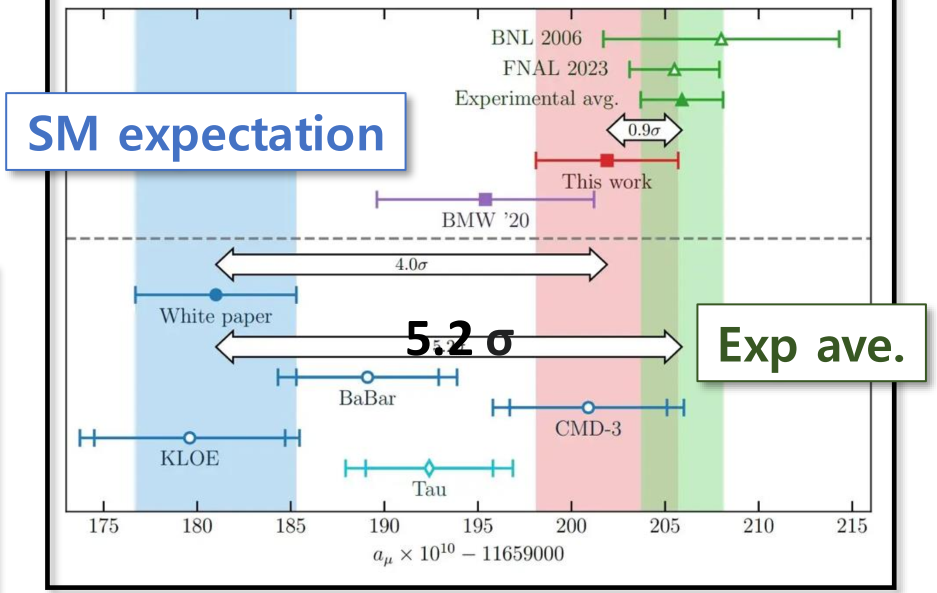
- There exists something we do not understand about muons and b quarks!

"B-anomalies"



Phys. Rev. D107, 052008

"Muon g-2 experiment"



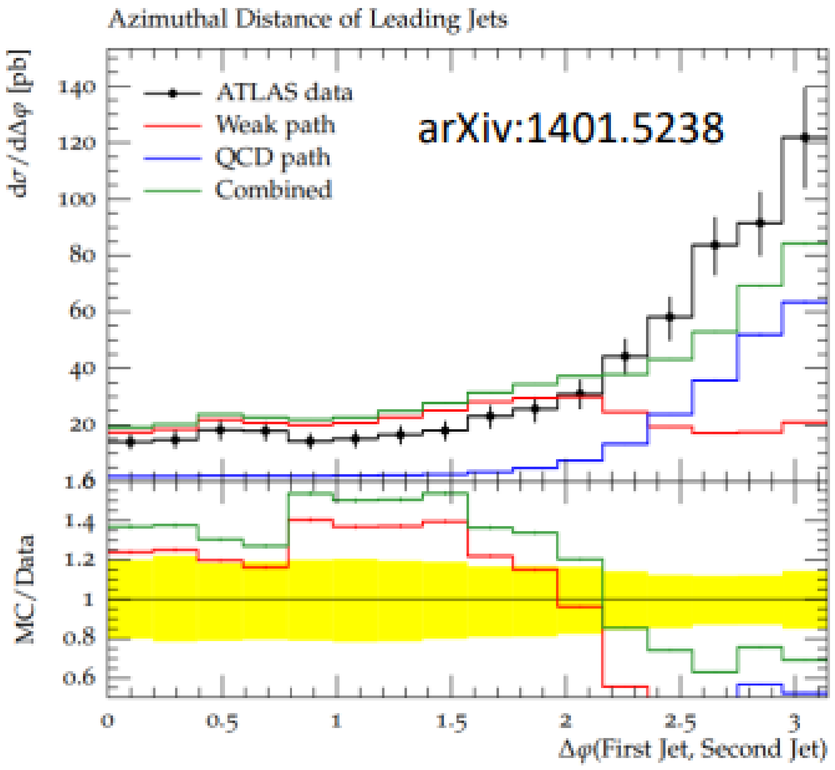
Nature 653, 373–377 (2026)

Maybe something new with muons in b-jets?

⇒ "*Non-isolated* lepton"

Motivations

- Radiation of a BSM particle can distort kinematic distributions



← Weak boson radiation example

Δϕ distribution between leading two jets in ATLAS W+jets sample

- Weak path: W sample + QCD radiation
- QCD path: QCD sample + QCD/weak radiation

! QCD path changes the distribution shape !
! Same thing can happen for the BSM radiation !

BSM Showers in Herwig7

Model-Independent Framework for New Physics Simulation

Phenomenology

Universal Splittings

- Only depends on spins, masses, and orderin g variables of participating particles
- Based on the **Master Formula by Altarelli a nd 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 informa tion automatically from **UFO model files wit hout manual intervention**
- Flexibility: can be interfaced with various mat rix-element generators such as Herwig7's int ernal ME calculator and MG5, ...

Automation is Key

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

Factorization Essentials

Total Cross Section Formula

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

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

Parton Shower Algorithms

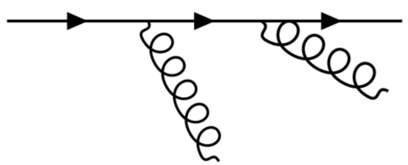
Comparing Approaches: Angular-Ordering vs. Dipole Shower

Herwig7

Angular-Ordered Shower

Strength

Color Coherence Captures the "Chudakov effect" natu rally via angular ordering property (simple).



Shower History Perfectly tracks shower history, makin g it ideal for recursive BSM implementations.

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

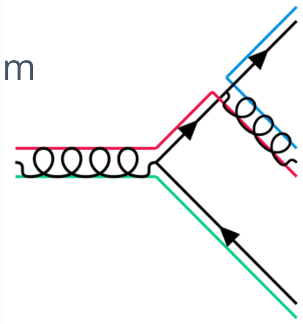
VS

Pythia8

pT-Ordered Dipole Shower

Strength

Color Coherence Dipole algorithm (with p_T ordering).



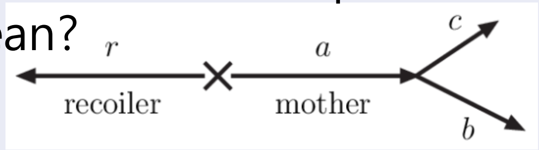
Adoption CMS default parton shower generator with extensive tuning.

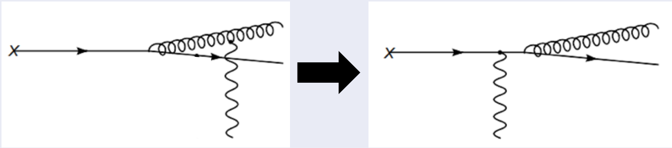
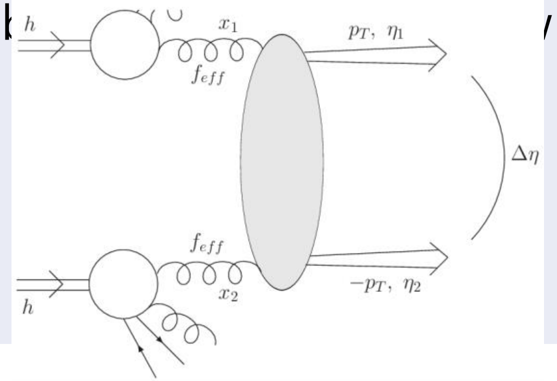
Trade-off: Shower history reconstruction can be mor e complex.

Why Angular Ordering?

Tracking shower history explicitly → Fits to new physics search

PYTHIA vs HERWIG

<table>
<tr><th></th><th>PYTHIA</th><th>HERWIG</th></tr>
<tr><td>shower algorithm</td><td>pT ordered dipole shower</td><td>angular order (averaging a radiation along the radiator)</td></tr>
<tr><td></td><td>What does the “dipole” mean?


E-p conservation is achieved by balancing the momentum of the daughter partons and it of recoiler</td><td>
“Chudakov effect”
A radiating parton only sees the total charge of initial partons</td></tr>
<tr><td>accuracy</td><td>only LL accuracy</td><td>+ NLL (+ NNLL, process dependent)</td></tr>
<tr><td>limitation</td><td></td><td>cannot be used for some ob jets

</td></tr>
</table>

Is it right?

Herwig7

- Logarithmic accuracy

Derivation of Sudakov form factor - 1: Unitarity property A mathematically simpler method is to use a unitarity at a moment:

$$\text{"No emission probability"} + \text{"Emission probability"} = 1 \tag{4.24}$$

where the instantaneous "Emission probability" is equal to $d\Delta(q^2)$, i.e. $d\Delta(q^2) + dP(q^2) = 1$. As a result, the Sudakov form factor becomes

$$\begin{aligned}
\Delta_i(Q^2, q^2) &= \prod_{j=0}^{n-1} \Delta_i(q_{j+1}^2, q_j^2) = \prod_{q_j^2}^{q_{j+1}^2} (1 - dP_i) \\
&= \exp\left[-\int_{q^2}^{Q^2} dP_i \right] \\
&= \exp\left[-\frac{\alpha}{2\pi} \int_{Q_0^2}^{Q^2} \frac{dk^2}{k^2} \int_{Q_0^2/k^2}^{1-Q_0^2/k^2} dz P_{ji}(z) \right],
\end{aligned} \tag{4.25}$$

where the last line is obtained by inserting eq. (4.23), If the splitting function is given as $P_{ij}(z) \sim 2C_F/(1-z)$, then $\int dz P_{ij}(z) \sim 2C_F \log k^2/Q^2$. It finally gives the Sudakov form factor in the approximated form as

$$\Delta_i(Q^2, Q_0^2) \sim \exp\left(-C_F \frac{\alpha}{2\pi} \log^2 \frac{Q^2}{Q_0^2} \right). \tag{4.26}$$

Rewriting this equation with Taylor expansion, we get

$$\Delta_i(Q^2, Q_0^2) \sim \sum_{n=0}^{\infty} \frac{(-1)^n}{n!} \left(C_F \frac{\alpha}{2\pi} \log^2 \frac{Q^2}{Q_0^2} \right)^n. \tag{4.27}$$

Herwig7

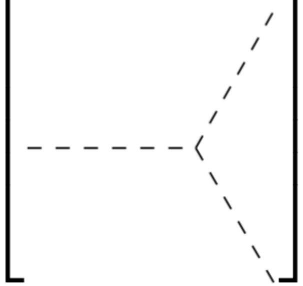
- Ordering-variables

$$\frac{\mathrm{d}\theta^2}{\theta^2} = \frac{\mathrm{d}q^2}{q^2} = \frac{\mathrm{d}k_\perp^2}{k_\perp^2}$$

give identical results in the collinear limit, but different extrapol
ations away from it

Simplest case: (spin) 0 → 00 splitting

- Fully symmetric and no spins!
  - → gives constant matrix element

$-i\mathcal{M}$ [] $= -ig$

→ No parton indices occured

- Splitting function from the master formula

$$P_{\phi\to\phi'\phi''}(z,\tilde{q}) = \frac{g^2}{2Sz(1-z)\tilde{q}^2}$$

- symmetric factor

$S = 1$ for $\phi' \neq \phi''$ and $S = 2$ for $\phi' = \phi''$

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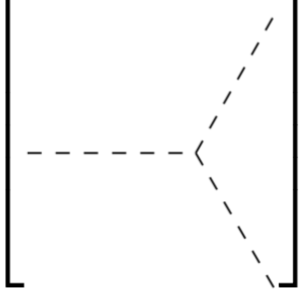
$-i\mathcal{M}$ [] $= -ig$

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- symmetric factor

$S = 1$ for $\phi' \neq \phi''$ and $S = 2$ for $\phi' = \phi''$

- Highlights
  1) Both CP-even/odd higgs bosons are included
  2) Charged higgs bosons and FCNCs can be treated

Simplest case: (spin) 0 → 00 splitting

- SM h → hh splitting can be obtained with SM higgs parameters

$$P_{h\to hh}(z,\tilde{q}) = \frac{g_W^2}{z(1-z)\tilde{q}^2}\frac{9m_h^4}{16m_W^2}$$

→ advantage of the generalized parton shower

- Validation
  - 100 TeV pp collider

  - **Resummed-shower (RS)** result

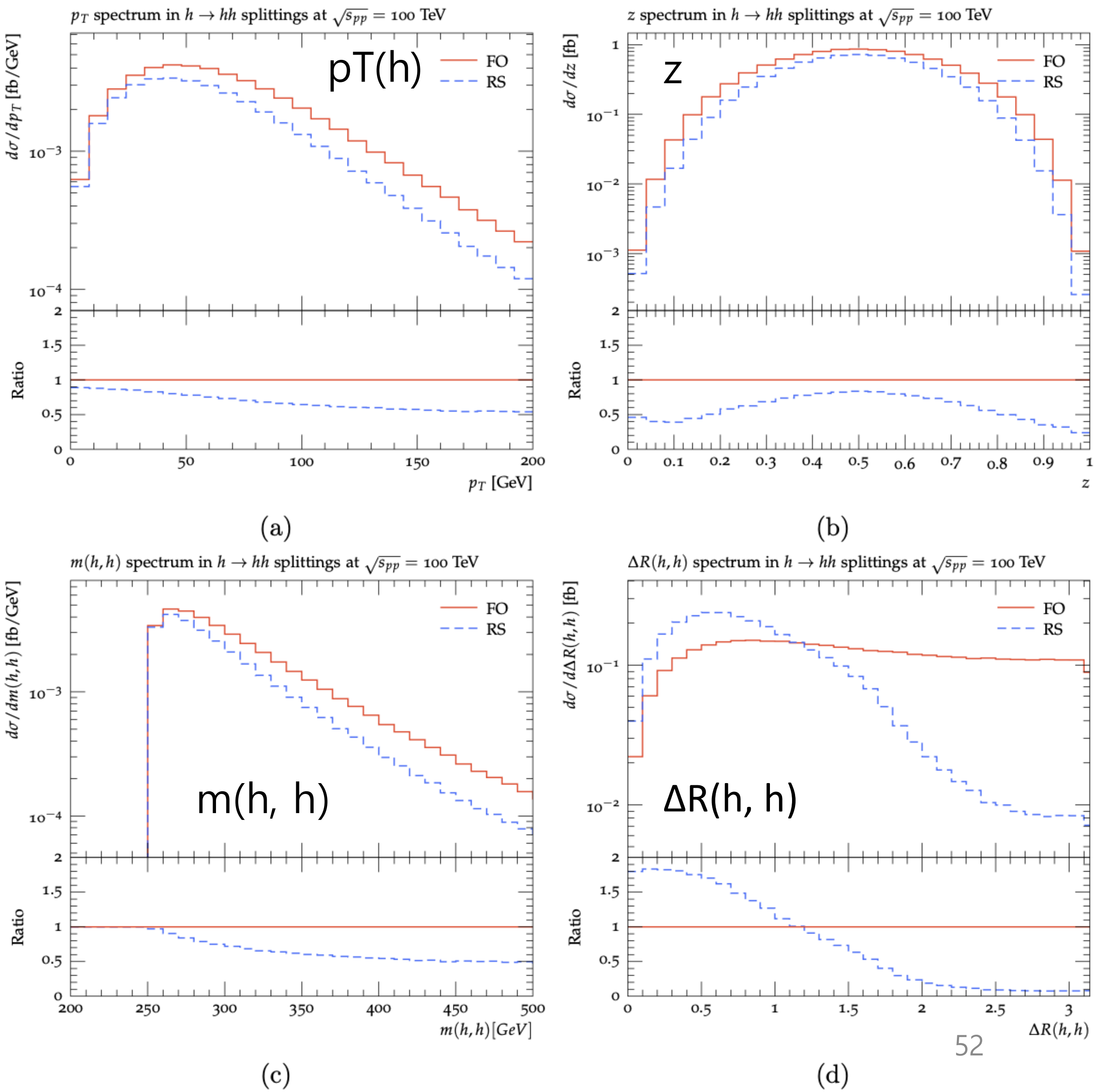
    pp → Zh (MG5) + h → hh (HW7)

  - restriced to have only 1 BSM splitting

  - **Fixed-order (FO)** result

    pp → Zhh (MG5)

  - the second higgs boson should come from the higgs boson (not from Z)



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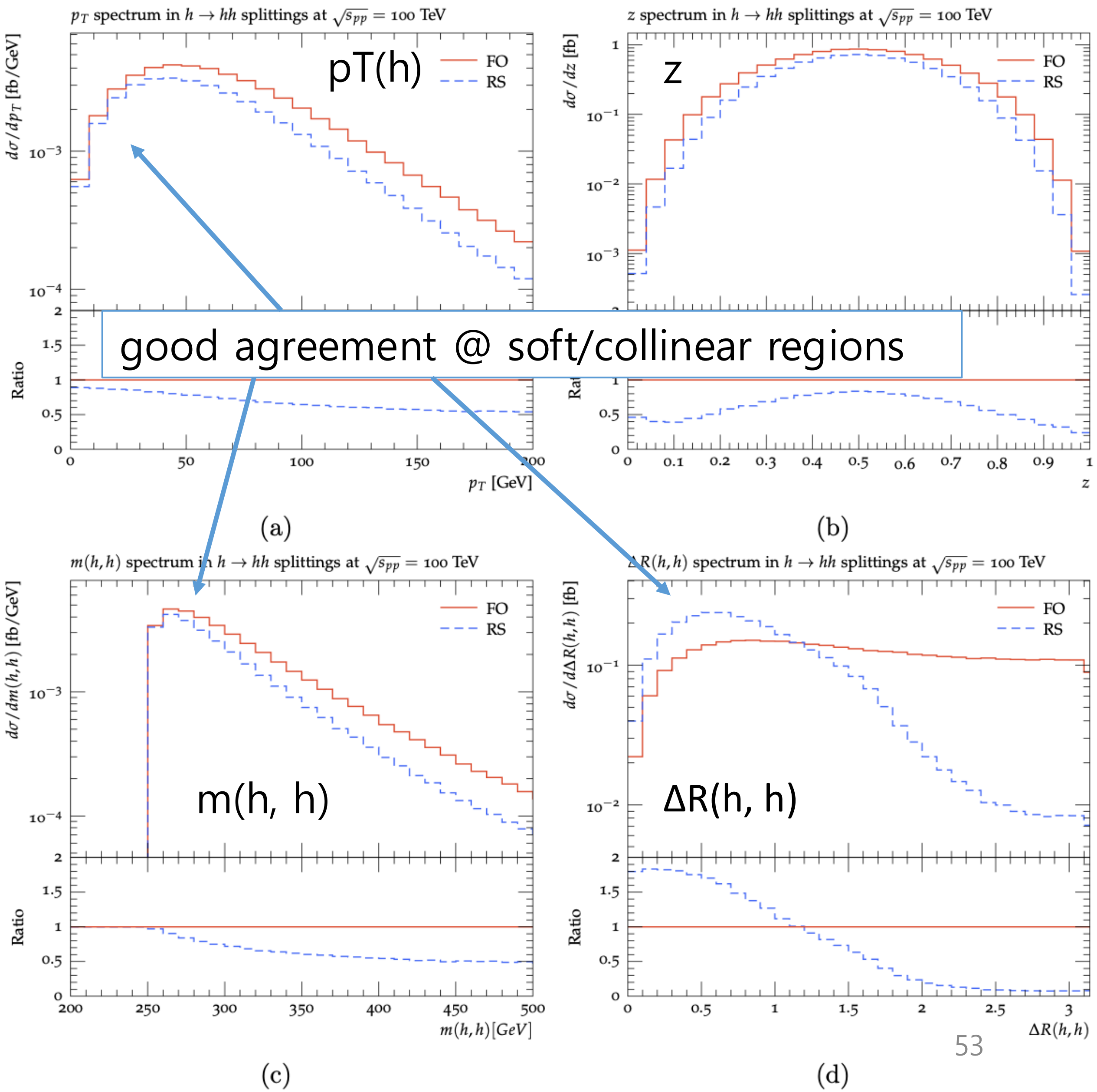

Simplest case: (spin) 0 → 00 splitting

- SM h → hh splitting can be obtained with SM higgs parameters

$$P_{h\to hh}(z,\tilde{q}) = \frac{g_W^2}{z(1-z)\tilde{q}^2}\frac{9m_h^4}{16m_W^2}$$

→ advantage of the generalized parton shower

- Validation
  - 100 TeV pp collider

  - **Resummed-shower (RS)** result

    pp → Zh (MG5) + h → hh (HW7)

  - restriced to have only 1 BSM splitting

  - **Fixed-order (FO)** result

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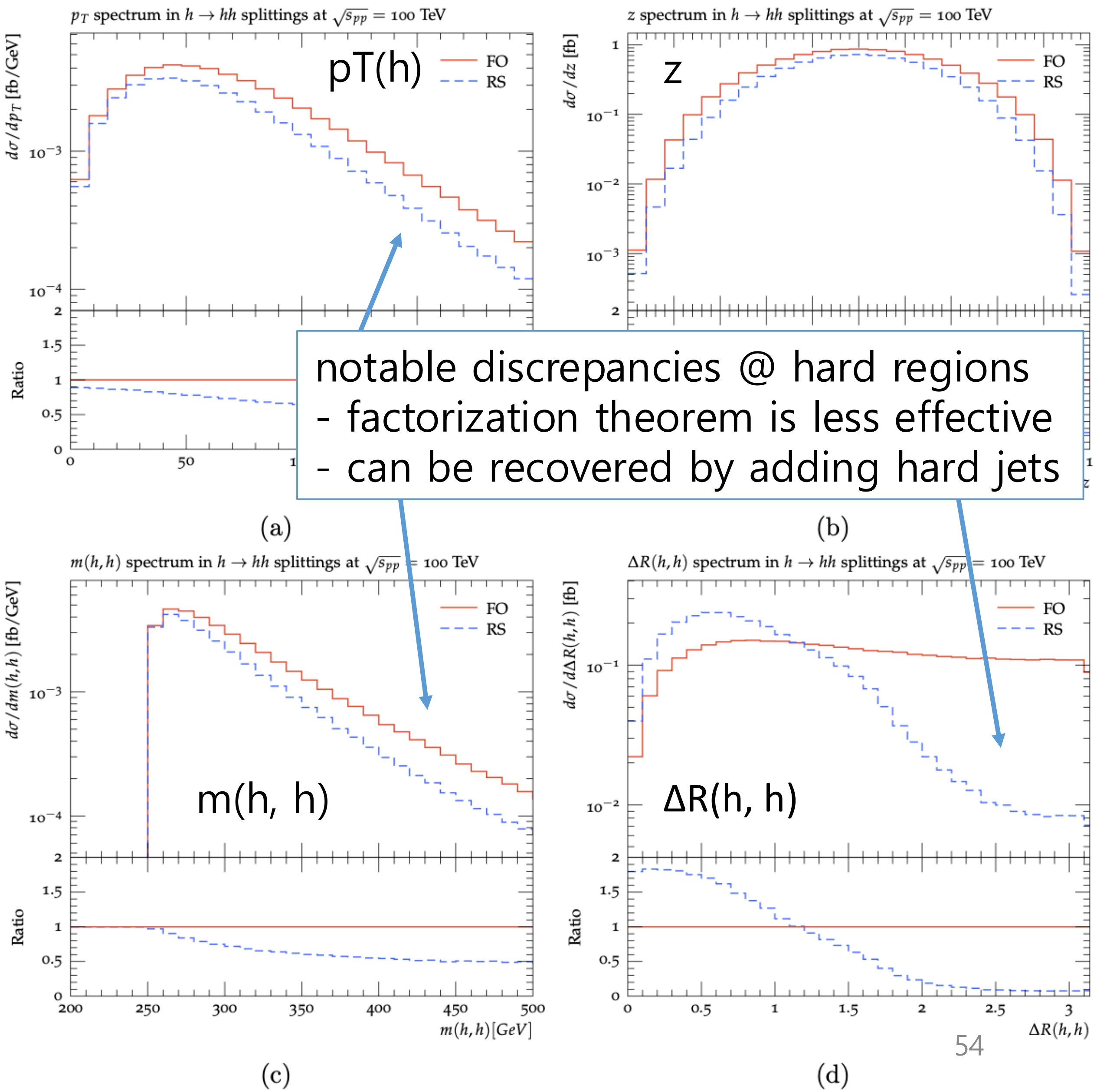

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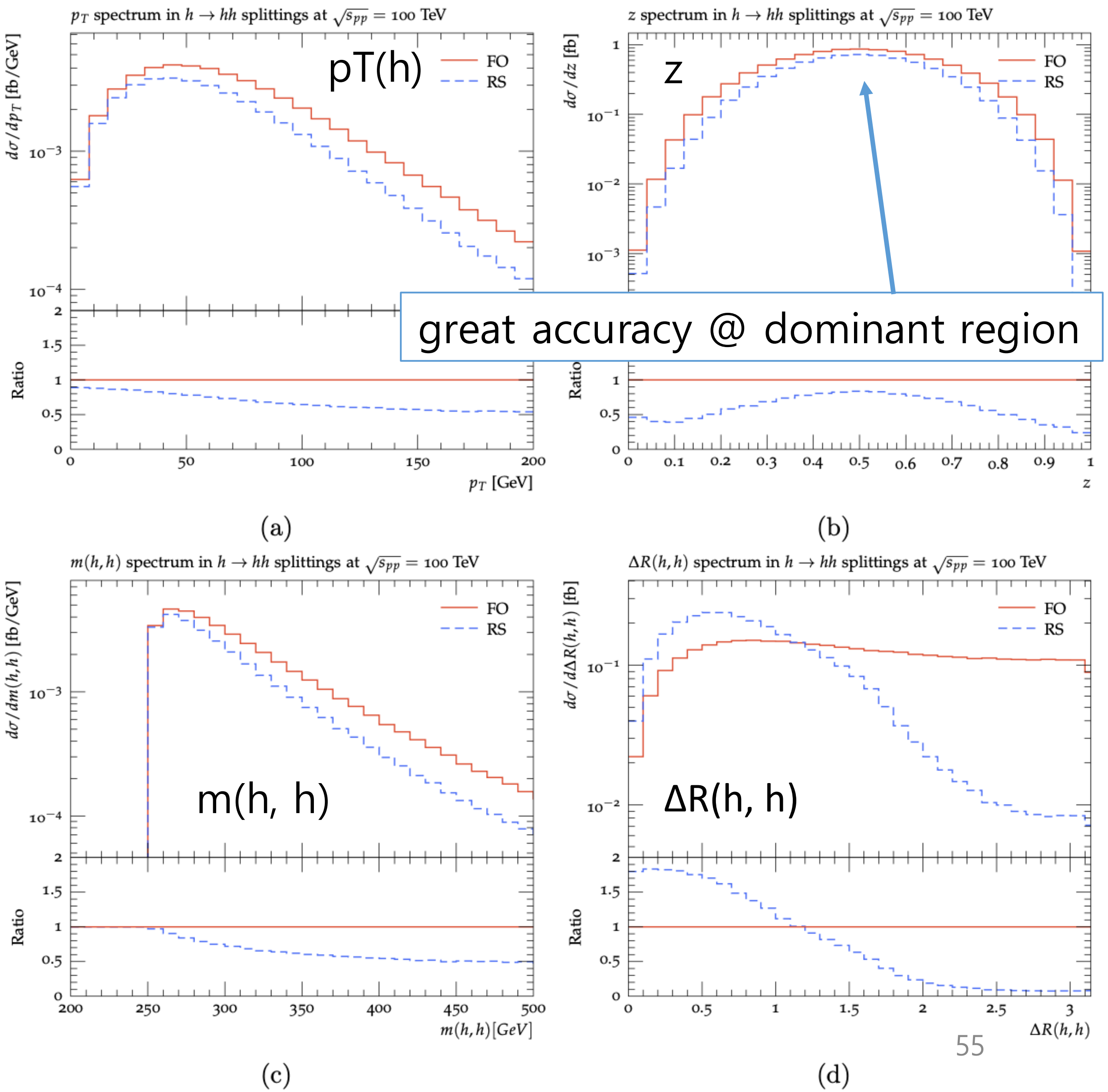
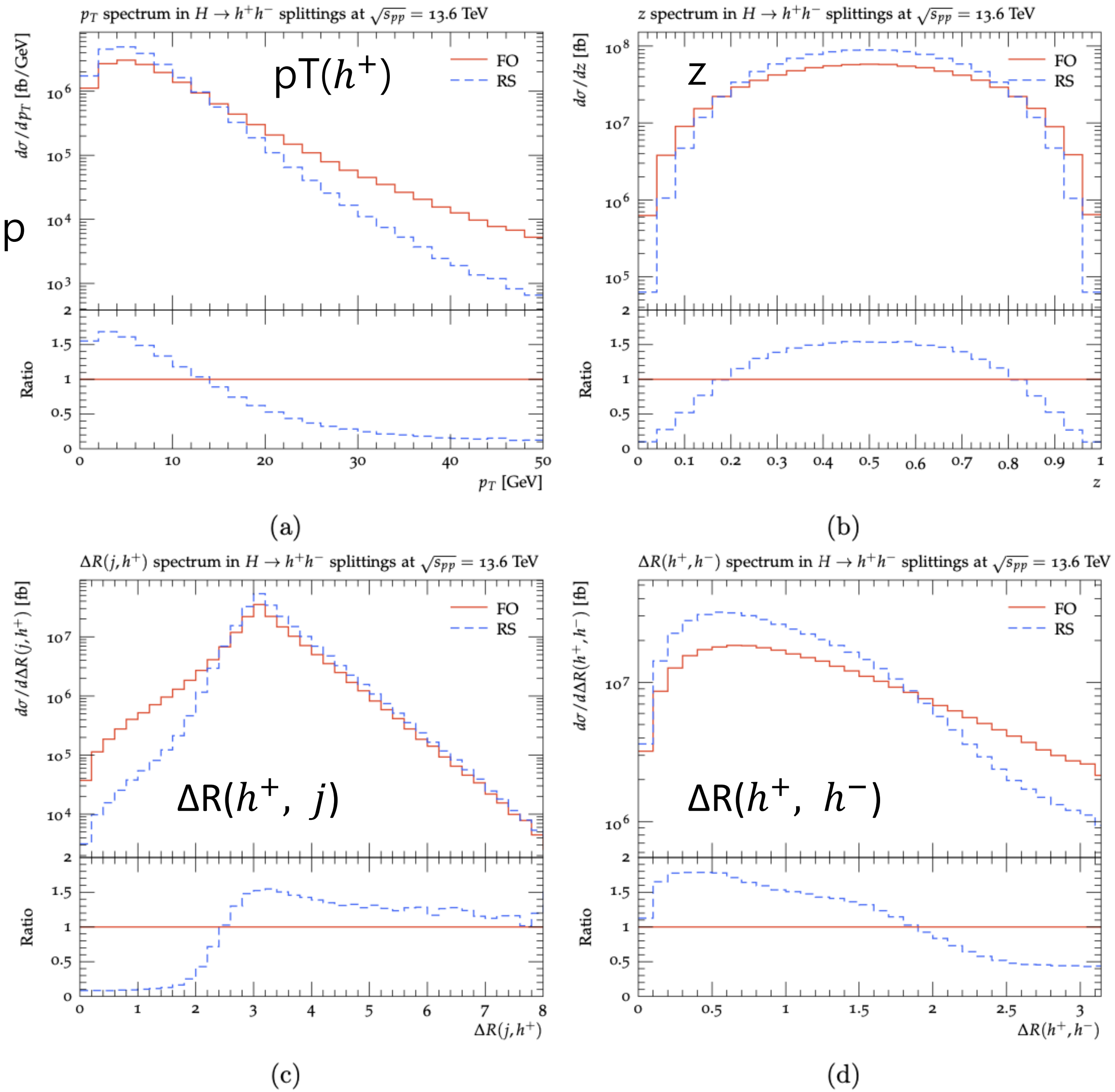


Simplest case: (spin) 0 → 00 splitting

- BSM $\boldsymbol{H \to h^+h^-}$ **splitting** in general 2HDM
  - m(H, h^+) = 10 GeV
- pp → H+j as a baseline @ 13.6 TeV LHC setup
  - **RS: pp → H j (MG5) + H → h⁺h⁻ (HW7)**
  - **FO: pp → h⁺h⁻ j (MG5)**
    (All irrelevant diagrams are removed)



- overall shapes are similar to the previous case
  ∵ in both cases $m/\sqrt{s}$ ~ 0.001

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- BSM $\boldsymbol{H \to h^+ h^-}$ **splitting** in general 2HDM
  - m(H, h^+) = 10 GeV
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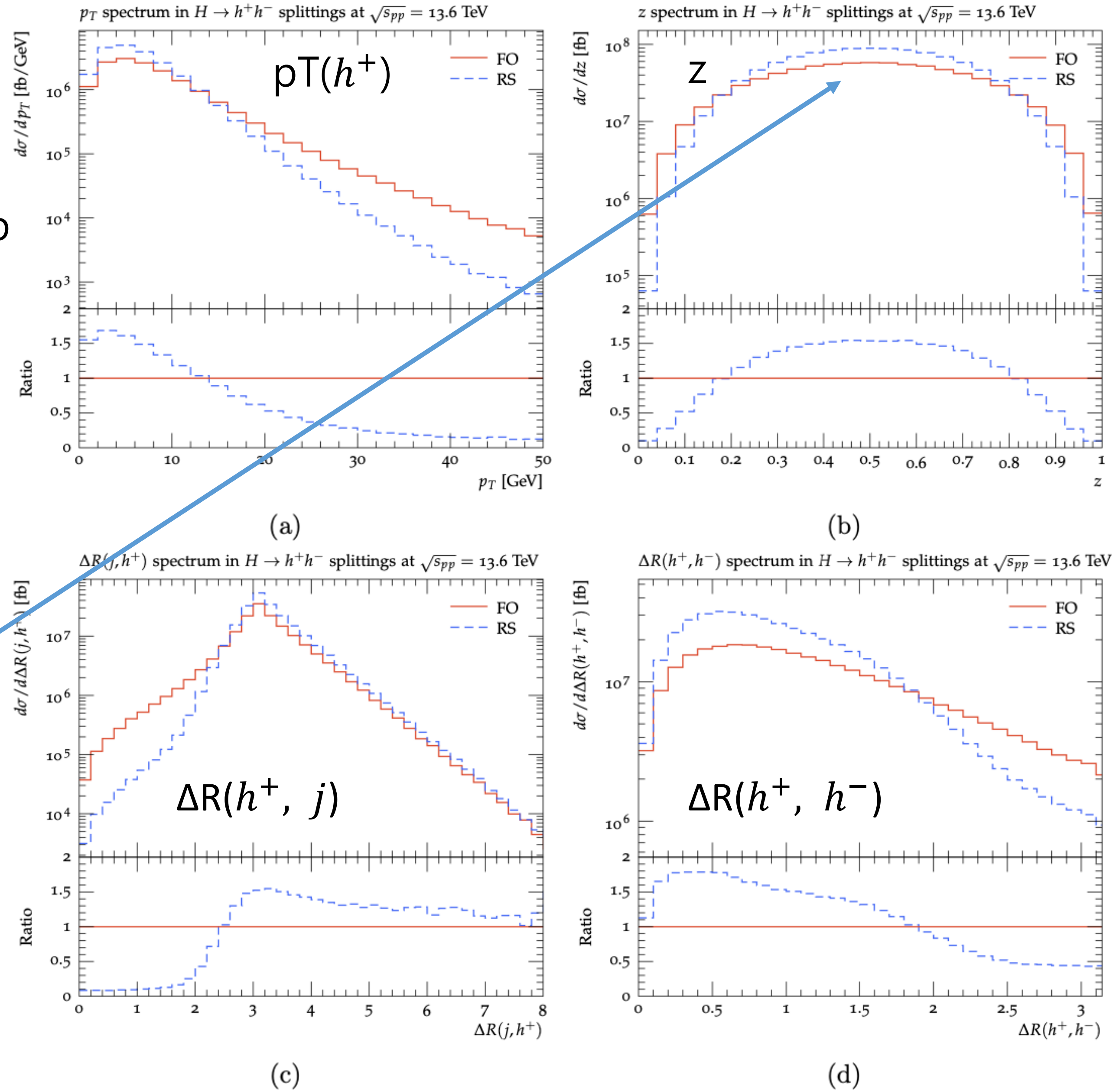
  - **RS: pp → H j (MG5) + H → $\mathbf{h^+h^-}$ (HW7)**
  - **FO: pp → $\mathbf{h^+h^-}$ j (MG5)**

    (All irrelevant diagrams are removed)

- overall shapes are similar to the previous case
  ∵ in both cases $m/\sqrt{s}$ ~ 0.001

→ but RS slightly overestimates FO due to the soft/collinear enhancement



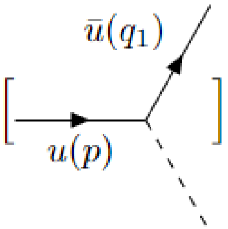
Example Splitting: q → q φ

Spin-Dependent Matrix Elements & General Coupling

Process: Fermion → Fermion + Scalar

Matrix Element Calculation

$$-i\mathcal{M}\Big[\quad\Big] = \bar{u}(q_1)\big[-ig(\kappa + i\tilde{\kappa}\gamma_5)\big]u(p)$$



Generalized Splitting Function

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

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

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

Validation

1. SM Limit Recovery

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

$$P^{SM}_{f\to f\phi}(z,\tilde{q}) = \frac{g_W^2}{8}\left(\frac{m_0}{m_W}\right)^2\left[(1-z)+\frac{4m_0^2-m_2^2}{z(1-z)\tilde{q}^2}\right]$$

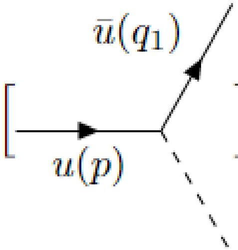
2. Performance test with FO

[JHEP 08 (2024) 064]

(spin) 1/2 → 1/2 0 splitting

- Matrix element of q→qφ

CP-odd coupling is added

$-i\mathcal{M}\Big[$  $\Big] = \bar{u}(q_1)\big[-ig(\kappa + i\tilde{\kappa}\gamma_5)\big]u(p)$

- Spin-dependent matrix elements in terms of kinematic variables

$V^{f\to f'\phi}_{\lambda_0,\ \lambda_1}$	$\lambda_1 = \uparrow$	$\downarrow$
$\lambda_0 = \uparrow$	$\frac{\kappa(zm_0+m_1)-i\tilde{\kappa}(zm_0-m_1)}{\sqrt{z}}$	$-\frac{(\kappa+i\tilde{\kappa})p_T \exp i\phi}{\sqrt{z}}$
$\downarrow$	$\frac{(\kappa-i\tilde{\kappa})p_T \exp -i\phi}{\sqrt{z}}$	$\frac{\kappa(zm_0+m_1)+i\tilde{\kappa}(zm_0-m_1)}{\sqrt{z}}$

- Spin-dependent splitting function

$$P_{f\to f'\phi}(z,\ \tilde{q}) = \frac{g^2}{2}\Big[\big(\rho_+|\kappa+i\tilde{\kappa}|^2 + \rho_-|\kappa-i\tilde{\kappa}|^2\big)\cdot\big[(1-z) - m_{2,t}^2\big] + (\rho_+ + \rho_-)\big[|\kappa|^2(m_{0,t}+m_{1,t})^2 + |\tilde{\kappa}|^2(m_{0,t}-m_{1,t})^2\big] + 2(\rho_+ - \rho_-)\Im(\kappa\tilde{\kappa})\big[(1-2z)m_{0,t}^2 + m_{1,t}^2\big]\Big],$$

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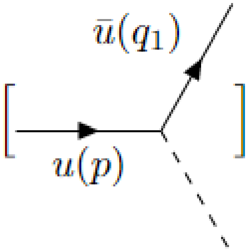

$$-i\mathcal{M}\left[\;\cdots\;\right] = \bar{u}(q_1)\left[-ig(\kappa + i\tilde{\kappa}\gamma_5)\right]u(p)$$

- Spin-dependent matrix elements

$V^{f\to f'\phi}_{\lambda_0,\,\lambda_1}$	$\lambda_1 = \uparrow$	$\downarrow$
$\lambda_0 = \uparrow$	$\frac{\kappa(zm_0+m_1)-i\tilde{\kappa}(zm_0-m_1)}{\sqrt{z}}$	$-\frac{(\kappa+i\tilde{\kappa})p_T \exp i\phi}{\sqrt{z}}$
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- Spin-dependent splitting function

"generalized" splitting function

$$P_{f\to f'\phi}(z,\,\tilde{q}) = \frac{g^2}{2}\Big[\left(\rho_+|\kappa+i\tilde{\kappa}|^2 + \rho_-|\kappa-i\tilde{\kappa}|^2\right)\cdot\left[(1-z) - m_{2,t}^2\right] + (\rho_+ + \rho_-)\left[|\kappa|^2(m_{0,t}+m_{1,t})^2 + |\tilde{\kappa}|^2(m_{0,t}-m_{1,t})^2\right] + 2(\rho_+ - \rho_-)\Im(\kappa\tilde{\kappa})\left[(1-2z)m_{0,t}^2 + m_{1,t}^2\right]\Big],$$

← SM setup

$$g = g_W m_0/2m_W,\ g_W = e/\sin\theta_W$$

$$m_0 = m_1,\ \kappa = 1,\ \tilde{\kappa} = 0,\ \text{and}\ \rho_0 + \rho_1 = 1,$$

- SM q→qH splitting function

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

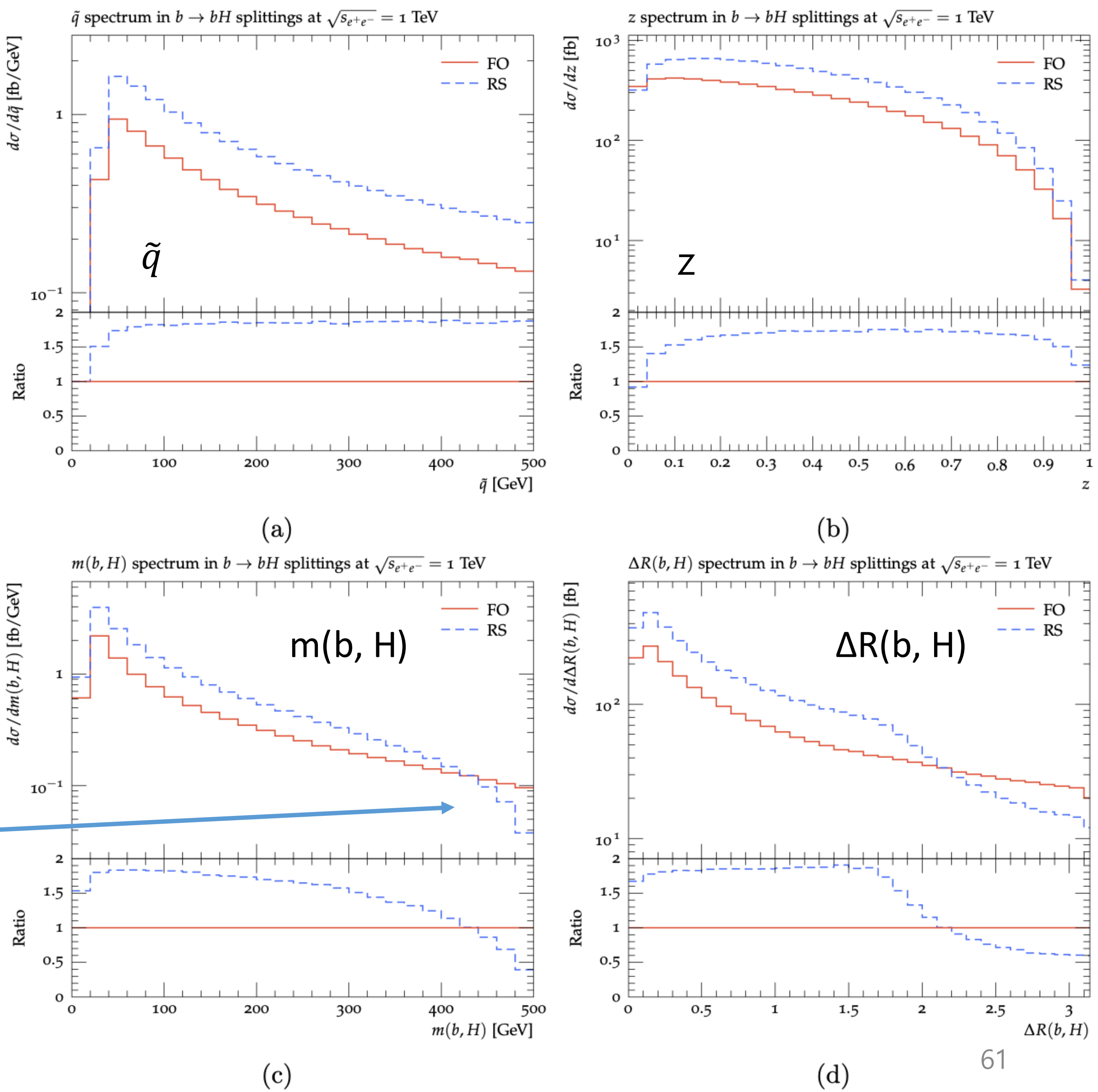
(spin) 1/2 → 1/2 0 splitting

- **b → bH splitting** in general 2HDM
  - m(H) = 10 GeV
- $e^+e^- \rightarrow b\bar{b}$ as a baseline @ 1 TeV
  - **RS**: $\boldsymbol{e^+e^- \rightarrow b\bar{b}}$ (MG5) **+ b** → $\boldsymbol{bH}$ (HW7)
  - **FO**: $\boldsymbol{e^+e^- \rightarrow b\bar{b}H}$ (MG5)

    (All irrelevant diagrams are removed)

* Shapes are identical

- notable decrease @ m ~ 500 GeV due to centre-of-mass energy limit



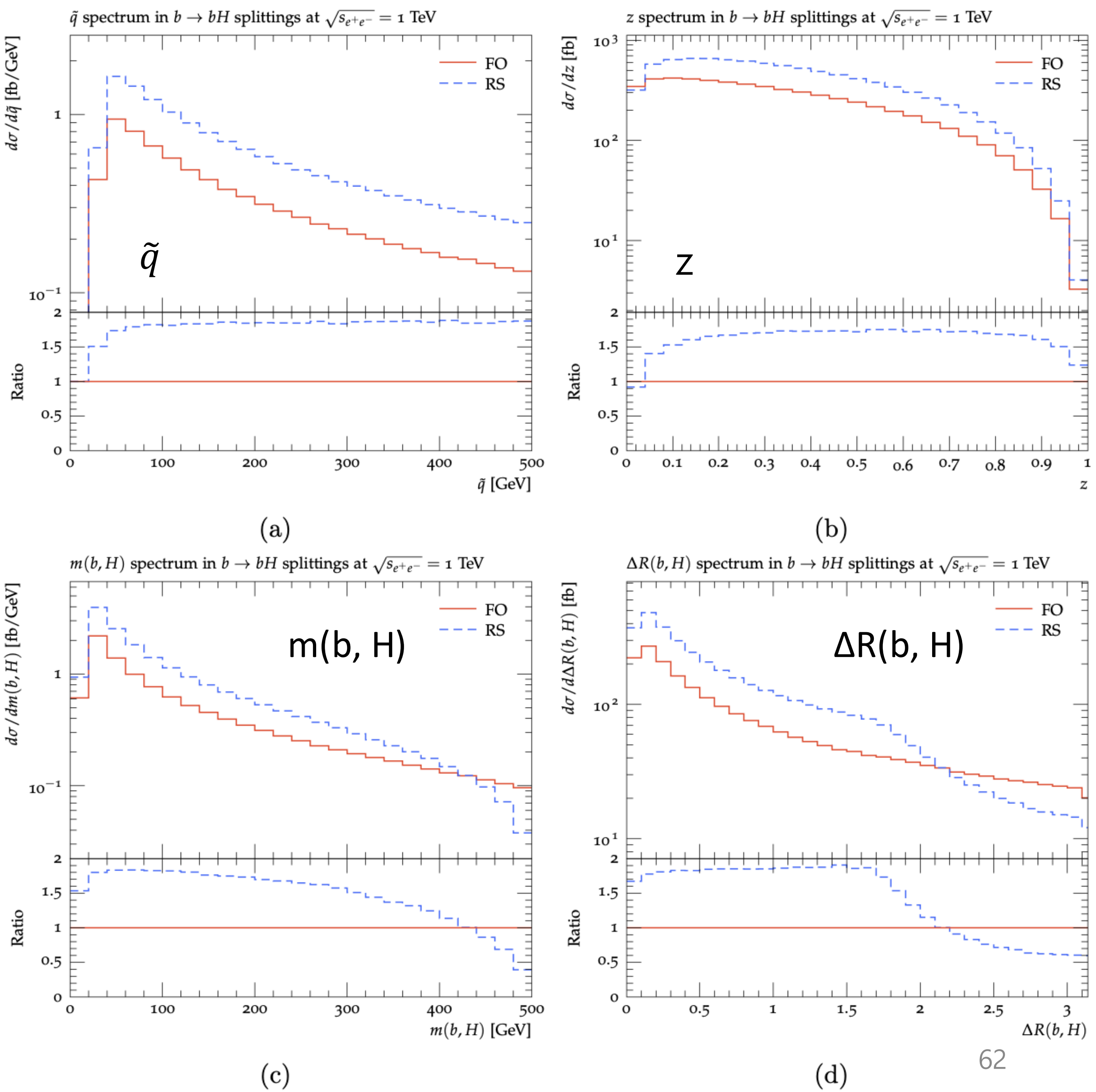
(spin) 1/2 → 1/2 0 splitting

- **b → bH splitting** in general 2HDM
  - m(H) = 10 GeV
- $e^+e^- \to b\bar{b}$ as a baseline @ 1 TeV
  - **RS**: $\boldsymbol{e^+e^- \to b\bar{b}}$ (MG5) **+ b** → $\boldsymbol{bH}$ (HW7)
  - **FO**: $\boldsymbol{e^+e^- \to b\bar{b}H}$ (MG5)

    (All irrelevant diagrams are removed)

- Overestimation of RS?

Herwig7 allows dynamial scale choices w.r.t the running b mass @ low scale



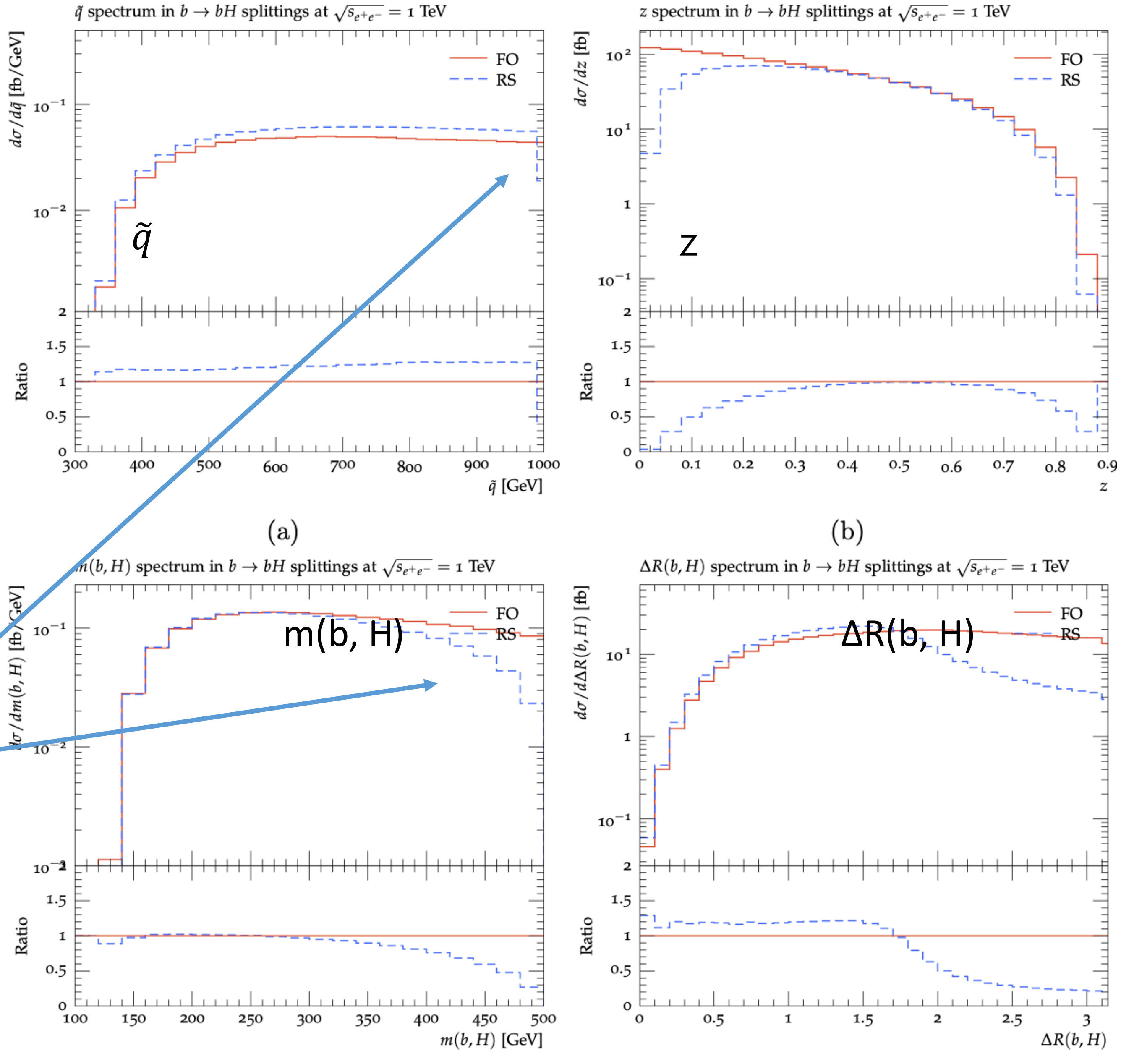
(spin) 1/2 → 1/2 0 splitting

- **b → bH splitting** in general 2HDM
  - m(H) = 130 GeV
- $e^+e^- \to b\bar{b}$ as a baseline @ 1 TeV
  - **RS**: $\boldsymbol{e^+e^- \to b\bar{b}}$ (MG5) **+ b** → $\boldsymbol{bH}$ (HW7)
  - **FO**: $\boldsymbol{e^+e^- \to b\bar{b}H}$ (MG5)

  (All irrelevant diagrams are removed)

* Wonderful overall agreements

- notable decrease @ m ~ 500 GeV & $\tilde{q}$ = 1 TeV due to $\sqrt{s}$ limit
- also affects to the z distribution

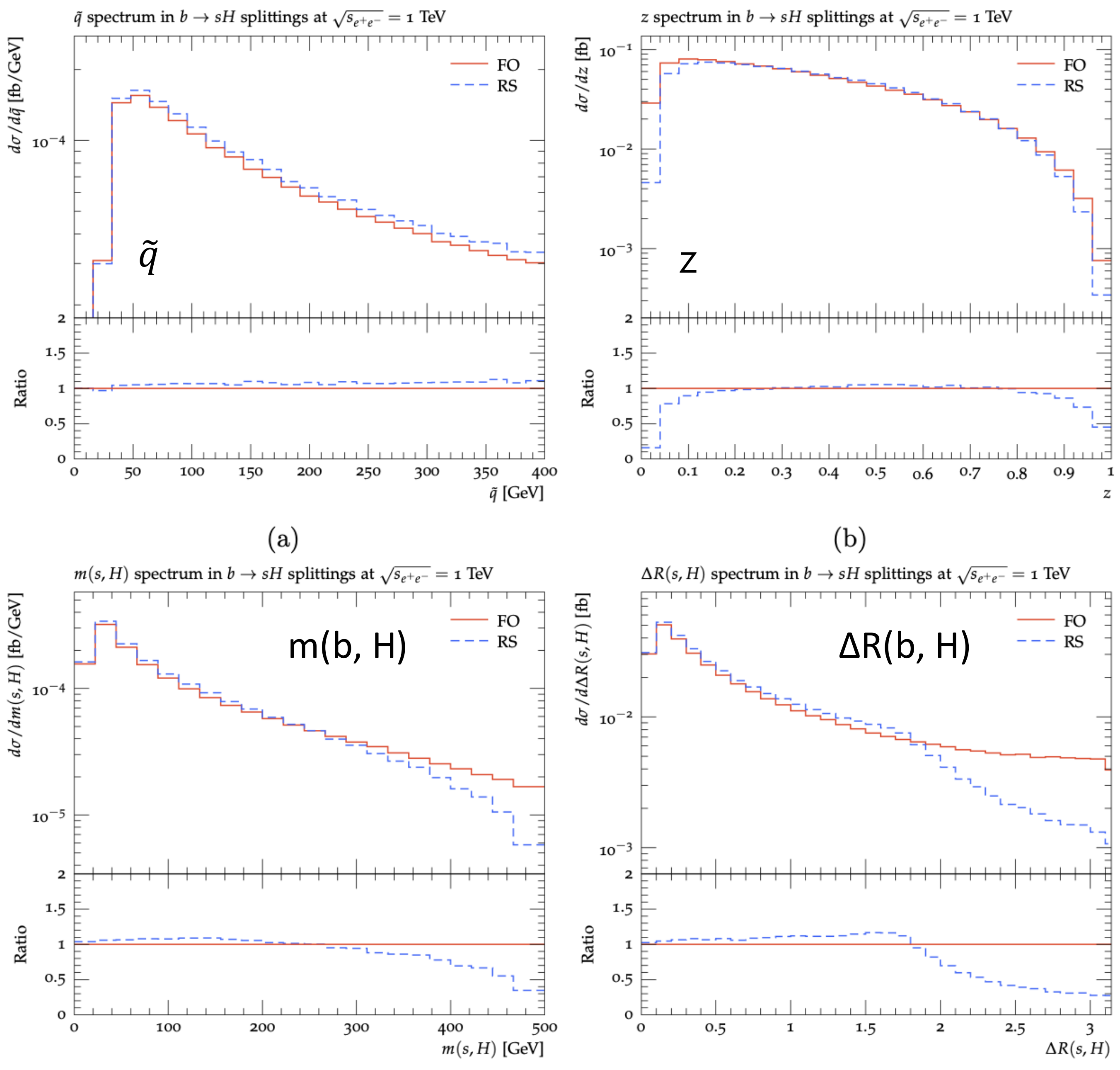


(a) (b) (c) (d)

(spin) 1/2 → 1/2 0 splitting

- Important BSM phenomena: **FCNC**!
- **b → sH splitting** in general 2HDM
  - m(H) = 10 GeV
- $e^+e^- \rightarrow b\bar{b}$ as a baseline @ 1 TeV
  - **RS**: $\boldsymbol{e^+e^- \rightarrow b\bar{b}}$ (MG5) **+ b** → $\boldsymbol{sH}$ (HW7)
  - **FO**: $\boldsymbol{e^+e^- \rightarrow s\bar{b}H}$ (MG5) + counter part
    (All irrelevant diagrams are removed)

* Wonderful overall agreements



(a) (b) (c) (d)

VVV Splitting functions

- upto $m^2(p_T^2)$ order in quasi-collinear limit(m, $p_T \to 0$)

Process	Splitting Function
V→V′V″	$P_{V\to V'V''}(z,\tilde{q}) = 2g^2\Big[\frac{(1-z(1-z))^2}{z(1-z)}(\rho_+ + \rho_-) + 2\rho_0(1-z)^2 m_{0,t}^2 + \frac{(1-z(1-z))^2\,(m_{0,t}^2) - (1-z^2(1-z))m_{1,t}^2 - (1-z(1-z)^2)m_{2,t}^2}{z(1-z)}(\rho_+ + \rho_-)\Big]$

- Crossing symmetry [57]:

$$\mathcal{M}^{A\to BC}_{\lambda_0,\lambda_1,\lambda_2}(z,\tilde{q};m_0,m_1,m_2) \propto \mathcal{M}^{A\to CB}_{\lambda_0,\lambda_2,\lambda_1}(1-z,\tilde{q};m_0,m_2,m_1).$$

- Drell-Levy-Yan relation:

$$P^{A\to BC}_{\lambda_A,\lambda_B,\lambda_C}(z) = (-1)^{\lambda_A+\lambda_B+\lambda_C}\, z P^{B\to AC}_{\lambda_B,\lambda_A,\lambda_C}(1/z).$$

- Parity [34, 35]:

$$\mathcal{M}_{-\lambda_0,-\lambda_1,-\lambda_2} = (-1)^{\lambda_0+\lambda_1+\lambda_2}\mathcal{M}_{\lambda_0,\lambda_1,\lambda_2}.$$

- VVV process is a maximally symmetric process, even though its form looks messy

1→10 spltting function

- We can restore an interesting feature of the goldstone mode in V→Vφ splitting

$$P_{V\to V'\phi}(z,\tilde{q}) = \frac{g_{BSM}^2}{2}\left[\frac{\rho_+ + \rho_-}{2m_1^2}\left(z(1-z) + z(1-z)m_{0,t}^2 + (1+z)m_{1,t}^2 - zm_{2,t}^2\right)\right.$$
$$\left. + \frac{\rho_0}{z^2 m_0^2}\left(z(1-z) + z(1-z)m_{0,t}^2 - (1-z)m_{1,t}^2 - zm_{2,t}^2\right)\right].$$

* massless case
No longitudinal polarization & mass

$$P_{V_{\text{massless}}\to V'_{\text{massless}}\phi}(z,\tilde{q}) = \frac{g_{BSM}^2}{2z(1-z)\tilde{q}^2}$$

[0→00 splitting function]

$$P_{\phi\to\phi'\phi''}(z,\tilde{q}) = \frac{g^2}{2Sz(1-z)\tilde{q}^2}$$

! The goldstone mode in the vector bosons pop up !

Spin-2 Splitting functions (next paper)

- Considering Kaluza-Klein excitations of gravitons

Eur.Phys.J.C56:435-447,2008

Fermion-Fermion-Graviton Lagrangian:

$$\mathcal{L}_{\mathrm{FFT}} = 4\mathrm{GT}\, T^{\mu\nu*}\Big[-\eta_{\mu\nu}\Big\{\bar{f}(i\gamma^{\rho}\partial_{\rho}-m_F)f-\frac{1}{2}\partial^{\rho}(\bar{f}i\gamma_{\rho}f)\Big\} + \Big\{\frac{1}{2}\bar{f}i\gamma_{\mu}\partial_{\nu}f - \frac{1}{4}\partial_{\mu}(\bar{f}i\gamma_{\nu}f) + (\mu\leftrightarrow\nu)\Big\}\Big], \quad (28)$$

$$P_{q\to qG} = \rho_+\Bigg[\Big[\frac{4p_T^2}{\sqrt{z}(1-z)^2}\Big]^2 + \Big[\frac{4p_T(m_1-zm_0)}{(1-z)\sqrt{z}}\Big]^2 + \Big[2p_T\frac{(1-z)^2(m_1+zm_0)m_1-2z^2m_2^2+(1-z)p_T^2}{(1-z)^2z^{3/2}m_2}\Big]^2 + \Big[2\frac{m_1\big(m_1^2(1-z)^2-z^2m_2^2+(1+z)p_T^2\big)-zm_0\big((1-z)^2m_1^2-z^2m_2^2+2p_T^2\big)}{(1-z)z^{3/2}m_2}\Big]^2+\ldots\Bigg] + \rho_-(\ldots)$$

\- This is completely new feature. Anyone has never seen this spin-2 splittings! -

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

Model Features

Gauge Symmetry

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

Covariant Derivative

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

Lagrangian

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

$$\mathcal{L}_{\rm int} \supset g_1' \, Z'_\mu \sum_f \left(Y^f_{B-L} \, \bar{f} \gamma^\mu f \right)$$

Properties

Vector coupling only

Anomaly Free

Mass = Gauge Eigenstate

No mixing

- The original splitting function

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

- 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

Motivation

Direction

First look

- **Search Z′ → μμ inside jets**
- **Model-independent**, but pick up one **example model (B-L extension) for interpretation**

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

- 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

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

Covariant Derivative

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

Lagrangian

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Systematics

Action item for the next work

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.