Light Dark World, 14.Aug.2024

Novel extensions of Herwig7
BSM Parton Showers

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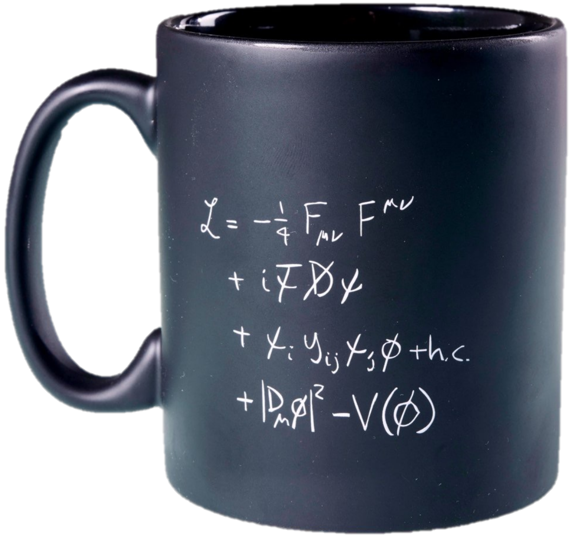
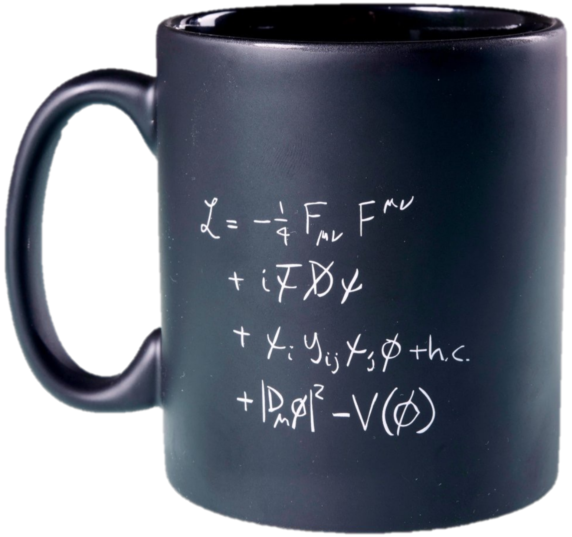
Meeting roon
Bridge ≈ Event Generator

Lagrangian

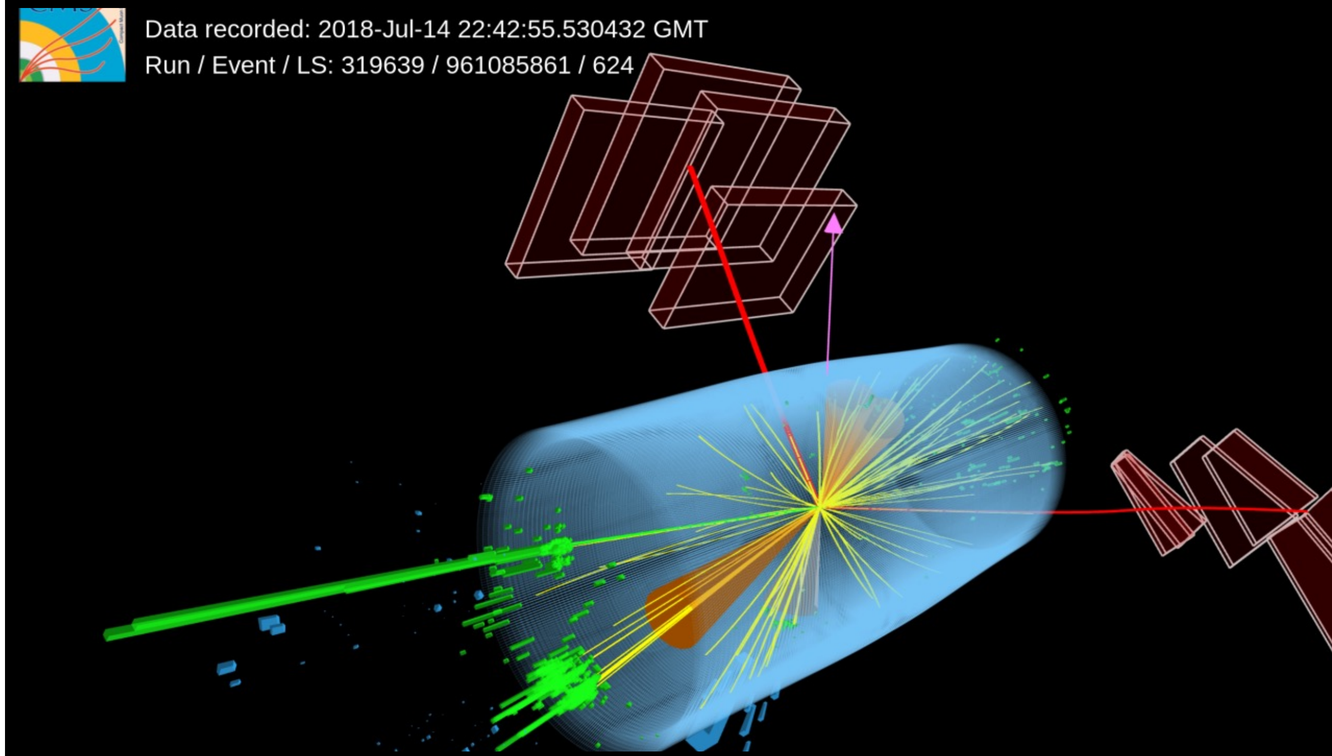


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

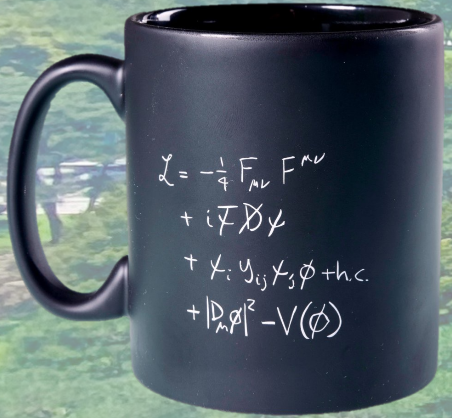
Lagrangian



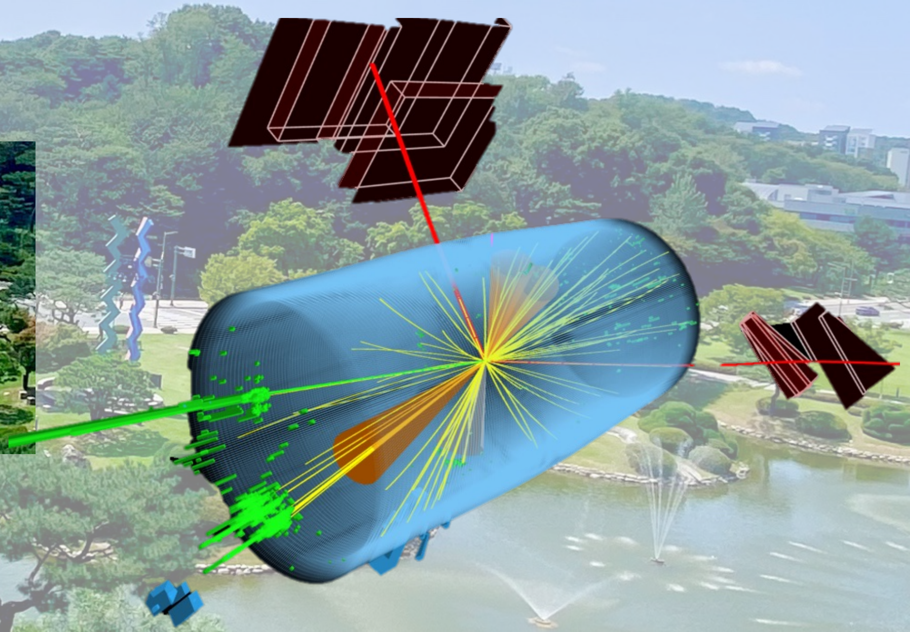
CMS event in real World



Theory



Experiment



Event Generator
(e.g. Herwig7)

- dictating experiments

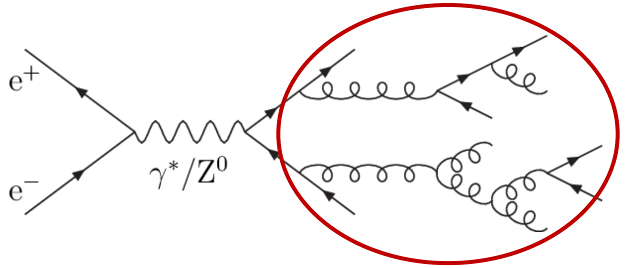
Herwig7

- **General-purpose event generator**
  - most kinds of collider experients
  - pp, e^-p, e^-e^+, heavy ion collisions …

- **QCD** simulation
  - How to control soft & collinear physics (divergences)?
  - For processes involving 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



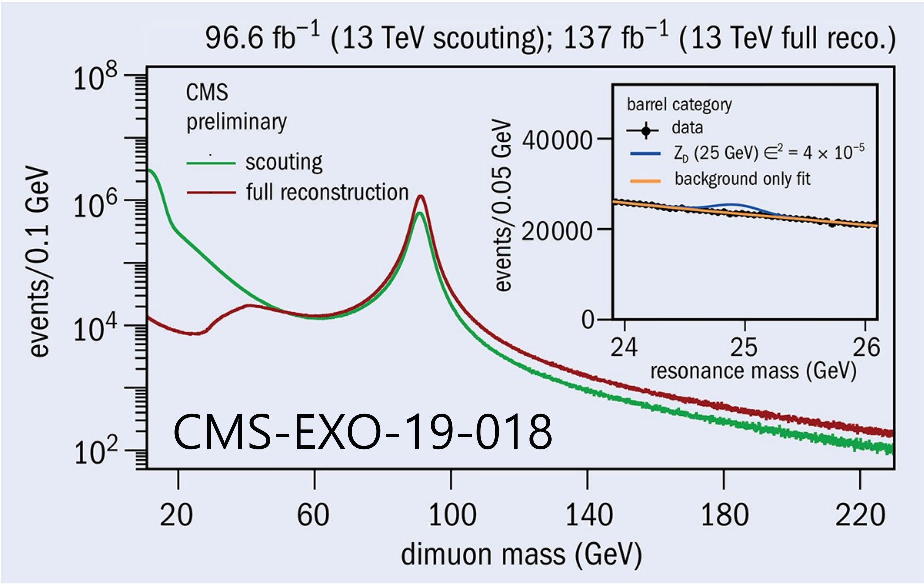
- Angular-order shower programs
  - handle color coherence
  - QCD shower (1988) → QED (2006) → EW (2022) → **"BSM"** extensions in the parton shower regime

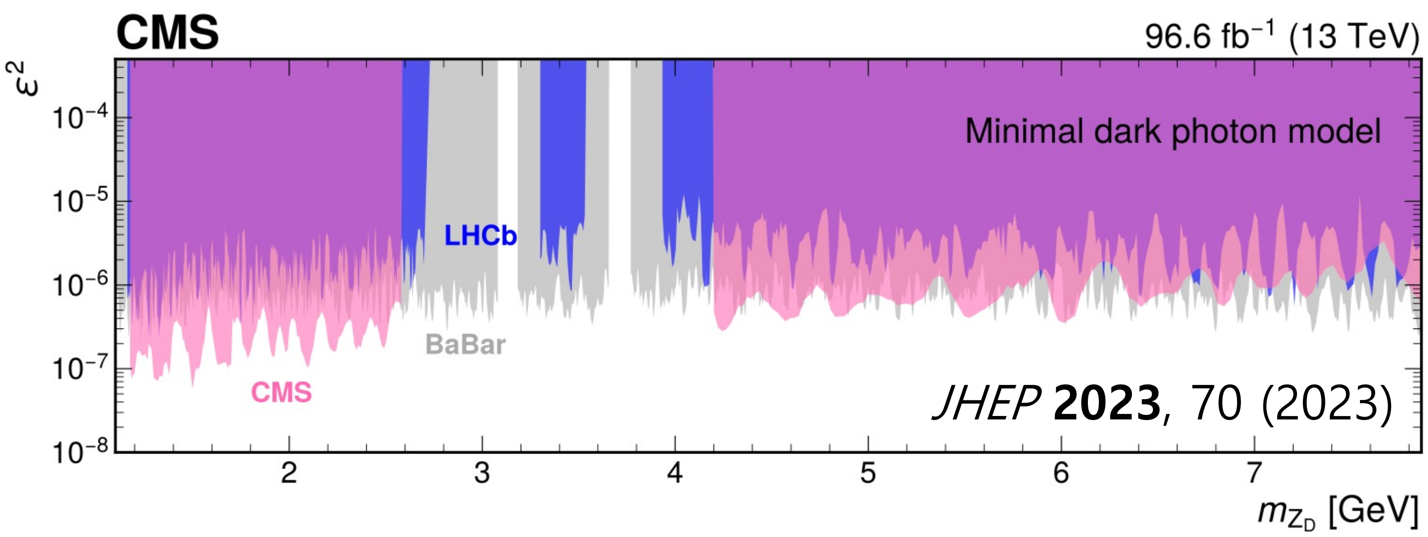
[Lee, Masouminia, Seymour, Yang, JHEP 08 (2024) 064]

Why BSM Parton Shower?

- In high energy colliders, **even W/Z bosons can be showered** [Masouminia, Richardson, JHEP04(2022)112]
  - The bunch of particles inside a jet can act as a source
  - Why not BSM particles? They can be even lighter?

- Low-scale BSM searches in the LHC are trending in recent years!





1. necessitates signal samples in enormous BSM phase spaces
2. due to the high trigger threshold, these samples need interplays with balancing jets
3. hard to consider all higher-order corrections for new light particles

Why BSM Parton Shower?

- In high energy colliders, **even W/Z bosons can be showered** [Masouminia, Richardson, JHEP04(2022)112]
  - The bunch of particles inside a jet can act as a source
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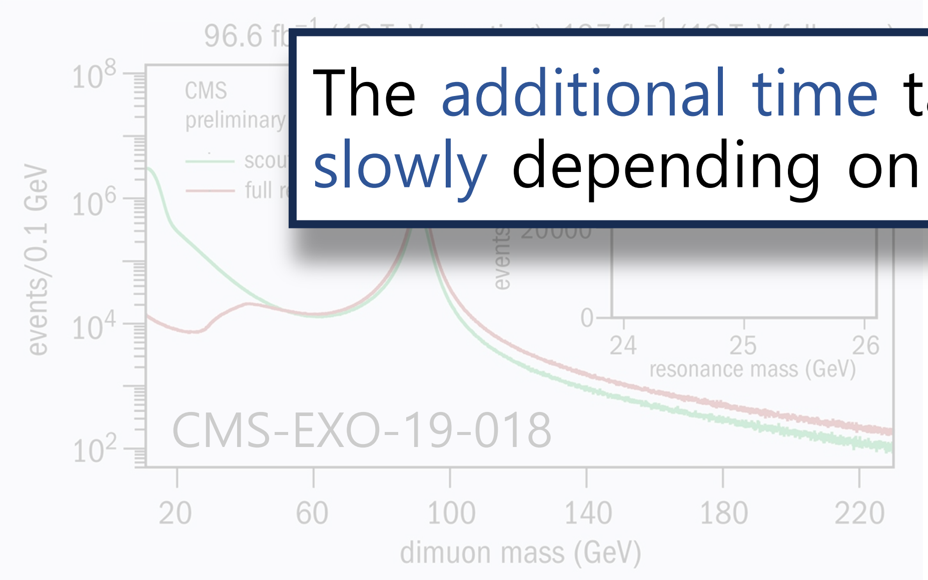
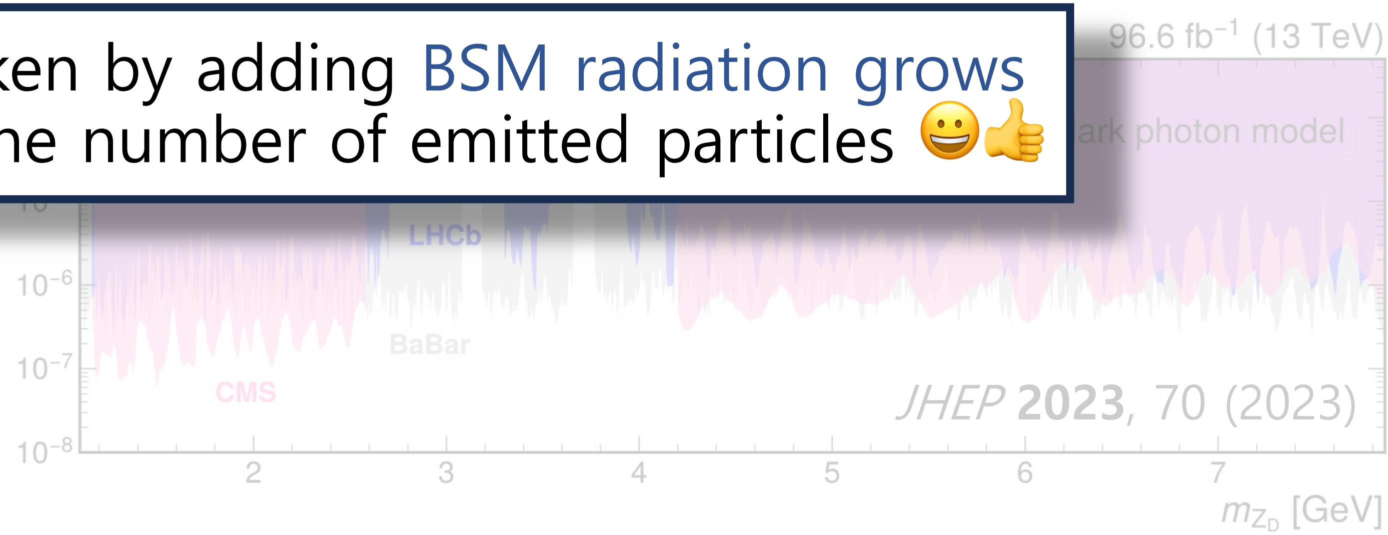




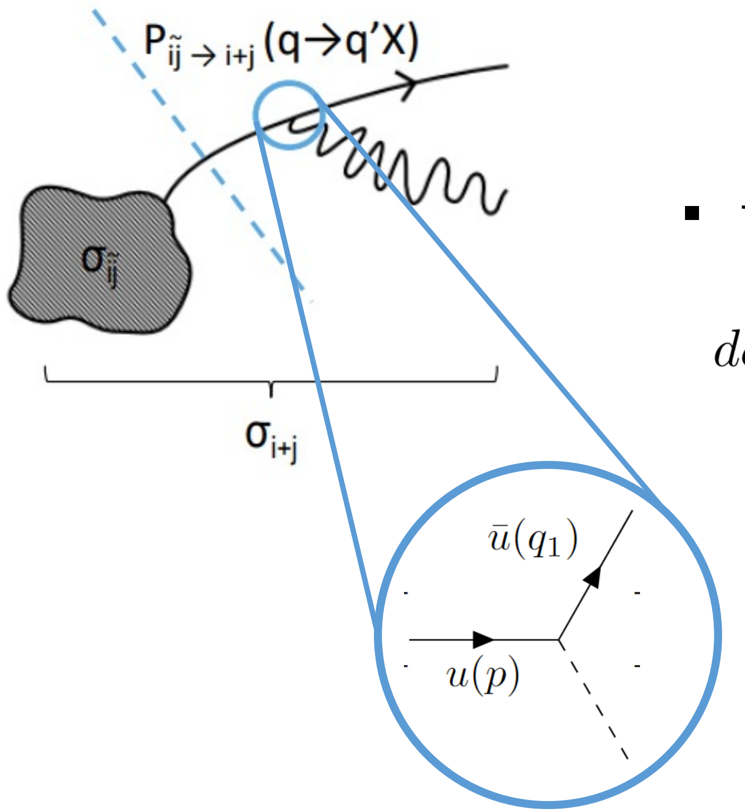
The additional time taken by adding BSM radiation grows slowly depending on the number of emitted particles 😀👍

  - necessitates signal samples in enormous BSM phase spaces
  - Hard to consider all higher-order corrections for new light particles

Showers in Herwig7

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

  Currently we only have restricted availability (such as some hidden valley scenarios or specific SUSY scenarios)



- total cross section

" Factorization Theorem "

! simple multiplication !

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

"splitting function"

\- Thank you Sokratis for the nice introduction! 😉

BSM showers in Herwig7

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

- Step by step guidelines
  1) **Calculate new splitting functions**
     - master formula by Altarelli and Parisi

$$P_{0\to 12}(z,\tilde{q}) = \frac{1}{2(q_0^2 - m_0^2)} \sum_{s_0,s_1,s_2} |\mathcal{M}_{s_0,s_1,s_2}|^2$$ [NPB 126, 2 (1977) 298-318]

     * Only depends on spins, masses, and ordering variables of participating particles in the splitting

  model independent

  No needs to calculate splitting functions for each BSM model/particle individually

  2) Herwig7 reads BSM model information and calculate all necessary ingredients automatically from UFO model files

- Splitting scenarios – all combinations with spin-0, 1/2, 1
  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

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

1. Splitting out of spin-0 particles

$$P_{f\to f'\phi}(z,\ \tilde{q}) = \frac{1}{2(q_0^2 - m_0^2)}\overline{\sum_{\text{pol}}}|\mathcal{M}|^2$$
$$= \frac{g^2}{2}\Big[\left(\rho_+|\kappa+\tilde{\kappa}|^2 + \rho_-|\kappa-\tilde{\kappa}|^2\right)\left[(1-z) - m_{2,t}^2\right] + (\rho_+ + \rho_-)\big[|\kappa|^2(m_{0,t}+m_{1,t})^2$$
$$+ |\tilde{\kappa}|^2(m_{0,t}-m_{1,t})^2\big] + 2(\rho_+ - \rho_-)\Re(\kappa\tilde{\kappa}^*)\big[(1-2z)m_{0,t}^2 + m_{1,t}^2\big]\Big],$$

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

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

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

2. Splitting out of spin-1 particles

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

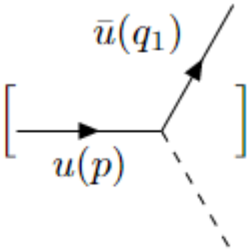
$$P_{V\to V'V''}(z,\tilde{q}) = 2g^2\Bigg[\frac{(1-z(1-z))^2}{z(1-z)}(\rho_+ + \rho_-) + 2\rho_0(1-z)^2m_{0,t}^2$$
$$+ \frac{(1-z(1-z))^2\,(m_{0,t}^2) - (1-z^2(1-z))m_{1,t}^2 - (1-z(1-z)^2)m_{2,t}^2}{z(1-z)}(\rho_+ + \rho_-)\Bigg]$$

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

(spin) 1/2 → 1/2 0 splitting

- Matrix element of f→f′φ

CP-odd coupling – as general as possible

$$-i\mathcal{M}\Big[$$ 

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

- Spin-dependent matrix elements in terms of kinematic variables

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

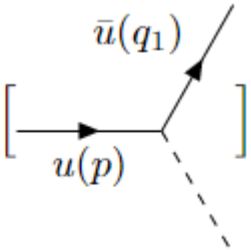
- Spin-dependent splitting function

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

(spin) 1/2 → 1/2 0 splitting

- Matrix element of q→qφ

general coupling



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

- 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

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

← 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 recovered

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

(spin) 1/2 → 1/2 0 splitting

- Matrix element of q→qφ

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

CP-odd coupling is added

- Spin-dependent matrix elements

Everything was integrated into Herwig7

- Spin-depend

"generalized" splitting function

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

← SM setup

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

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

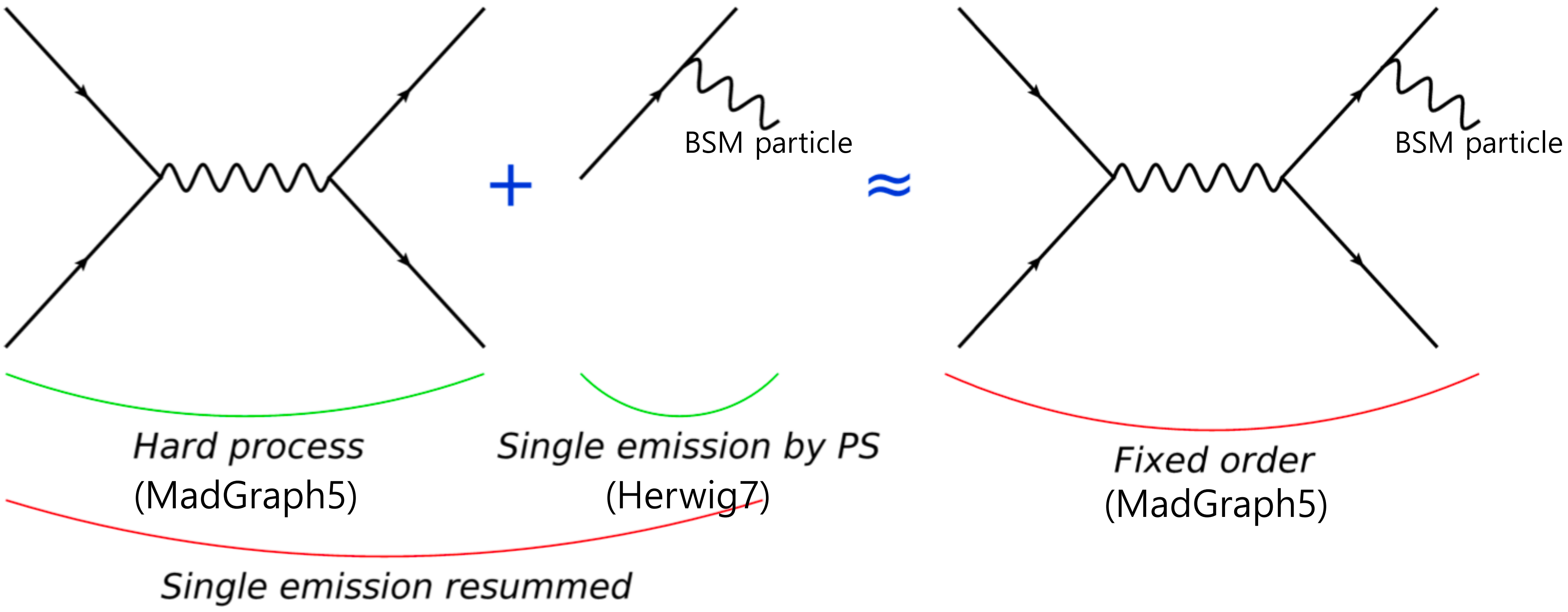
- SM q→qH splitting function

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

Performance test

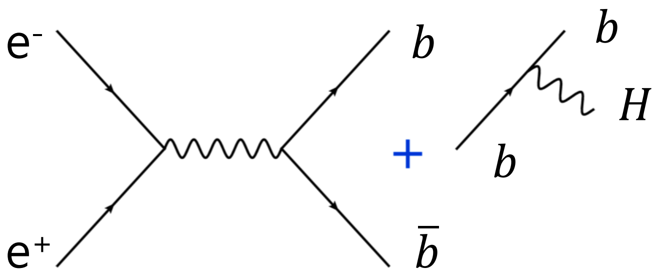
Resummed shower (RS)
– additional leg from Herwig7 parton shower

Fixed-order (FO)
– additional leg from MadGraph5



(spin) 1/2 → 1/2 0 splitting

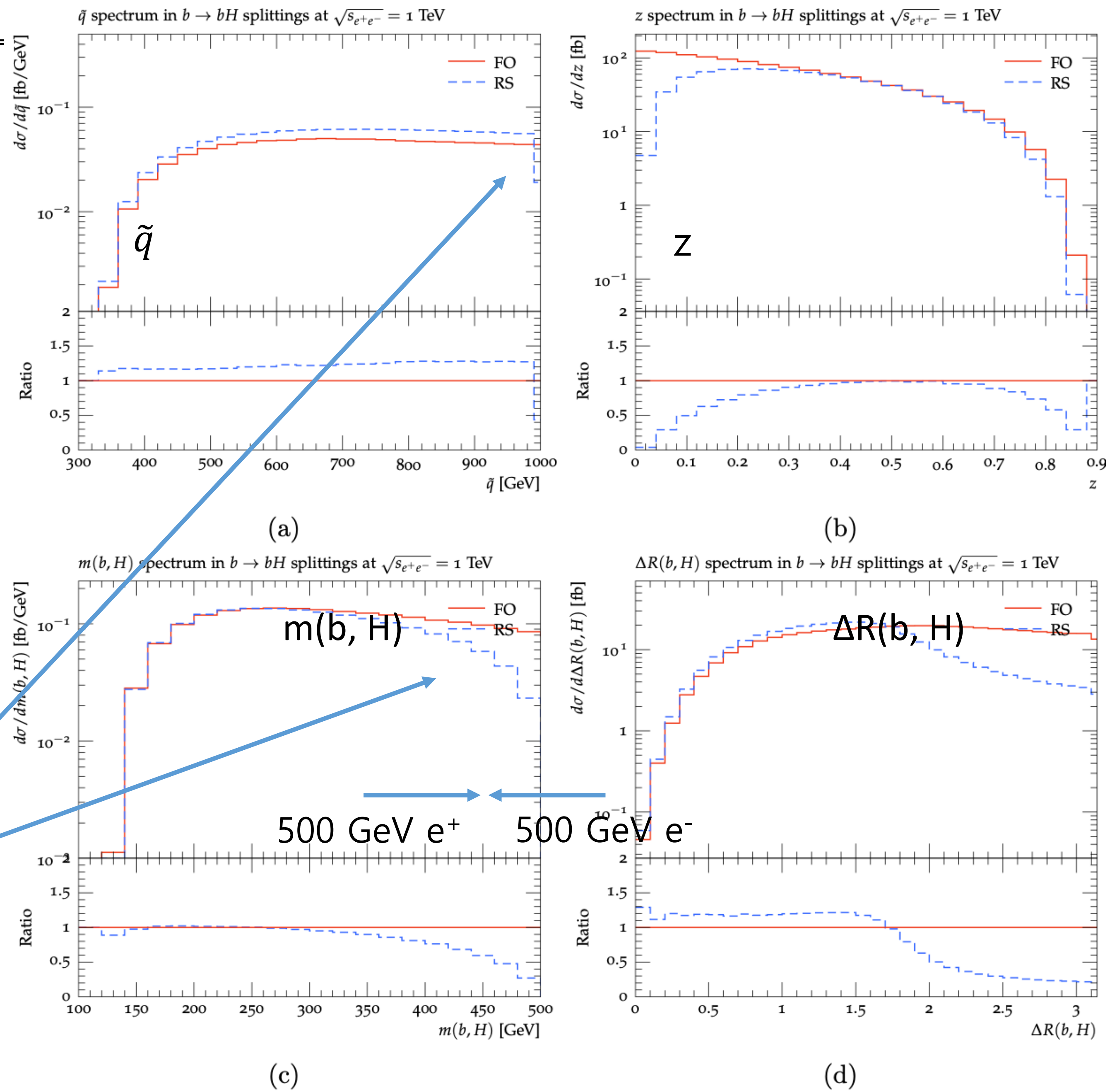
- **b → bH splitting** in general 2HDM
  - m(H) = 130 GeV
- $e^+e^- \to b\bar{b}$ as a baseline @ 1 TeV



- **RS**: $e^+e^- \to b\bar{b}$ (MG5) + **b** → bH (HW7)
- **FO**: $e^+e^- \to b\bar{b}H$ (MG5)
  (All irrelevant diagrams are removed)

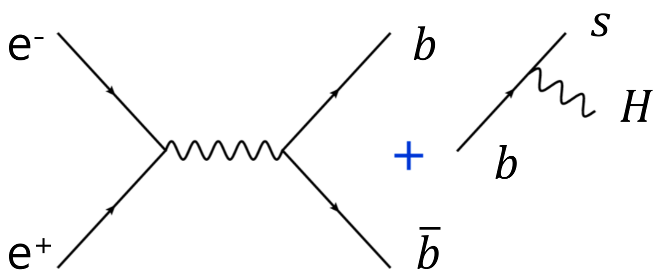
* Wonderful overall agreements

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



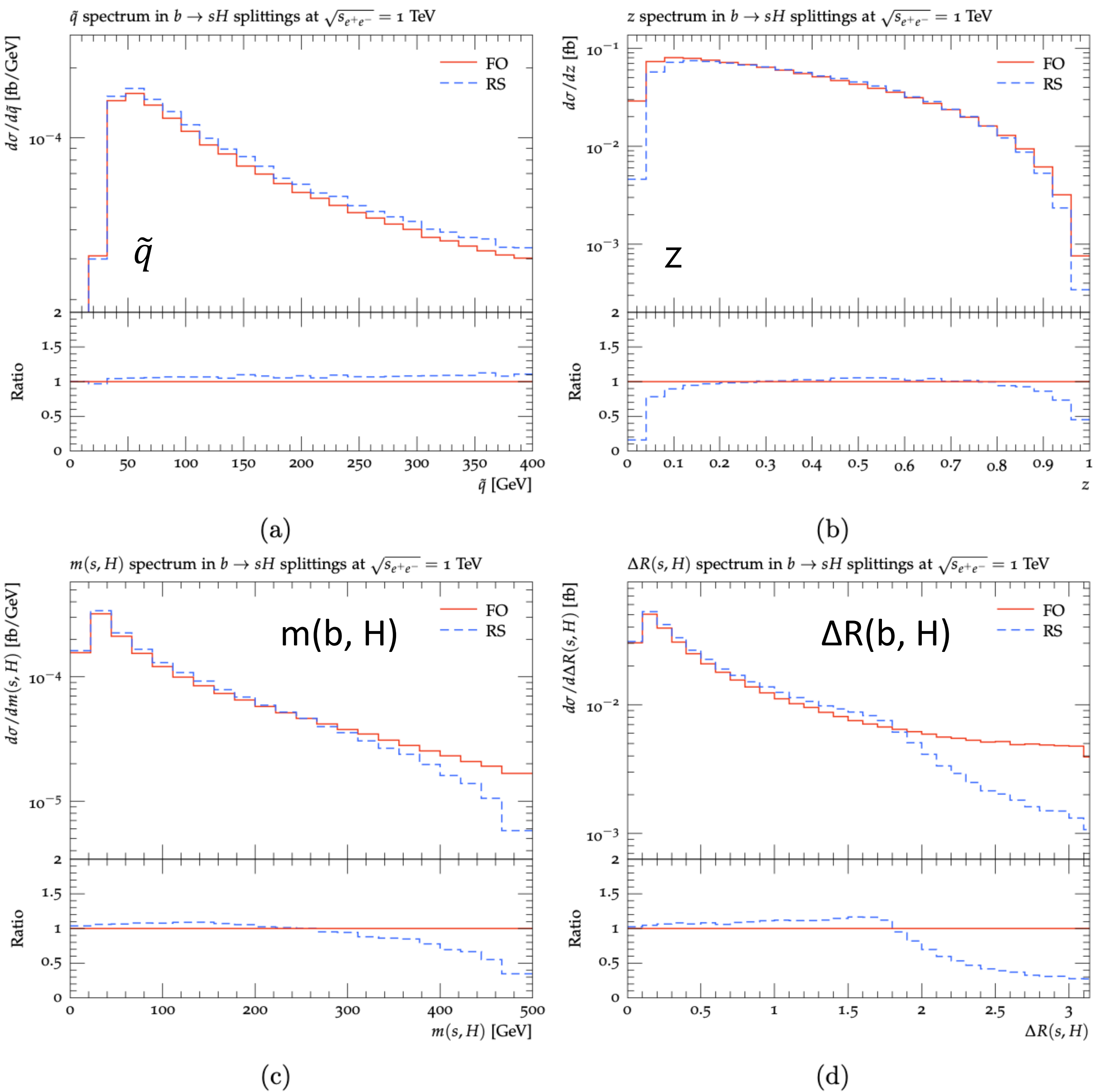
(spin) 1/2 → 1/2 0 splitting

- 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** $\rightarrow \boldsymbol{sH}$ (HW7)
- **FO**: $\boldsymbol{e^+e^- \rightarrow s\bar{b}H}$ (MG5) + counter part
  (All irrelevant diagrams are removed)

* Wonderful overall agreements

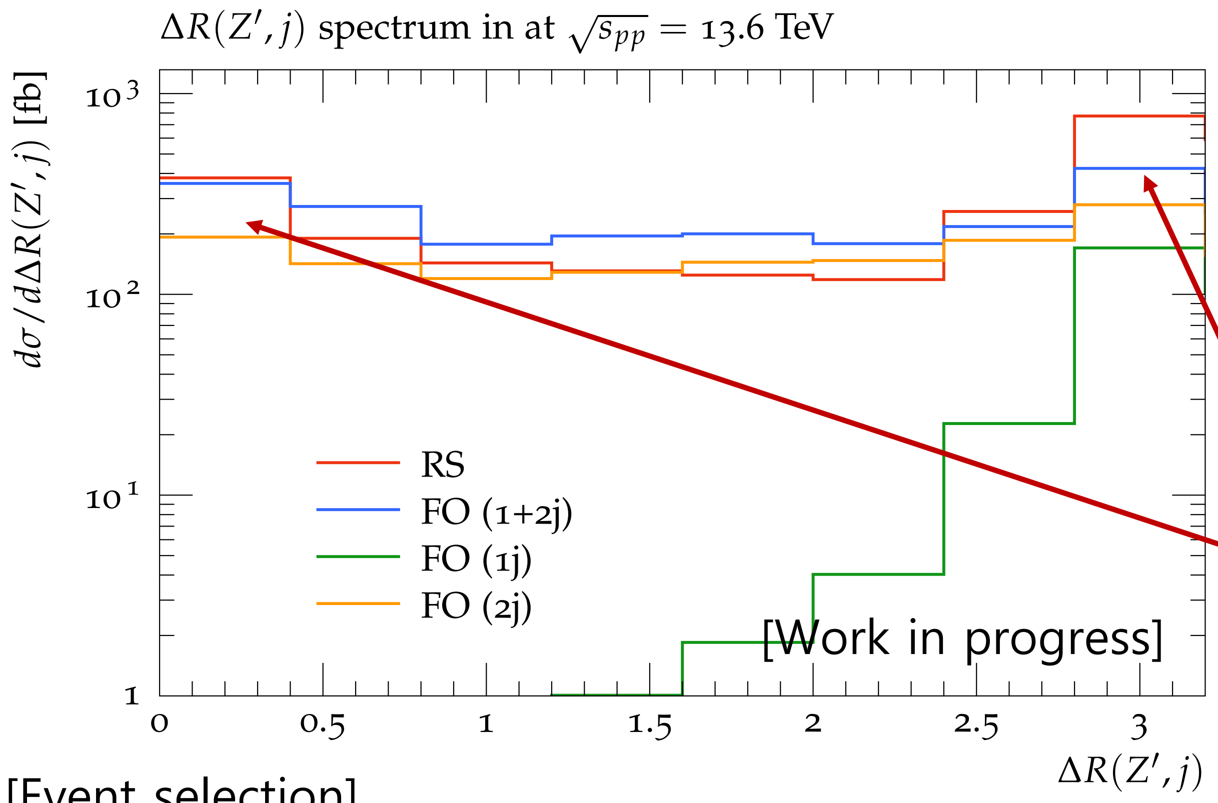


Phenominology of Showered Dark Photons

- BSM parton shower can change event shapes

γ_D radiation in Hidden Abelian Higgs Model (HAHM_variableMW_UFO)

[Curtin, Essig, Gori, Shelton, JHEP 02 (2015) 157]



RS: pp → jj (MG5) with full shower (∋ Z′ radiation)

FO: pp → Z′ j & pp → Z′ j j (MG5)
with QCD+QED+EW shower

Z′ shower shows more events @ ΔR = 0, π

- A jet after Z′ shower lost its energy so that rejected by the event selection: ΔR = 0 → π

[Event selection]

$Z' - p_T > 20$ GeV (trigger), $|\eta| < 2.4$
jet $- p_T > 30$ GeV, $|\eta| < 2.4$

cost?

- parton shower (+ rivet analysis) time for 100K events

with Intel(R) Core(TM) i7-4790 CPU @ 3.60GHz

hard process (MG5)	**pp → jj (4-flavor scheme)**			
parton shower (HW7)	QCD only	QCD+QED	QCD+QED+EW	QCD+QED+EW **+BSM**
shower time [s]	547	610	609	612

No ewk radiation due to small coupling & large mass
(i.e. identical with QCD+QED shower)

only q→qZ′ splittings available (x100 larger coupling)

* note – 82 Z′ bosons are generated from this run

Take home messages

- Anyone can easily utilize **BSM parton showers with Herwig7.4** -- main feature of Herwig7.4
  The only thing you need to prepare is the UFO model file and do

  – Translate a UFO into a Herwig model file:

  ```
  ufo2herwig <UFO_directory> --enable-bsm-shower --allow-fcnc
  ```

  – Model properties written into "FRModel.model" file:

  ```
  read FRModel.model
  ```

  → These are the only things you need to do!

- **Efficient way to simulate light BSM particles** in soft & collinear regime
  - will make your valuable time more valuable
  - now we can control all types of showers!

- The paper is still warm! (published on last Thursday)
  [Lee, Masouminia, Seymour, Yang, JHEP 08 (2024) 064]
  Do not miss the golden hour for k-chickens and BSM PS

Special Thanks to

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MCnet

Monte Carlo *net*

MARIE CURIE ACTIONS

MANCHESTER 1824

The University of Manchester

Light Dark World, 14.Aug.2024

Thanks for your concentration

Technical inquiry: joon.bin.lee@cern.ch

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Joon-Bin Lee

1→10 splting function

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

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

* massless case
No longitudinal polarization & mass

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

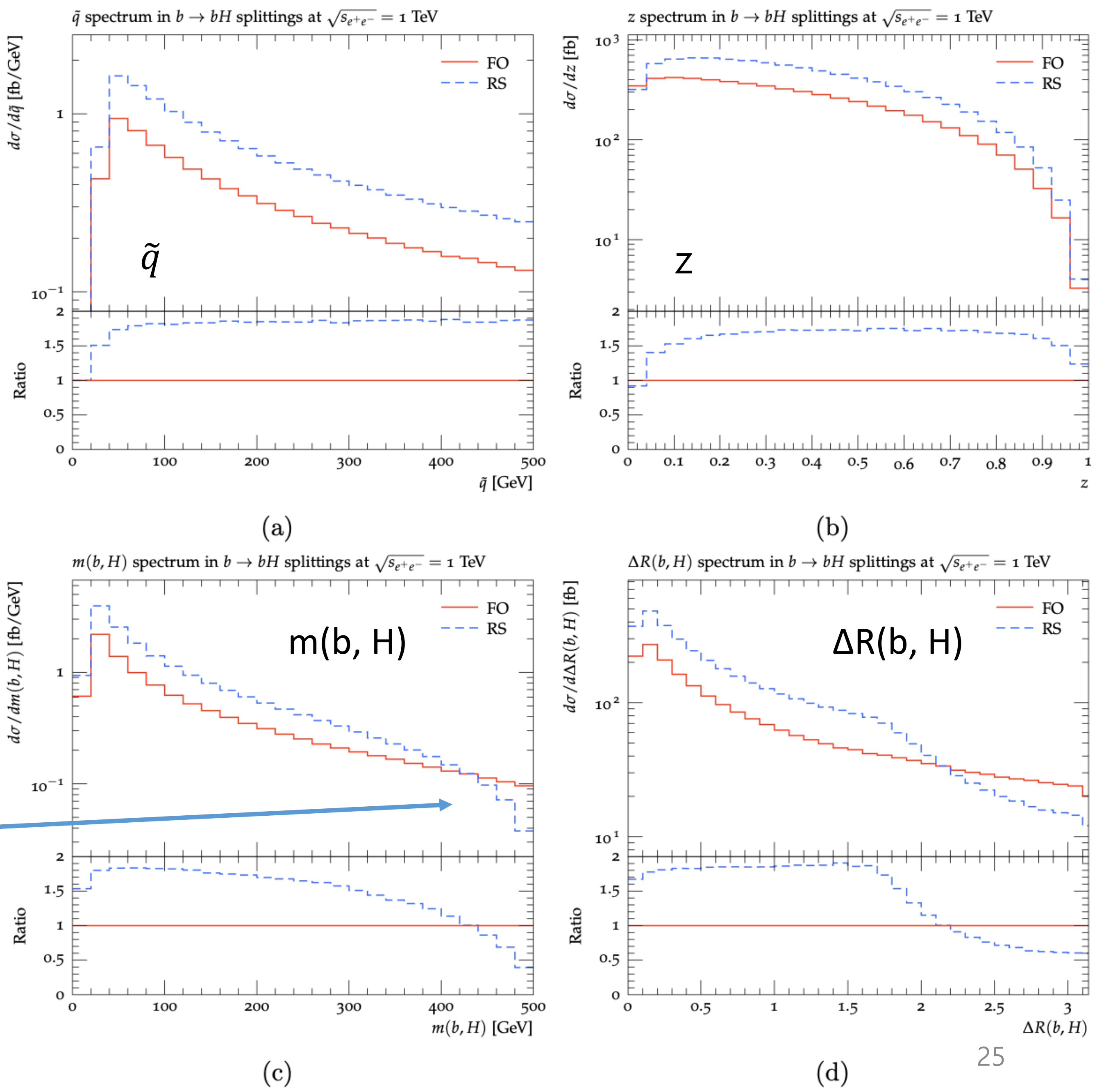
[0→00 splitting function]

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

<u>!? The goldstone mode in the vector bosons pop up ?!</u>

(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
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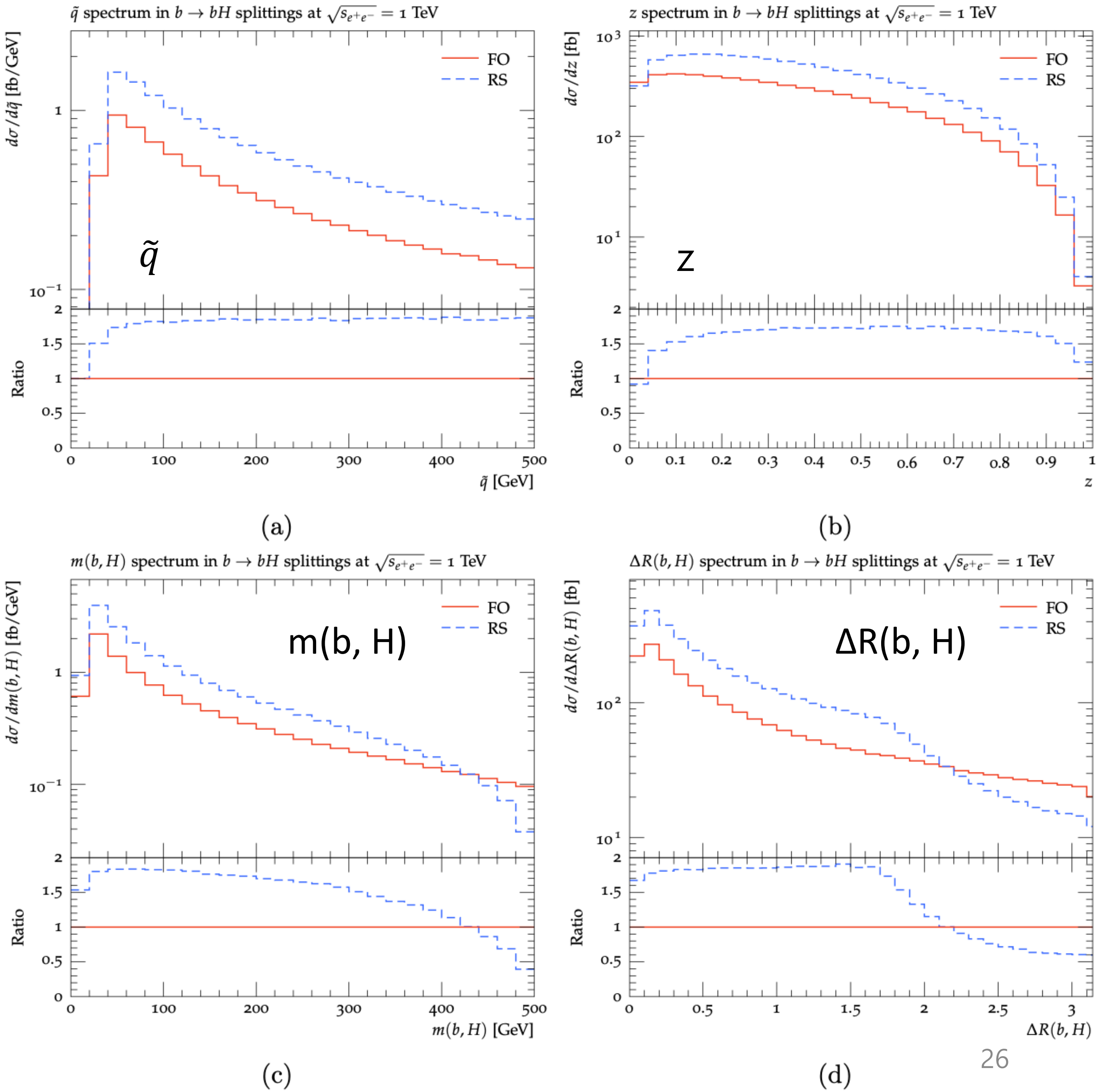
    (All irrelevant diagrams are removed)

- Overestimation of RS?

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



Current status of hidden valley simulations

- Limited availability
  - Mostly recycling of SM QCD splitting functions (not generalized)
  - All in the massless limit (massive particles decay imediately after production from the hard process)
  - f→f′φ splittings recycle f→f′V splitting functions

- BSM PS
  - correct descriptions of all kinds of BSM splittings
  - can control massive particles
  - more flexible couplings

- BSM PS + Hidden Valley
  - handling of dark colors and dark hadronizations
  - [Kulkarni, Papaefstathioi, Plätzer, Siódmok, Stafford, AM, Work in Progress]