Electroweak Radiation in the Vincia Parton Shower

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Overview

1. Monte Carlo’s for future colliders
2. Electroweak Showers in Vincia

Monte Carlo Challenges at Future Colliders

Monte Carlo Challenges

Computational Challenges

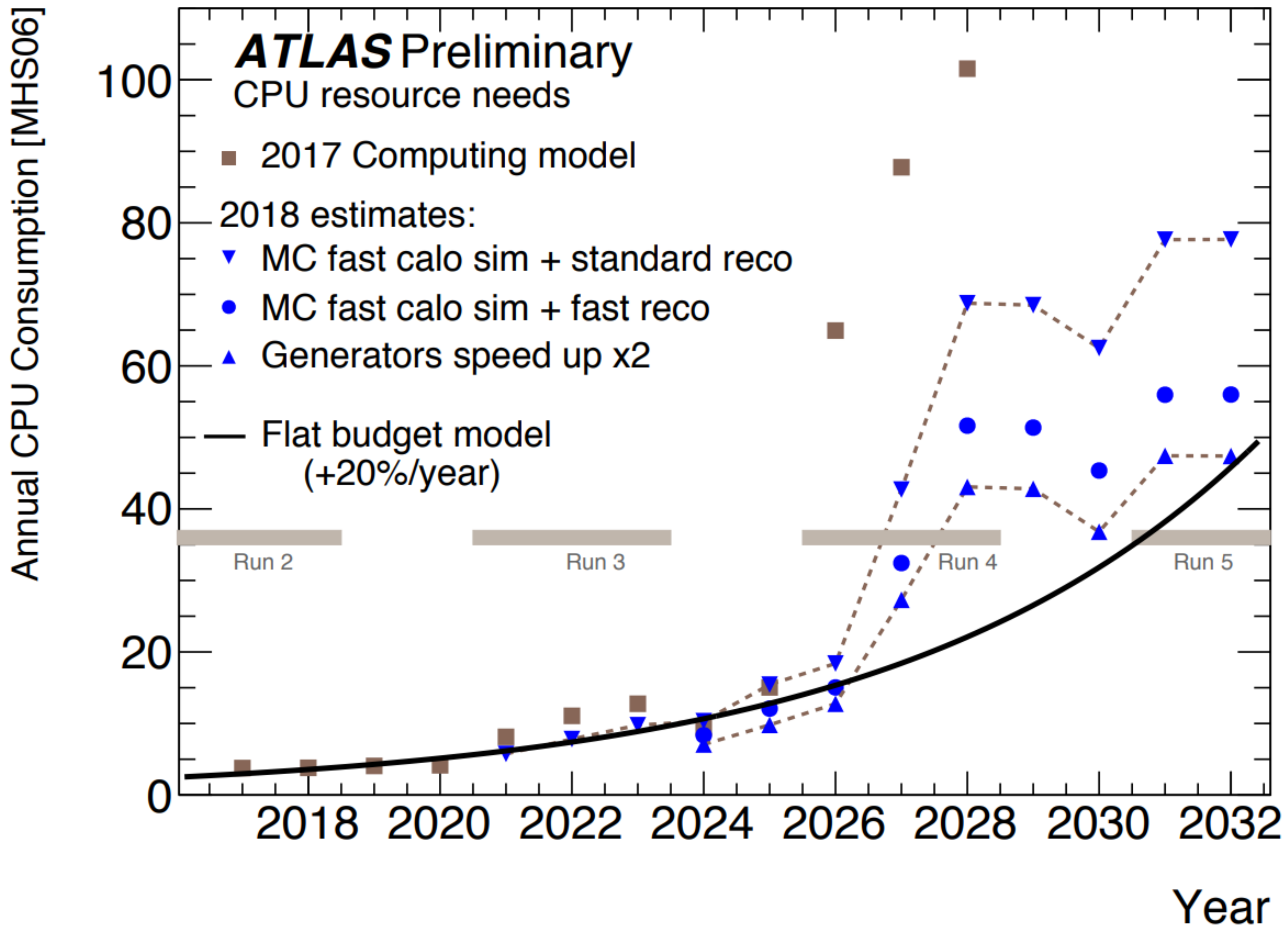
State of the art is now NLO/LO multileg merging

⟶ Event generation has become expensive

Improvements are required in multiple areas

Physics Challenges

- NNLO fixed order increasingly available
  - Matching algorithms exist, but not part of standard codes yet
  - Work needed before computationally feasible
- Accuracy + subleading effects in parton showers
- Improvements & better understanding of nonperturbative effects

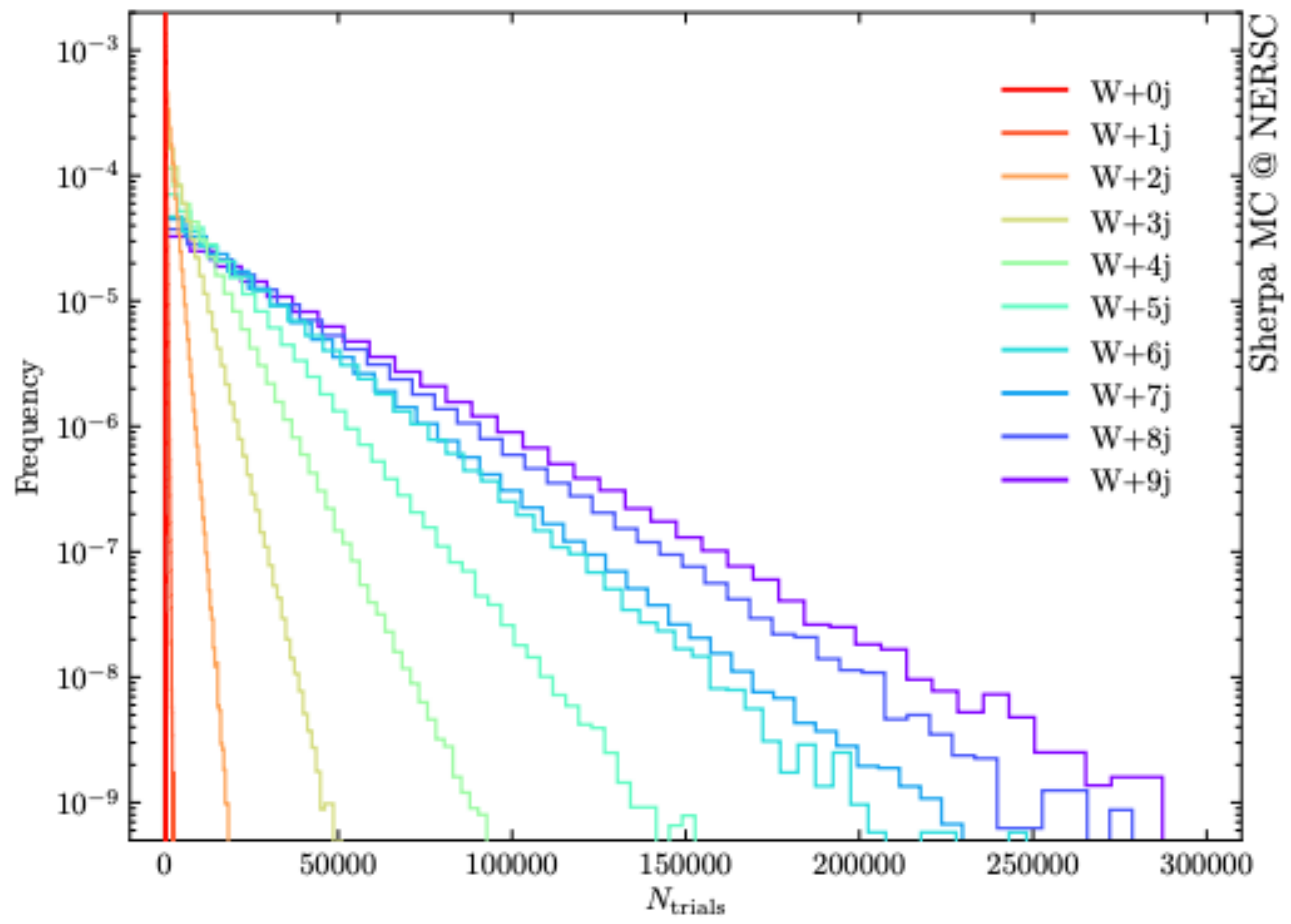


Matrix Element Sampling

Often still reliant on VEGAS + multi channeling

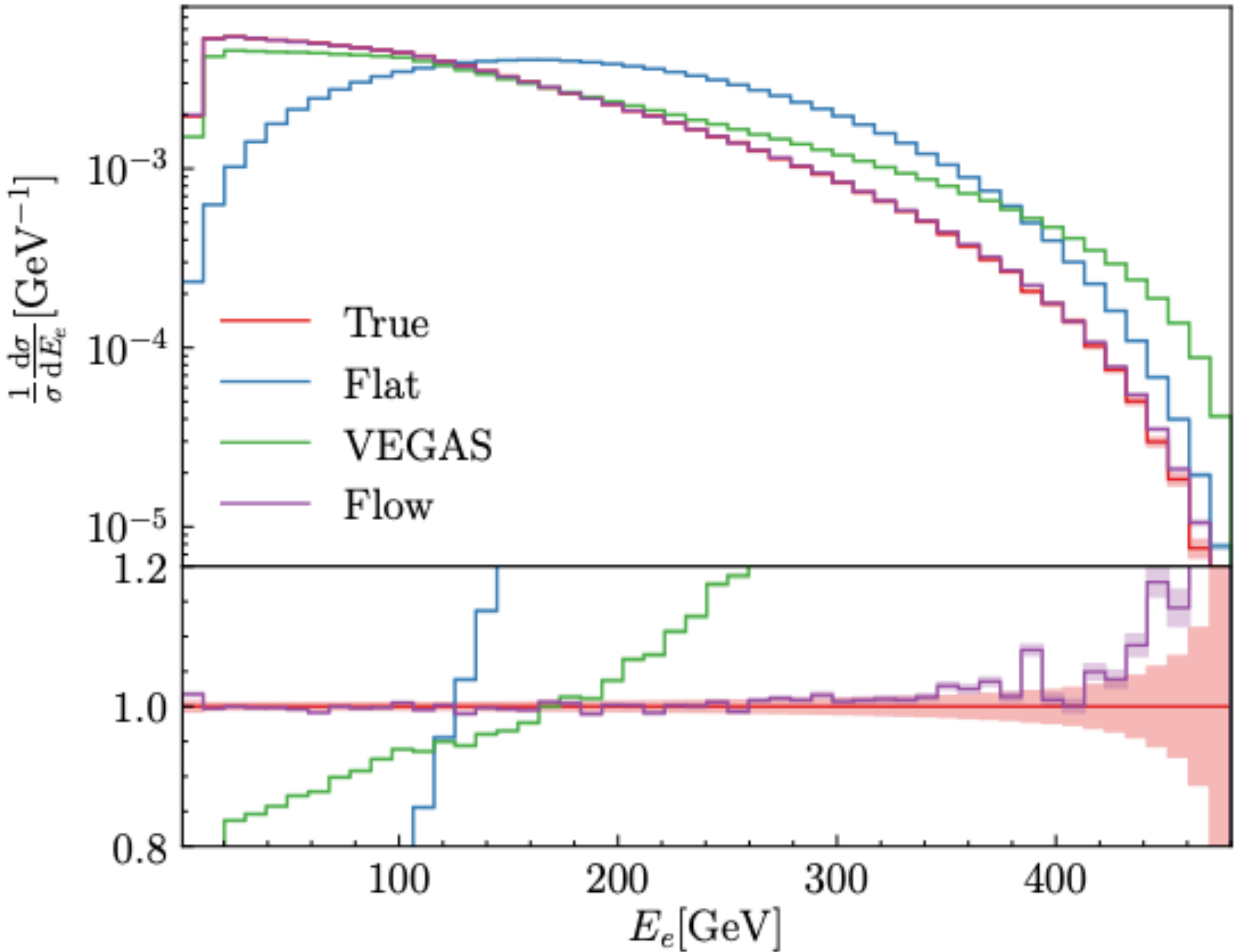
⟶ Many case-specific algorithms exist (FOAM, HAAG)

Gao, Isaacson, Krause 2001.05486
Gao, Hoche, Isaacson, Krause, Schulz 2001.10028
Bothmann, Janssen, Knobbe, Schmale, Schumann 2001.05478
Stienen, RV 2011:13445



Recent developments from generative machine learning models

unweighting efficiency $\langle w\rangle/w_{\max}$		LO QCD $n=0$	$n=1$	$n=2$	$n=3$	$n=4$	NLO QCD (RS) $n=0$	$n=1$
$W^+ + n$ jets	Sherpa	$2.8\cdot10^{-1}$	$3.8\cdot10^{-2}$	$7.5\cdot10^{-3}$	$1.5\cdot10^{-3}$	$8.3\cdot10^{-4}$	$9.5\cdot10^{-2}$	$4.5\cdot10^{-3}$
	NN+NF	$6.1\cdot10^{-1}$	$1.2\cdot10^{-1}$	$1.0\cdot10^{-2}$	$1.8\cdot10^{-3}$	$8.9\cdot10^{-4}$	$1.6\cdot10^{-1}$	$4.1\cdot10^{-3}$
	Gain	2.2	3.3	1.4	1.2	1.1	1.6	0.91
$W^- + n$ jets	Sherpa	$2.9\cdot10^{-1}$	$4.0\cdot10^{-2}$	$7.7\cdot10^{-3}$	$2.0\cdot10^{-3}$	$9.7\cdot10^{-4}$	$1.0\cdot10^{-1}$	$4.5\cdot10^{-3}$
	NN+NF	$7.0\cdot10^{-1}$	$1.5\cdot10^{-1}$	$1.1\cdot10^{-2}$	$2.2\cdot10^{-3}$	$7.9\cdot10^{-4}$	$1.5\cdot10^{-1}$	$4.2\cdot10^{-3}$
	Gain	2.4	3.3	1.4	1.1	0.82	1.5	0.91
$Z + n$ jets	Sherpa	$3.1\cdot10^{-1}$	$3.6\cdot10^{-2}$	$1.5\cdot10^{-2}$	$4.7\cdot10^{-3}$		$1.2\cdot10^{-1}$	$5.3\cdot10^{-3}$
	NN+NF	$3.8\cdot10^{-1}$	$1.0\cdot10^{-1}$	$1.4\cdot10^{-2}$	$2.4\cdot10^{-3}$		$1.8\cdot10^{-3}$	$5.7\cdot10^{-3}$
	Gain	1.2	2.9	0.91	0.51		1.5	1.1



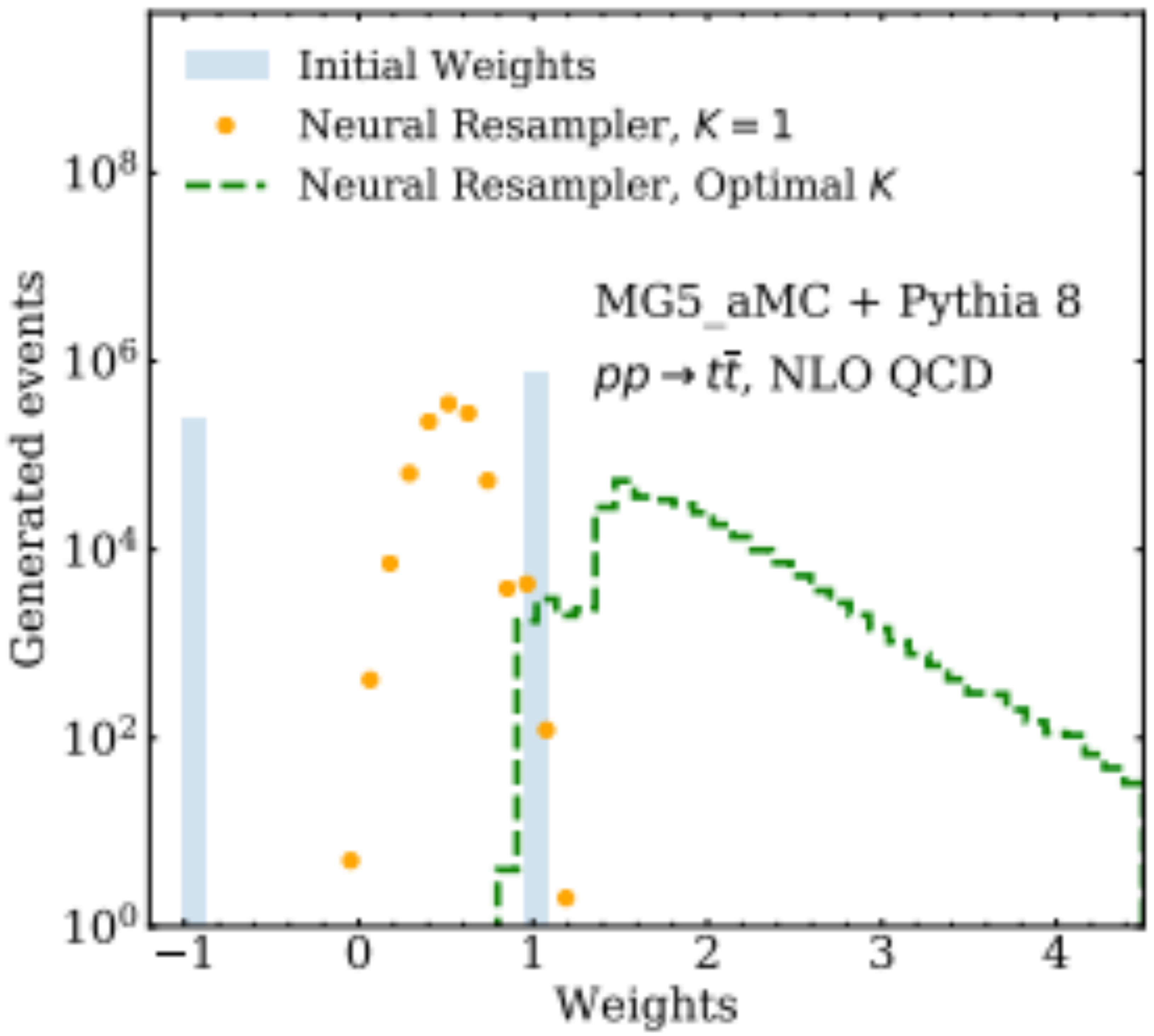
Negative Weights

NLO corrections often lead to negative weights

→ Requires a factor of $1/(1-f_{\rm neg})^2$ more events

Several improvements being explored

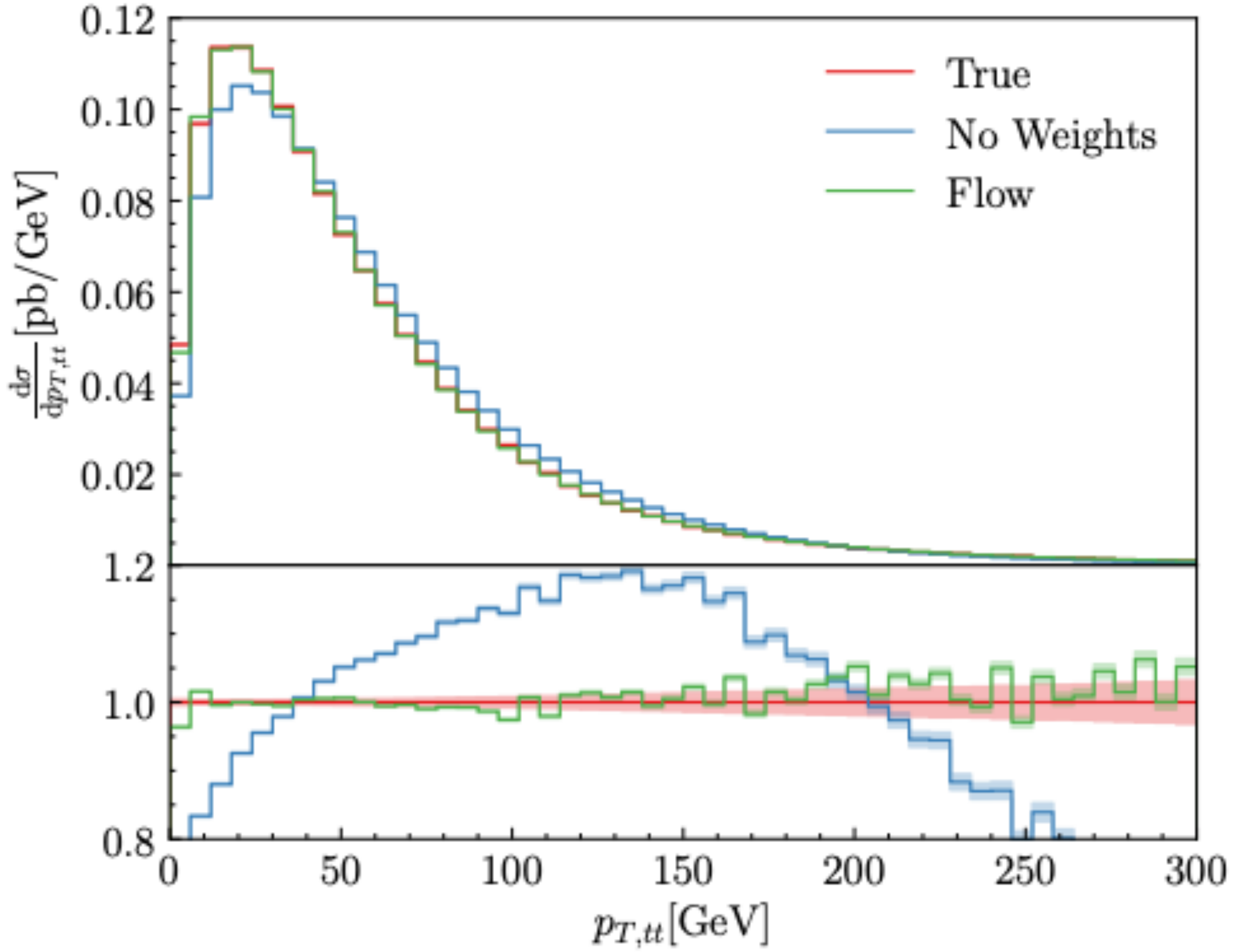
- Resampling Andersen, Gutschow, Maier, Prestel 2005.09375 Nachman, Thaler 2007.11586



- Improving MC@NLO Frederix, Frixione, Prestel, Torrielli 2002:12716

	MC@NLO			MC@NLO-Δ		
	111	221	441	Δ-111	Δ-221	Δ-441
$pp \to e^+e^-$	6.9% (1.3)	3.5% (1.2)	3.2% (1.1)	5.7% (1.3)	2.4% (1.1)	2.0% (1.1)
$pp \to e^+\nu_e$	7.2% (1.4)	3.8% (1.2)	3.4% (1.2)	5.9% (1.3)	2.5% (1.1)	2.3% (1.1)
$pp \to H$	10.4% (1.6)	4.9% (1.2)	3.4% (1.2)	7.5% (1.4)	2.0% (1.1)	0.5% (1.0)
$pp \to Hb\bar{b}$	40.3% (27)	38.4% (19)	38.0% (17)	36.6% (14)	32.6% (8.2)	31.3% (7.2)
$pp \to W^+j$	21.7% (3.1)	16.5% (2.2)	15.7% (2.1)	14.2% (2.0)	7.9% (1.4)	7.4% (1.4)
$pp \to W^+t\bar{t}$	16.2% (2.2)	15.2% (2.1)	15.1% (2.1)	13.2% (1.8)	11.9% (1.7)	11.5% (1.7)
$pp \to t\bar{t}$	23.0% (3.4)	20.2% (2.8)	19.6% (2.7)	13.6% (1.9)	9.3% (1.5)	7.7% (1.4)

- Generative Models Stienen, RV 2011:13445 Butter, Plehm. Winterhalder 1912.08824

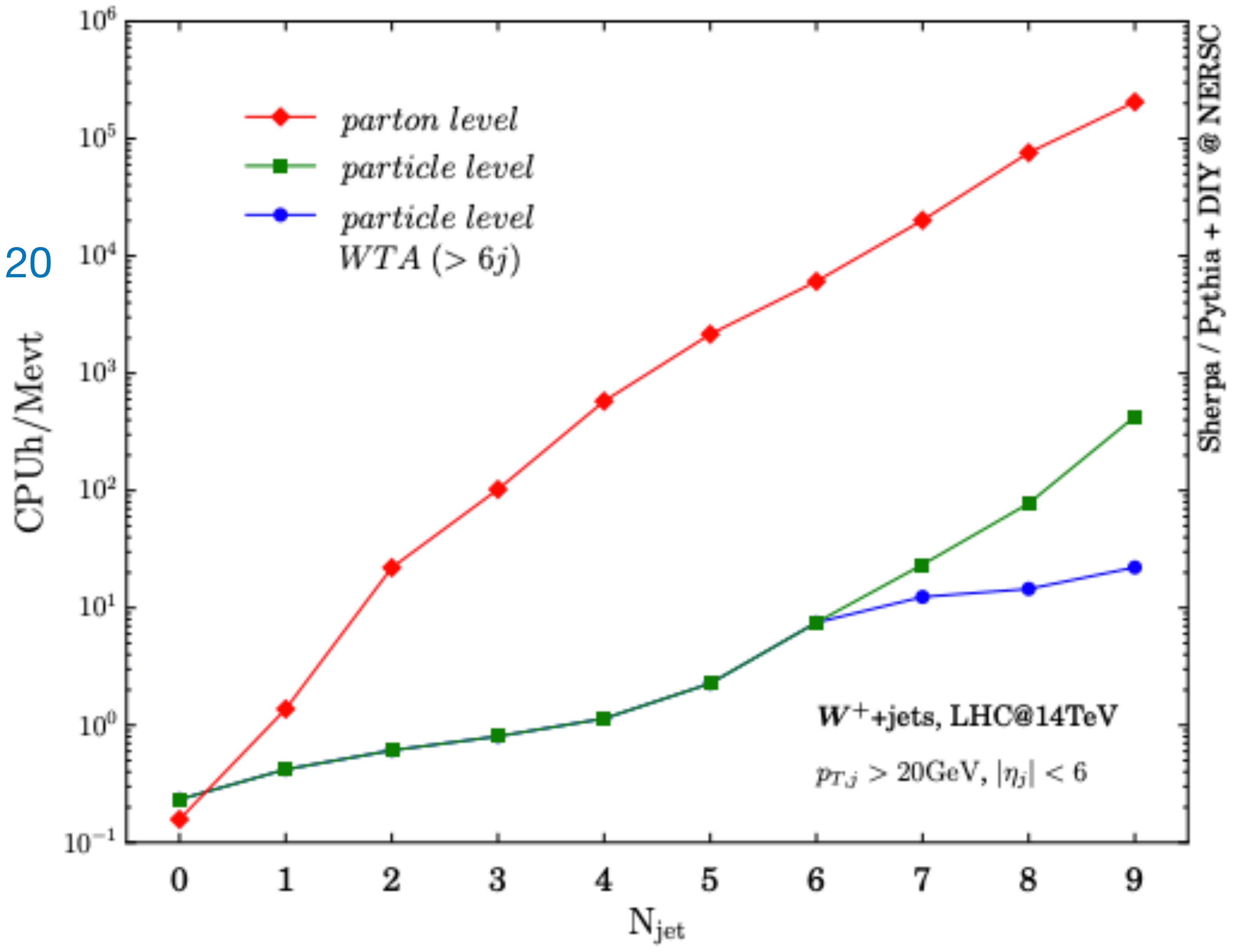


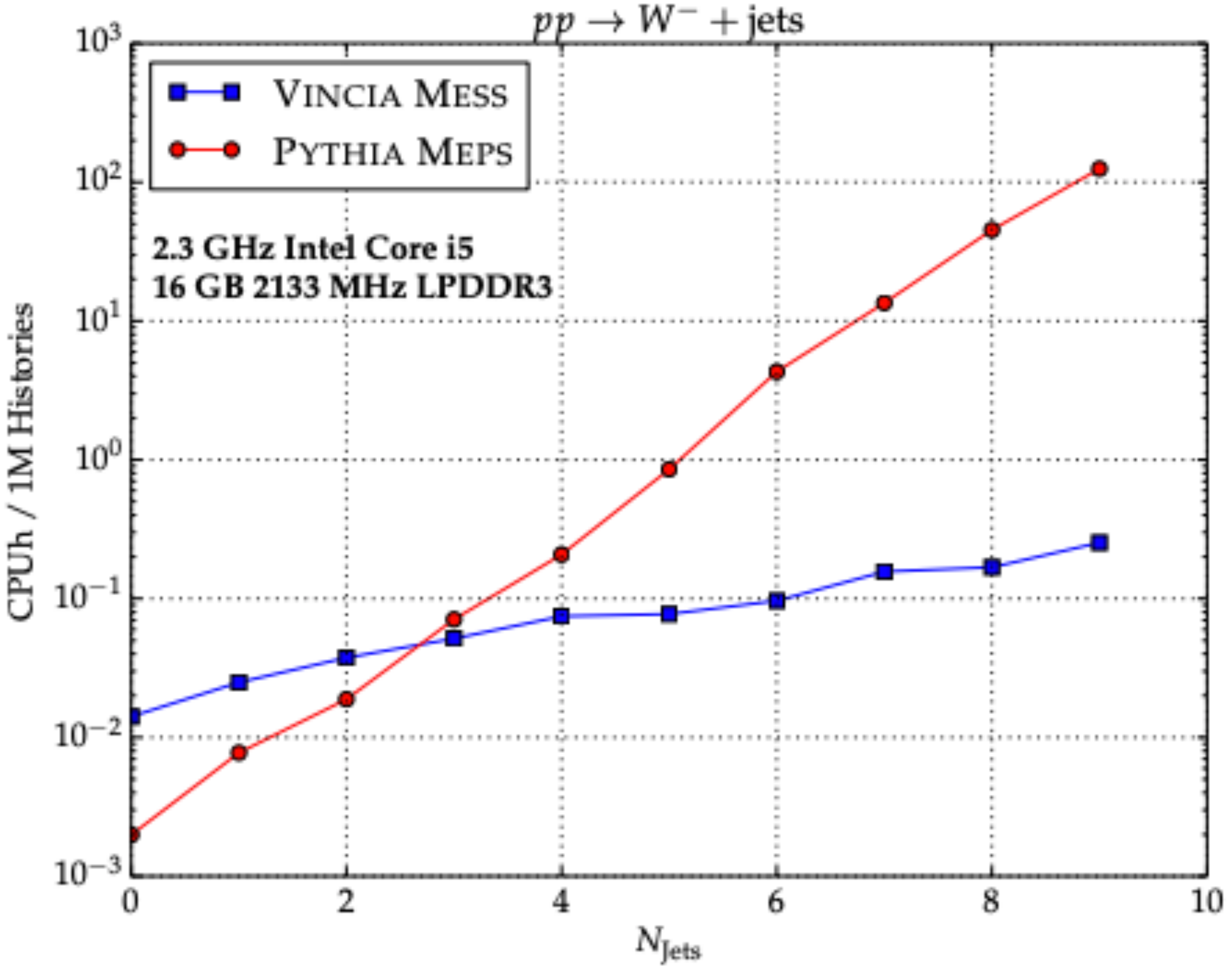
Efficient Multileg Merging

Hoche, Prestel, Schulz 1905.05120

Multileg merging is expensive for two reasons

- Sampling high-multiplicity MEs
- Reconstructing shower histories





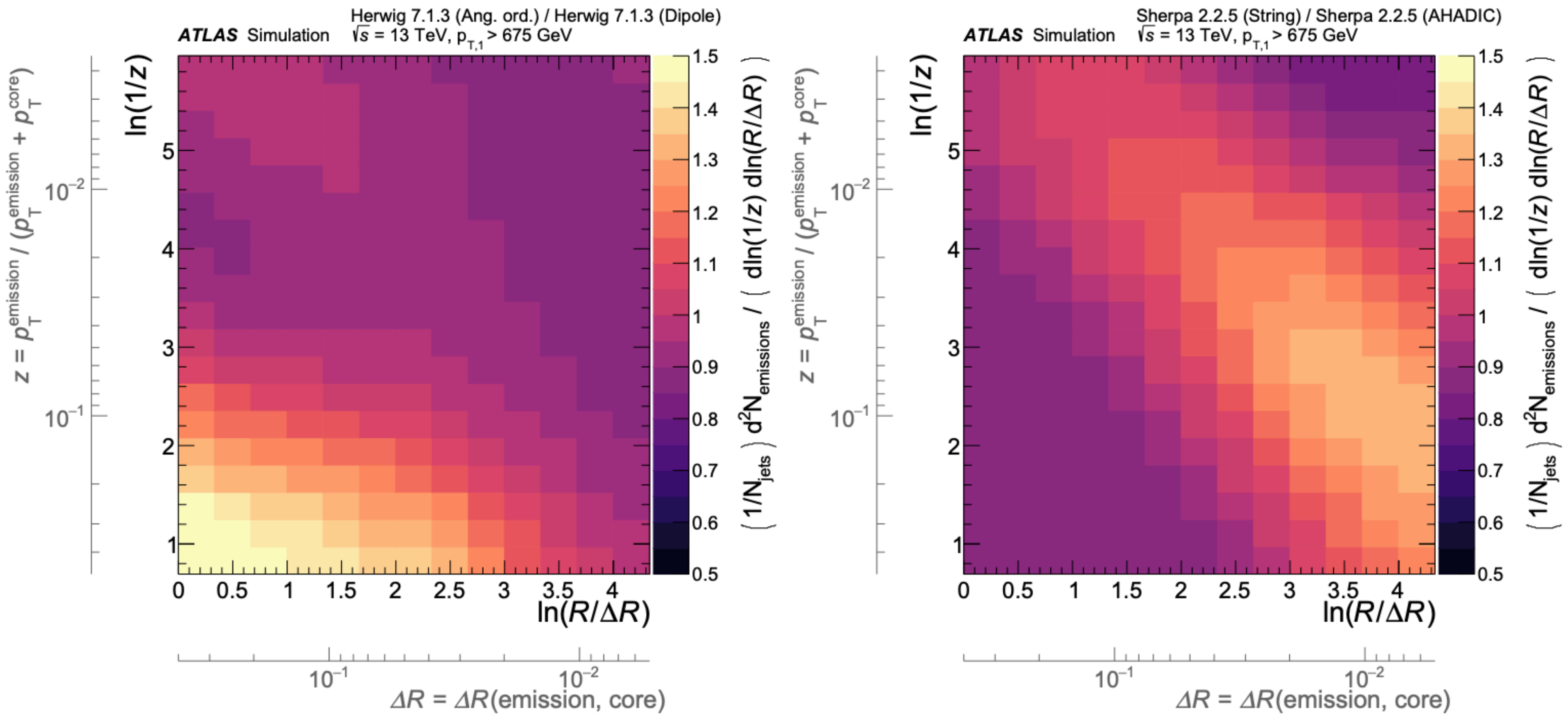
The Vincia parton shower: sector showering

Unique shower history ⟶ fast clustering

Brooks, Preuss 2008.09468

Parton Shower Accuracy

ATLAS 2004.03540

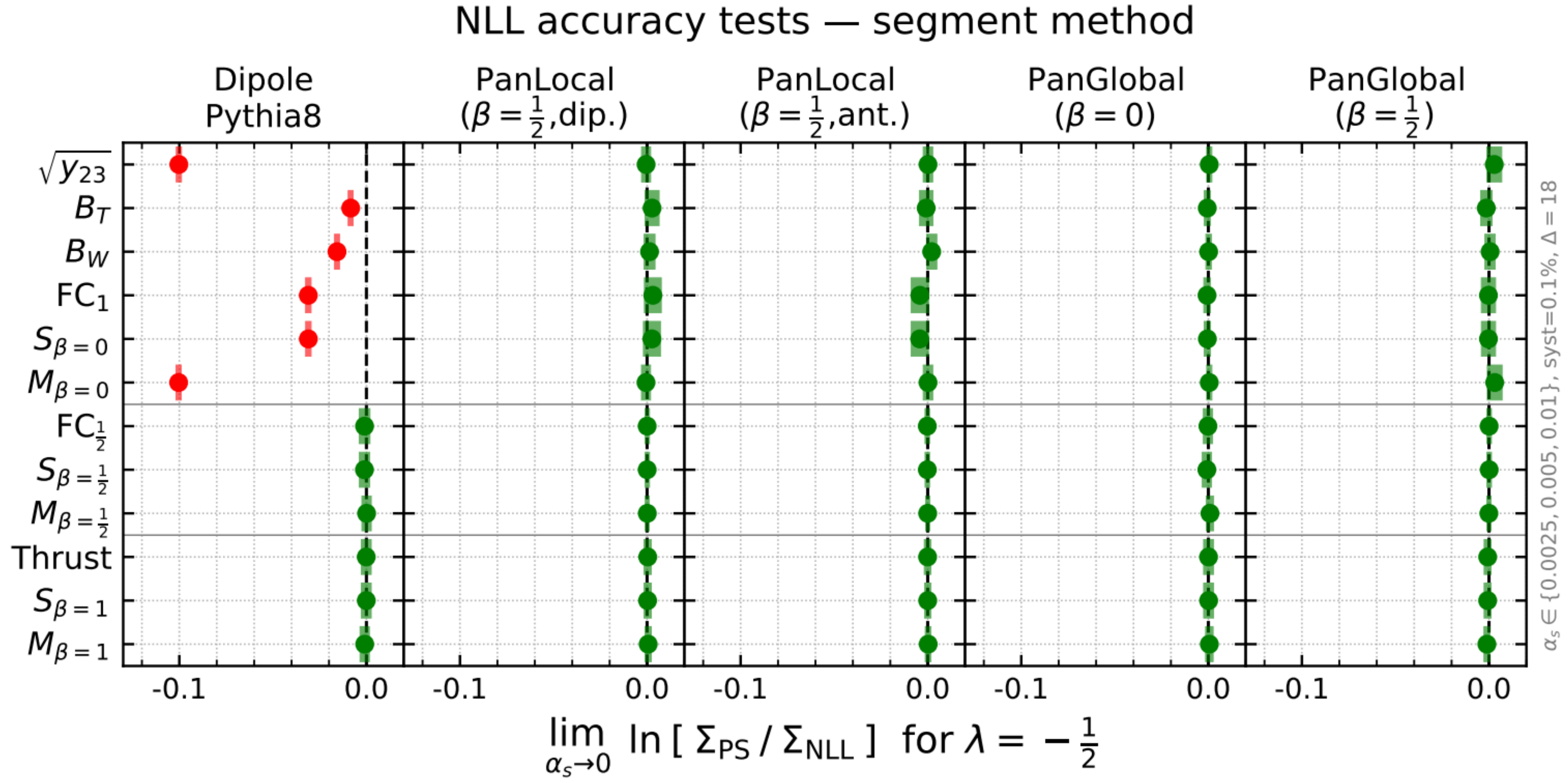


Currently large differences between models

Recent significant progress:

- Formal NLL accuracy
  - Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez 2002.11114
  - Nagy, Soper 2011.04773
  - Forshaw, Holguin, Platzer 2003.06400

- Inclusion of higher-order branching kernels
  → Requirement for NNLL
  - Hoche, Krauss, Prestel 1705.00982
  - Li, Skands 1611.00013



- Subleading colour effects $1/N_c^2 \sim 10\%$
  - Hamilton, Medves, Salam, Scyboz, Soyez 2011.10054
  - Nagy, Soper 1501.00778
  - Platzer, Sjodahl, Thoren 1808.00332
  - Forshaw, Holguin, Platzer 1905.08686
  - Isaacson, Prestel 1806.10102

- Electroweak corrections $\alpha/\alpha_s \sim 10\%$
  - Christiansen, Sjostrand arXiv:1401.5238
  - Krauss, Petrov, Schoenherr, Spannowsky arXiv:1403.4788
  - Chen, Han, Tweedie arXiv:1611.00788
  - Kleiss, RV 2002.09248

Electroweak Showers in Vincia

One-Slide Parton Shower Summary

Process-independent, fully differential resumption framework

Incorporates logarithms associated with soft and collinear branchings

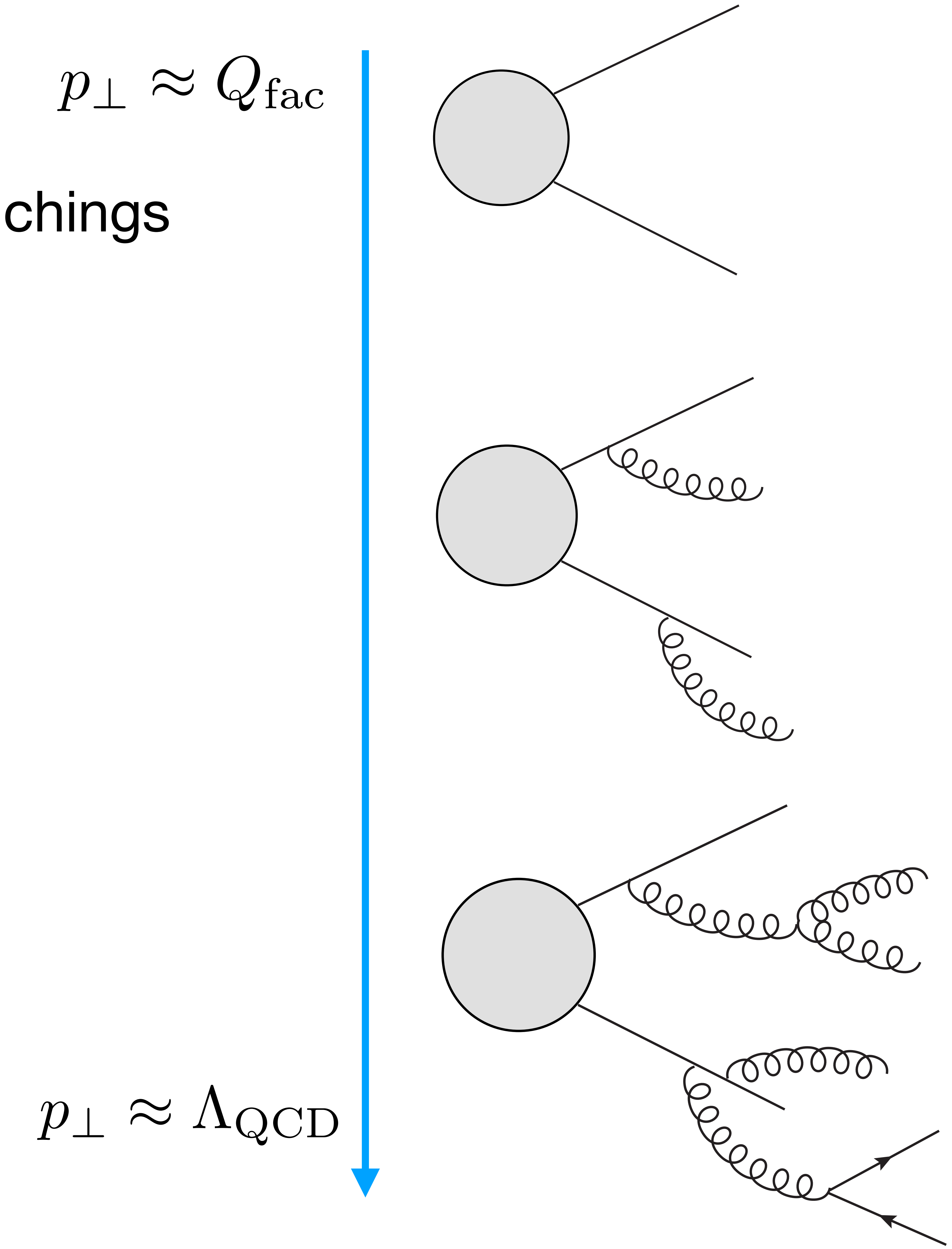
Repeatedly sample emissions from:

Branching kernel (real corrections)

$$P_i(p_{\perp,i}^2) = B(p_{\perp,i}^2) \times \Theta\left(p_{\perp,i-1}^2 - p_{\perp,i}^2\right) \times \Delta\left(p_{\perp,i-1}, p_{\perp,i}\right)$$

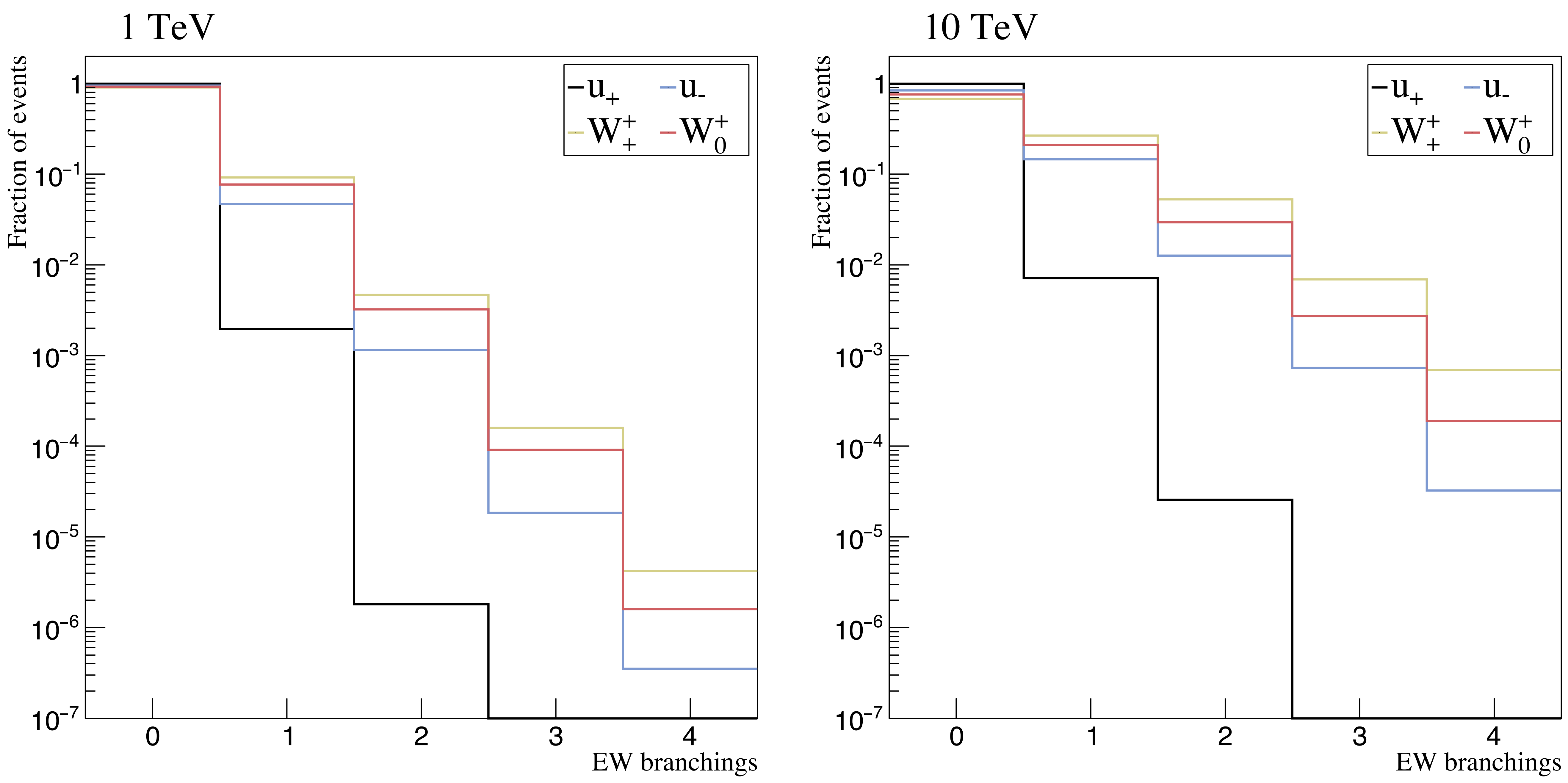
Sudakov factor (virtual corrections)

$$\Delta\left(Q_{\rm fac}, \Lambda_{\rm QCD}\right) \propto \exp\left(-\alpha_s \log^2 \frac{Q_{\rm fac}}{\Lambda_{\rm QCD}} + \ldots\right)$$



Why EW Showers?

- **EW gauge bosons, tops, Higgs part of jets**
- **Universal incorporation of EW virtual corrections** $\propto \log\left(\frac{\hat{s}}{Q^2_{EW}}\right)$



Just starting to become relevant

- (HL)-LHC ATLAS 1609.07045
- Future colliders

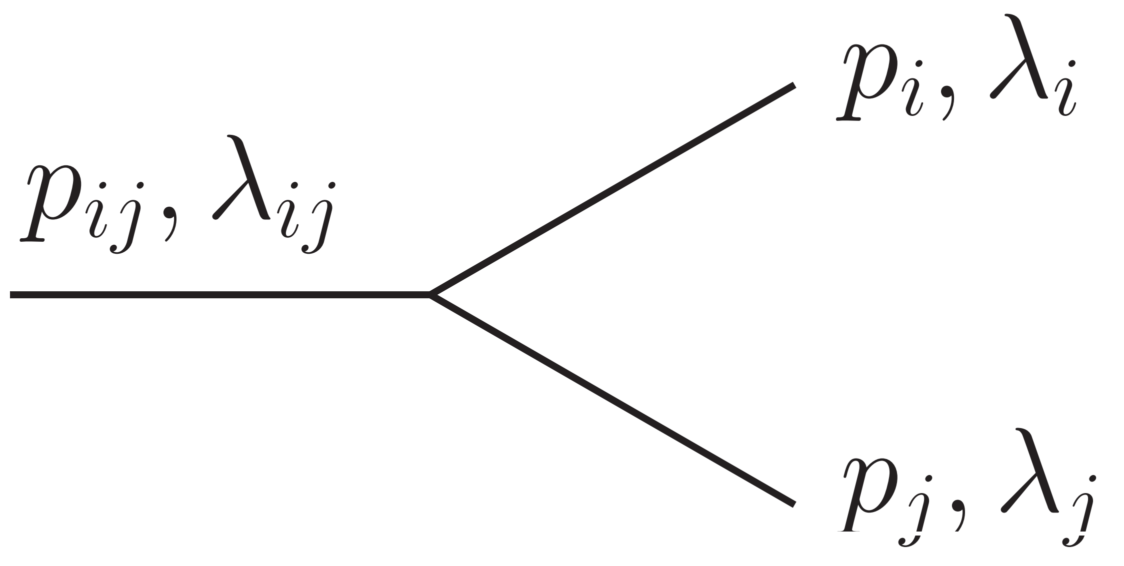
Existing implementations

- Only vector boson emissions
  Christiansen, Sjostrand arXiv:1401.5238
  Krauss, Petrov, Schoenherr, Spannowsky arXiv:1403.4788
- Full-fledged EW shower
  Chen, Han, Tweedie arXiv:1611.00788

Electroweak Branching Kernels

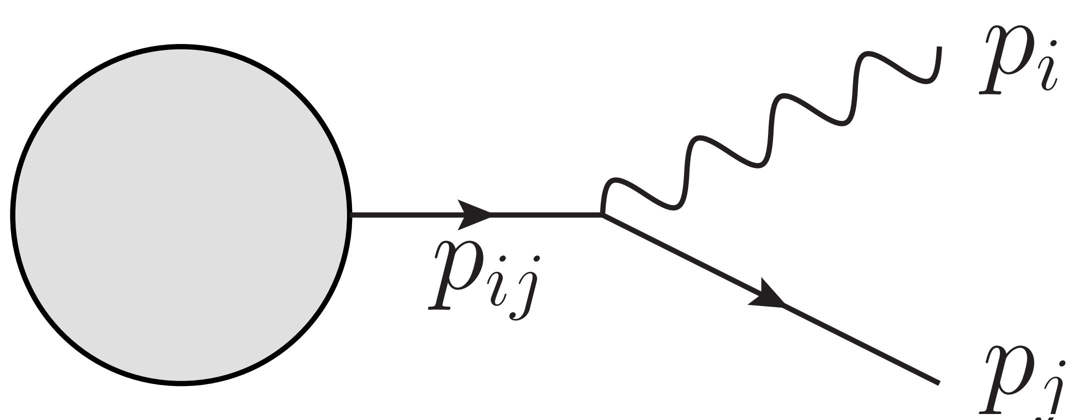
Use spinor-helicity formalism

$$M_{\lambda_{ij},\lambda_i,\lambda_j}(p_i, p_j) =$$



Transform to Vincia phase space

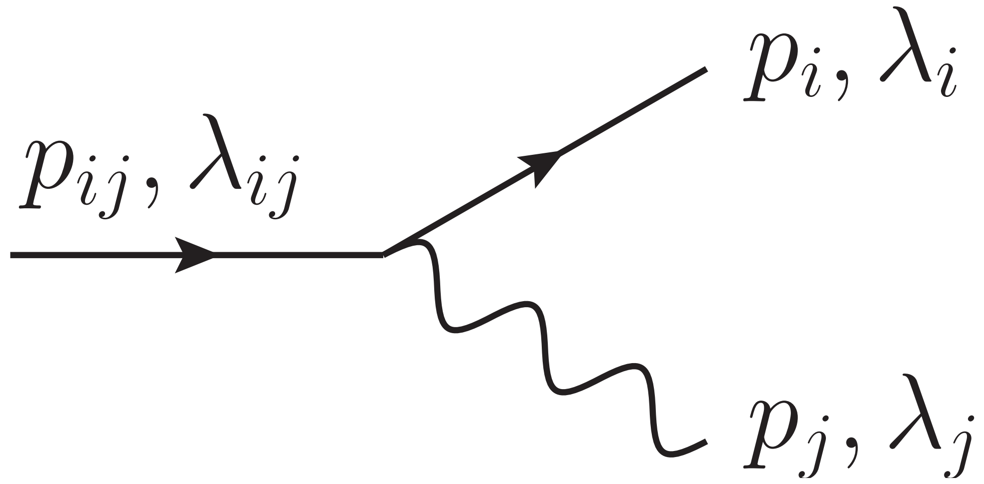
$$a_{\lambda_{ij},\lambda_i,\lambda_j}(s_{ij}, s_{jk}) = \left[\left| \frac{1}{Q^2} M_{\lambda_{ij},\lambda_i,\lambda_j}(p_i, p_j) \right|^2 \right]^{z \to x_i}_{(1-z) \to x_j}$$



$$x_i = \frac{s_{ij} + s_{ik} + m_i^2}{m_{IK}^2} \qquad x_j = \frac{s_{ij} + s_{jk} + m_j^2}{m_{IK}^2}$$

$$Q^2 = s_{ij} + m_i^2 + m_j^2 - m_{ij}^2$$

Longitudinal Polarisations



→ $M_{\lambda_{ij},\lambda_i,\lambda_j}(p_i, p_j) = \bar{u}_{\lambda_i}(p_i)(v + a\gamma^5)\not{\epsilon}_{\lambda_j}(p_j) u_{\lambda_{ij}}(p_{ij})$

↓

1. Insert spinor representations
2. Consider longitudinal polarisation
3. Do some Dirac algebra

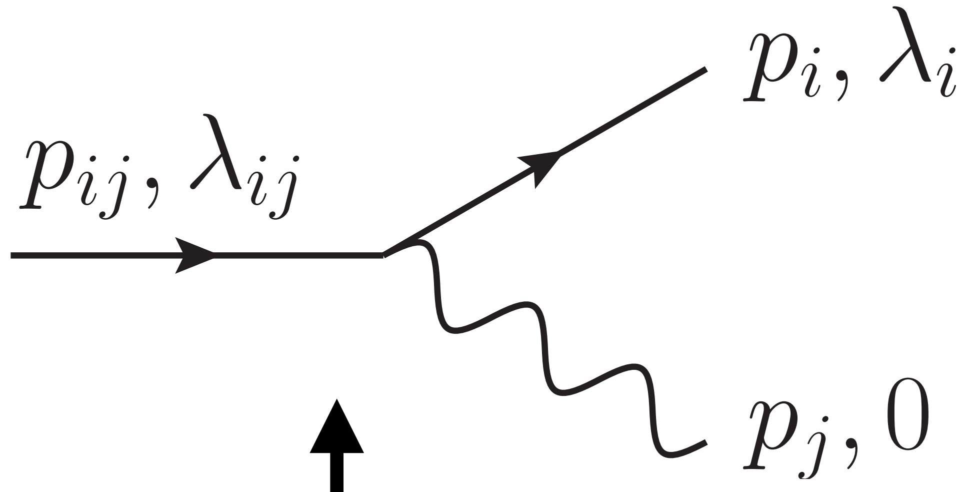
←

$$M_{+,+,0}(p_i, p_j) \propto \frac{1}{m_j}\left((Q^2 + m_{ij}^2)\not{p}_{ij} - m_i^2 \not{p}_{ij}\right)$$

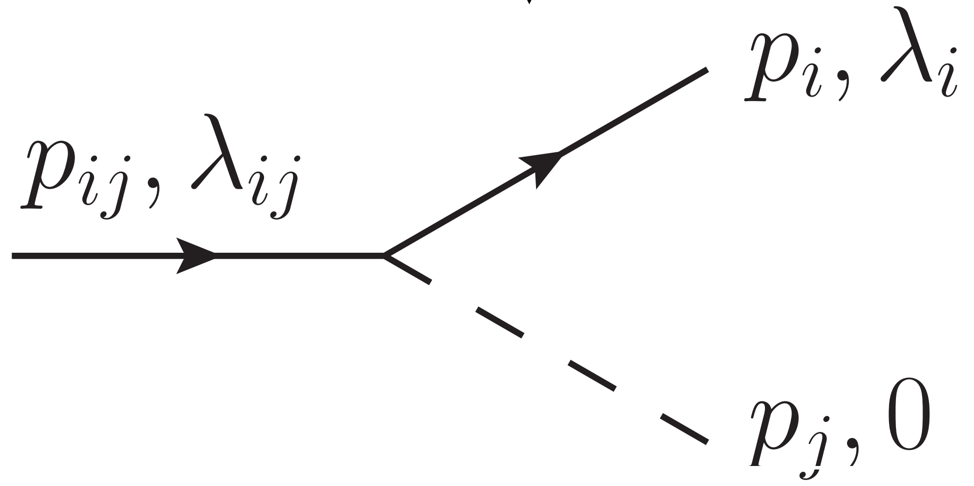
↓

Q^2 drops out → Unitarity violation → ???

Goldstone Bosons



$$\epsilon_0^\mu(p) = \frac{1}{m}\left(p^\mu - \frac{m^2}{p\cdot k}k^\mu\right)$$



Goldstone piece actually couples to Yukawa

Possible to solve with Goldstone equivalence and suitable gauge choice

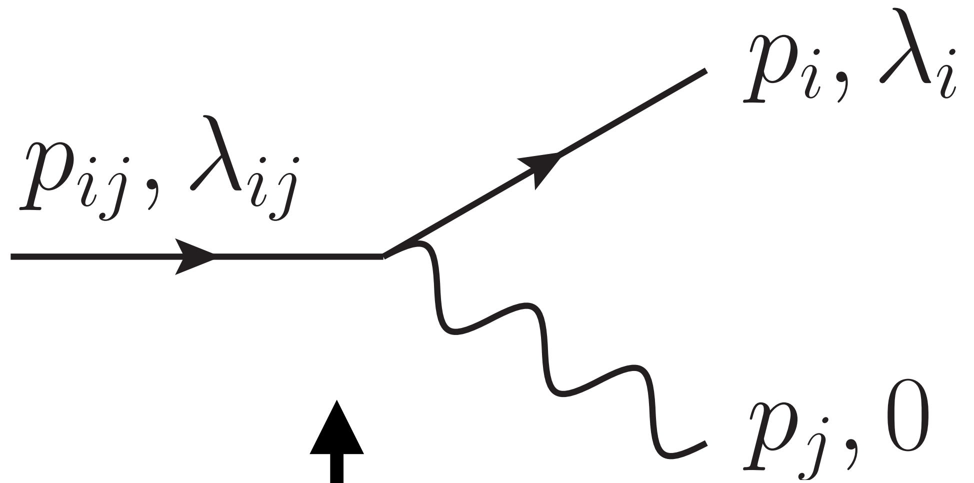
Spinor helicity formalism enables much simpler solution:

Yukawa couplings

$$\frac{1}{m_j}\left((Q^2 + m_{ij}^2)\not{p}_i - m_i^2\not{p}_{ij}\right)$$

Off-shellness

Goldstone Bosons



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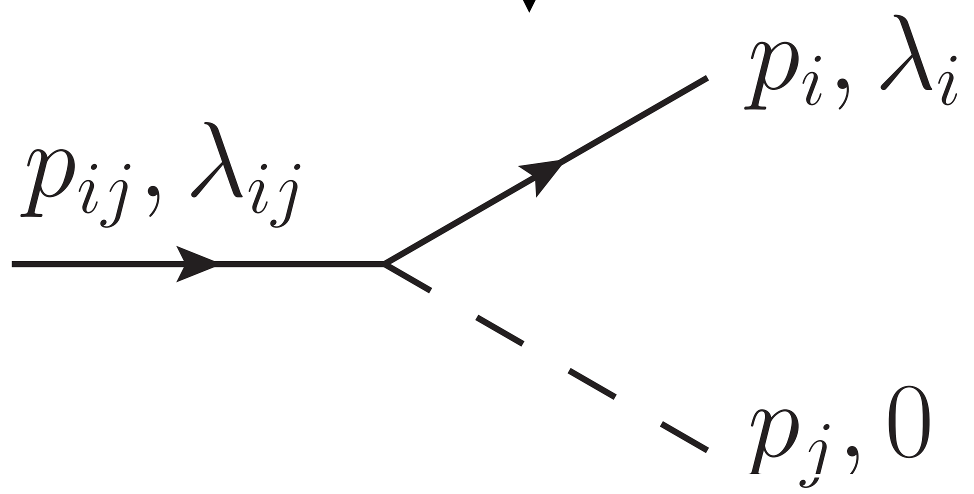

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Off-shellness

Collinear Limits

λ_I	λ_i	λ_j	$V \to f\bar{f}'$
λ	λ	$-\lambda$	$\sqrt{2}\lambda(v-\lambda a)\sqrt{\tilde{Q}^2}\, z$
λ	$-\lambda$	λ	$\sqrt{2}\lambda(v+\lambda a)\sqrt{\tilde{Q}^2}\,(1-z)$
λ	λ	λ	$\sqrt{2}\lambda\left[m_i(v+\lambda a)\sqrt{\frac{1-z}{z}} + m_j(v-\lambda a)\sqrt{\frac{z}{1-z}}\right]$
λ	$-\lambda$	$-\lambda$	0
0	λ	λ	$\sqrt{\tilde{Q}^2}\left[\frac{m_i}{m_{ij}}(v+\lambda a) + \frac{m_j}{m_{ij}}(v-\lambda a)\right]$
0	λ	$-\lambda$	$(v-\lambda a)\left[2m_{ij}\sqrt{z(1-z)} - \frac{m_i^2}{m_{ij}}\sqrt{\frac{1-z}{z}} - \frac{m_j^2}{m_{ij}}\sqrt{\frac{z}{1-z}}\right] + (v+\lambda a)\frac{m_i m_j}{m_{ij}}\frac{1}{\sqrt{z(1-z)}}$

λ_{ij}	λ_i	λ_j	$f \to f'V$ and $\bar{f} \to \bar{f}'V$
λ	λ	λ	$\sqrt{2}\lambda(v-\lambda a)\sqrt{\tilde{Q}^2}\,\frac{1}{\sqrt{1-z}}$
λ	λ	$-\lambda$	$\sqrt{2}\lambda(v-\lambda a)\sqrt{\tilde{Q}^2}\,\frac{z}{\sqrt{1-z}}$
λ	$-\lambda$	λ	$\sqrt{2}\lambda\left[m_{ij}(v-\lambda a)\sqrt{z} - m_i(v+\lambda a)\frac{1}{\sqrt{z}}\right]$
λ	$-\lambda$	$-\lambda$	0
λ	λ	0	$(v-\lambda a)\left[\frac{m_{ij}^2}{m_j}\sqrt{z} - \frac{m_i^2}{m_j}\frac{1}{\sqrt{z}} - 2m_j\frac{\sqrt{z}}{1-z}\right] + (v+\lambda a)\frac{m_i m_{ij}}{m_j}\frac{1-z}{\sqrt{z}}$
λ	$-\lambda$	0	$\sqrt{\tilde{Q}^2}\sqrt{1-z}\left[\frac{m_i}{m_j}(v-\lambda a) - \frac{m_{ij}}{m_j}(v+\lambda a)\right]$

λ_I	λ_i	$(f \to fh$ and $\bar{f} \to \bar{f}h) \times \frac{e}{2s_w}\frac{m_f}{m_w}$
λ	λ	$m_f\left[\sqrt{z} + \frac{1}{\sqrt{z}}\right]$
λ	$-\lambda$	$\sqrt{1-z}\sqrt{\tilde{Q}^2}$

λ_I	λ_i	$V \to Vh \times g_h$
λ	λ	-1
λ	$-\lambda$	0
0	λ	$\frac{1}{m_{ij}}\frac{\lambda}{\sqrt{2}}\sqrt{\tilde{Q}^2}\sqrt{z(1-z)}$
λ	0	$\frac{1}{m_i}\frac{\lambda}{\sqrt{2}}\sqrt{\tilde{Q}^2}\sqrt{\frac{1-z}{z}}$
0	0	$\frac{1}{2}\frac{m_j^2}{m_i^2} + \frac{1-z}{z} + z$

λ_i	λ_i	$h \to VV \times g_V$
λ	λ	0
λ	$-\lambda$	-1
0	λ	$\frac{1}{m_i}\frac{\lambda}{\sqrt{2}}\sqrt{\tilde{Q}^2}\sqrt{\frac{1-z}{z}}$
λ	0	$\frac{1}{m_j}\frac{\lambda}{\sqrt{2}}\sqrt{\tilde{Q}^2}\sqrt{\frac{z}{1-z}}$
0	0	$\frac{1}{2}\frac{m_{ij}^2}{m_i^2} - 1 - \frac{1-z}{z} - \frac{z}{1-z}$

λ_i	λ_j	$h \to f\bar{f} \times \frac{e}{2s_w}\frac{m_f}{m_w}$
λ	λ	$\sqrt{\tilde{Q}^2}$
λ	$-\lambda$	$m_f\left[\sqrt{\frac{1-z}{z}} - \sqrt{\frac{z}{1-z}}\right]$

λ_I	λ_i	λ_j	$V \to V'V'' \times g_V$
λ	λ	λ	$\sqrt{2}\lambda\sqrt{\tilde{Q}^2}\sqrt{\frac{1}{z(1-z)}}$
λ	λ	$-\lambda$	$\sqrt{2}\lambda\sqrt{\tilde{Q}^2}z\sqrt{\frac{z}{1-z}}$
λ	$-\lambda$	λ	$\sqrt{2}\lambda\sqrt{\tilde{Q}^2}(1-z)\sqrt{\frac{1-z}{z}}$
λ	$-\lambda$	$-\lambda$	0
0	λ	λ	0
0	λ	$-\lambda$	$m_{ij}(2z-1) + \frac{m_j^2}{m_{ij}} - \frac{m_i^2}{m_{ij}}$
λ	0	λ	$m_i\left(1 + 2\frac{1-z}{z}\right) + \frac{m_j^2}{m_i} - \frac{m_{ij}^2}{m_i}$
λ	0	$-\lambda$	0
λ	λ	0	$m_j\left(1 + 2\frac{z}{1-z}\right) + \frac{m_i^2}{m_j} - \frac{m_{ij}^2}{m_j}$
λ	$-\lambda$	0	0
λ	0	0	$\frac{\lambda}{\sqrt{2}}\frac{m_i^2+m_j^2-m_{ij}^2}{m_i m_j}\sqrt{\tilde{Q}^2}\sqrt{z(1-z)}$
0	λ	0	$\frac{\lambda}{\sqrt{2}}\frac{m_{ij}^2+m_j^2-m_i^2}{m_{ij} m_j}\sqrt{\tilde{Q}^2}\sqrt{\frac{1-z}{z}}$
0	0	λ	$\frac{\lambda}{\sqrt{2}}\frac{m_{ij}^2+m_i^2-m_j^2}{m_{ij} m_i}\sqrt{\tilde{Q}^2}\sqrt{\frac{z}{1-z}}$
0	0	0	$\frac{1}{2}\frac{m_{ij}^3}{m_i m_j}(2z-1) - \frac{m_i^3}{m_{ij}m_j}\left(\frac{1}{2} + \frac{1-z}{z}\right) + \frac{m_j^3}{m_{ij}m_i}\left(\frac{1}{2} + \frac{z}{1-z}\right) + \frac{m_i m_j}{m_{ij}}\left(\frac{1-z}{z} - \frac{z}{1-z}\right) + \frac{m_{ij}m_i}{m_j}(1-z)\left(2 + \frac{1-z}{z}\right) - \frac{m_{ij}m_j}{m_i}z\left(2 + \frac{z}{1-z}\right)$

Collinear Limits

λ_{ij}	λ_i	λ_j	$f \to f'V$ and $\bar{f} \to \bar{f}'V$
λ	λ	λ	$\sqrt{2}\lambda(v-\lambda a)\sqrt{\tilde{Q}^2}\,\frac{1}{\sqrt{1-z}}$
λ	λ	$-\lambda$	$\sqrt{2}\lambda(v-\lambda a)\sqrt{\tilde{Q}^2}\,\frac{z}{\sqrt{1-z}}$
λ	$-\lambda$	λ	$\sqrt{2}\lambda\left[m_{ij}(v-\lambda a)\sqrt{z} - m_i(v+\lambda a)\frac{1}{\sqrt{z}}\right]$
λ	$-\lambda$	$-\lambda$	0
λ	λ	0	$(v-\lambda a)\left[\frac{m_{ij}^2}{m_j}\sqrt{z} - \frac{m_i^2}{m_j}\frac{1}{\sqrt{z}} - 2m_j\frac{\sqrt{z}}{1-z}\right] + (v+\lambda a)\frac{m_i m_{ij}}{m_j}\frac{1-z}{\sqrt{z}}$
λ	$-\lambda$	0	$\sqrt{\tilde{Q}^2}\sqrt{1-z}\left[\frac{m_i}{m_j}(v-\lambda a) - \frac{m_{ij}}{m_j}(v+\lambda a)\right]$

$$P(z) \propto \frac{\tilde{Q}^2}{Q^4}\frac{1+z^2}{1-z}$$

$$P(z) \propto \frac{m^2}{Q^4}$$

$$P(z) \propto \frac{\tilde{Q}^2}{Q^4}(1-z)$$

$$\tilde{Q}^2 = Q^2 + m_{ij}^2 - \frac{m_i^2}{z} - \frac{m_j^2}{1-z}$$

The Electroweak Shower

- As similar as possible to the QCD shower
- $\mathcal{O}(1000)$ branchings (all FSR + ffV ISR)
- Ordering scale $p_\perp^2 = \dfrac{(s_{ij} + m_i^2 + m_j^2 - m_I^2)(s_{jk} + m_j^2)}{s_{IK}}$

Novel features in the Electroweak Sector

Resonance Matching

Branchings like $t \to bW, Z \to q\bar{q}$ etc.

- Large scales:
  EW shower offers best description
- Small scales:
  Breit-Wigner distribution

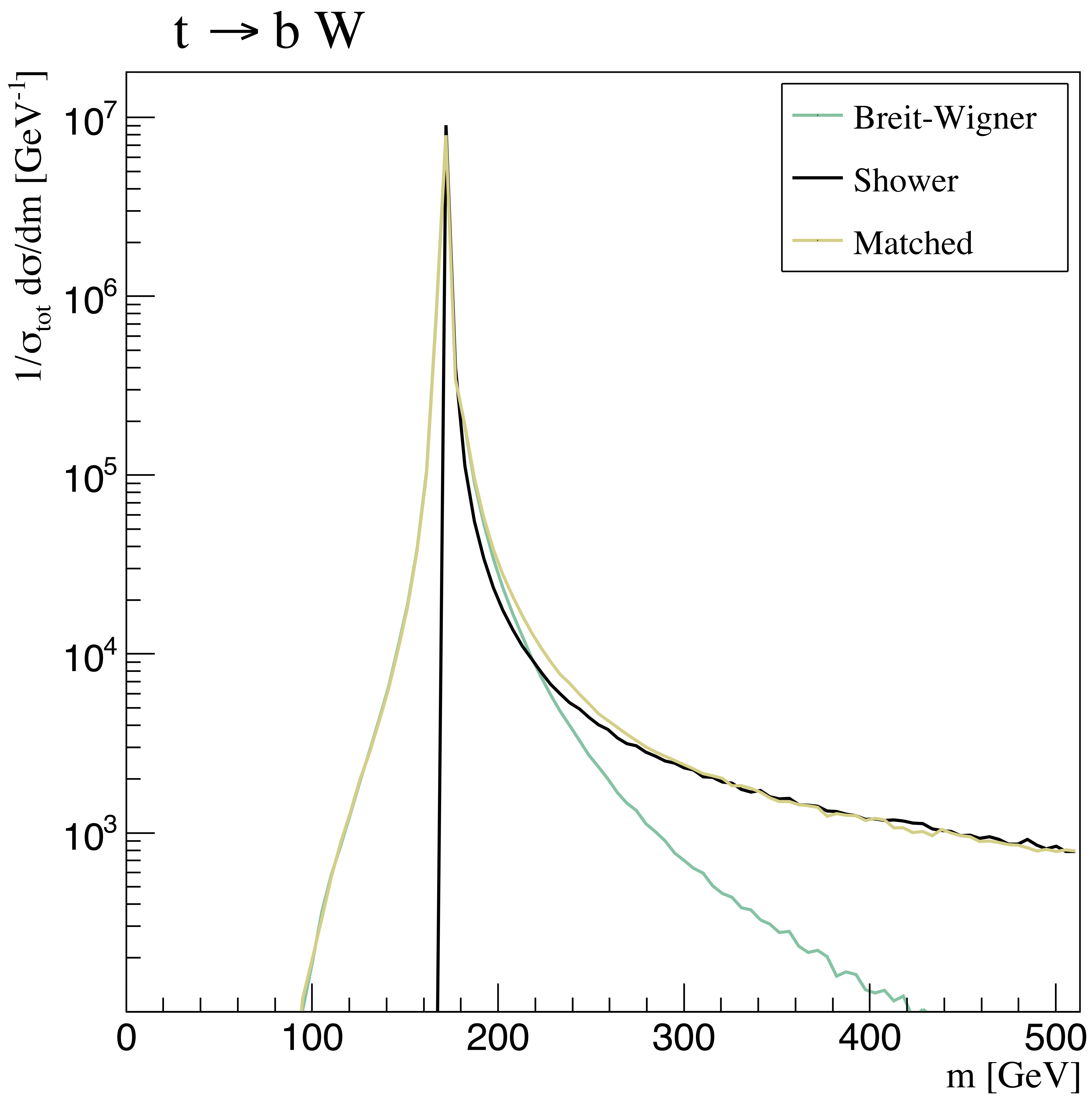
$$\mathrm{BW}(Q^2) \propto \frac{m_0\Gamma(m)}{Q^4 + m_0^2\Gamma(m)^2}$$

Matching:

- Sample mass from Breit-Wigner upon production
- Suppress shower by factor

$$\frac{Q^4}{(Q^2 + Q_{\mathrm{EW}}^2)^2}$$

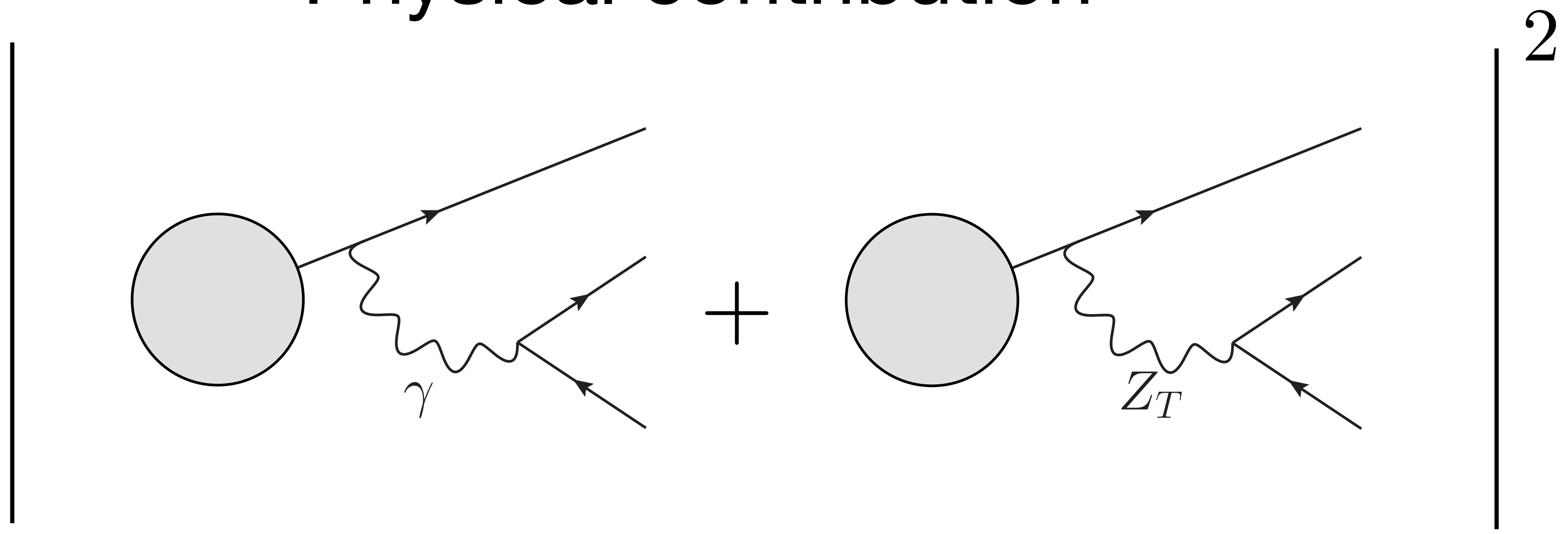
- Decay when shower hits off-shellness scale



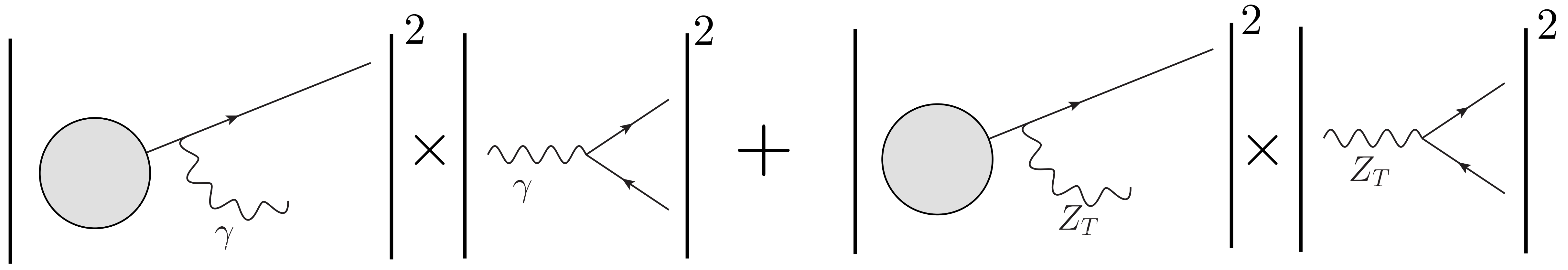
Neutral Boson Interference

Interference between γ, Z_T and h, Z_L

Physical contribution



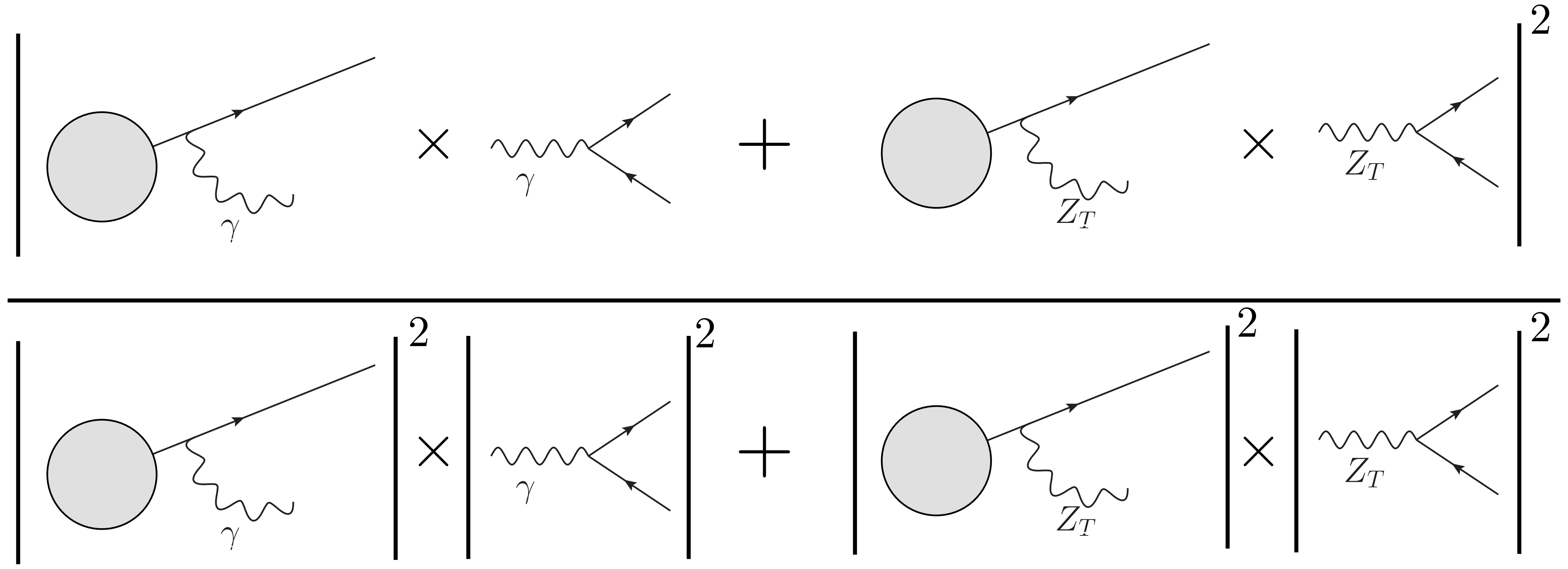
Shower approximation



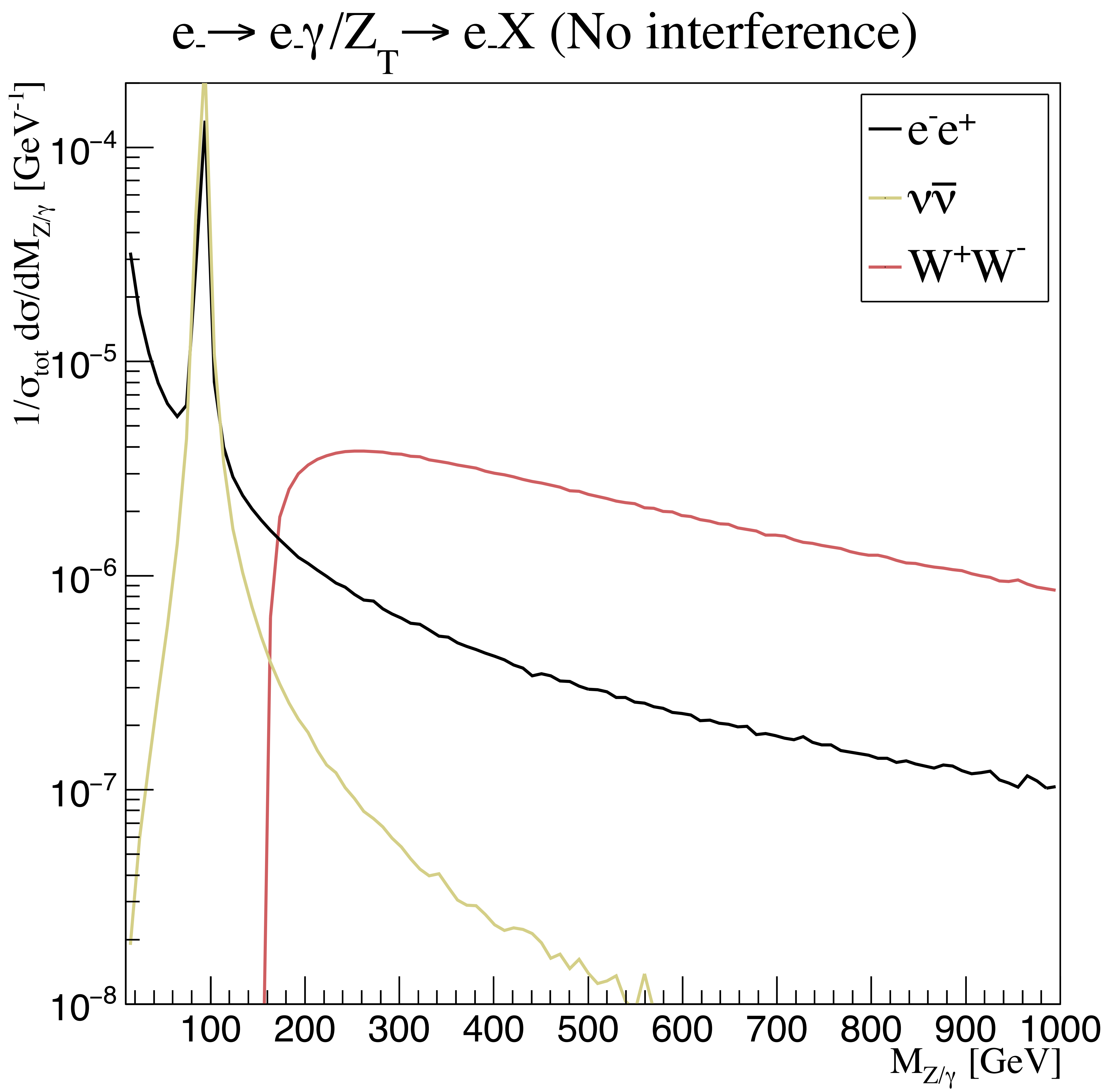
- Complicated solution: Evolve density matrices
  $\longrightarrow$ Very computationally expensive

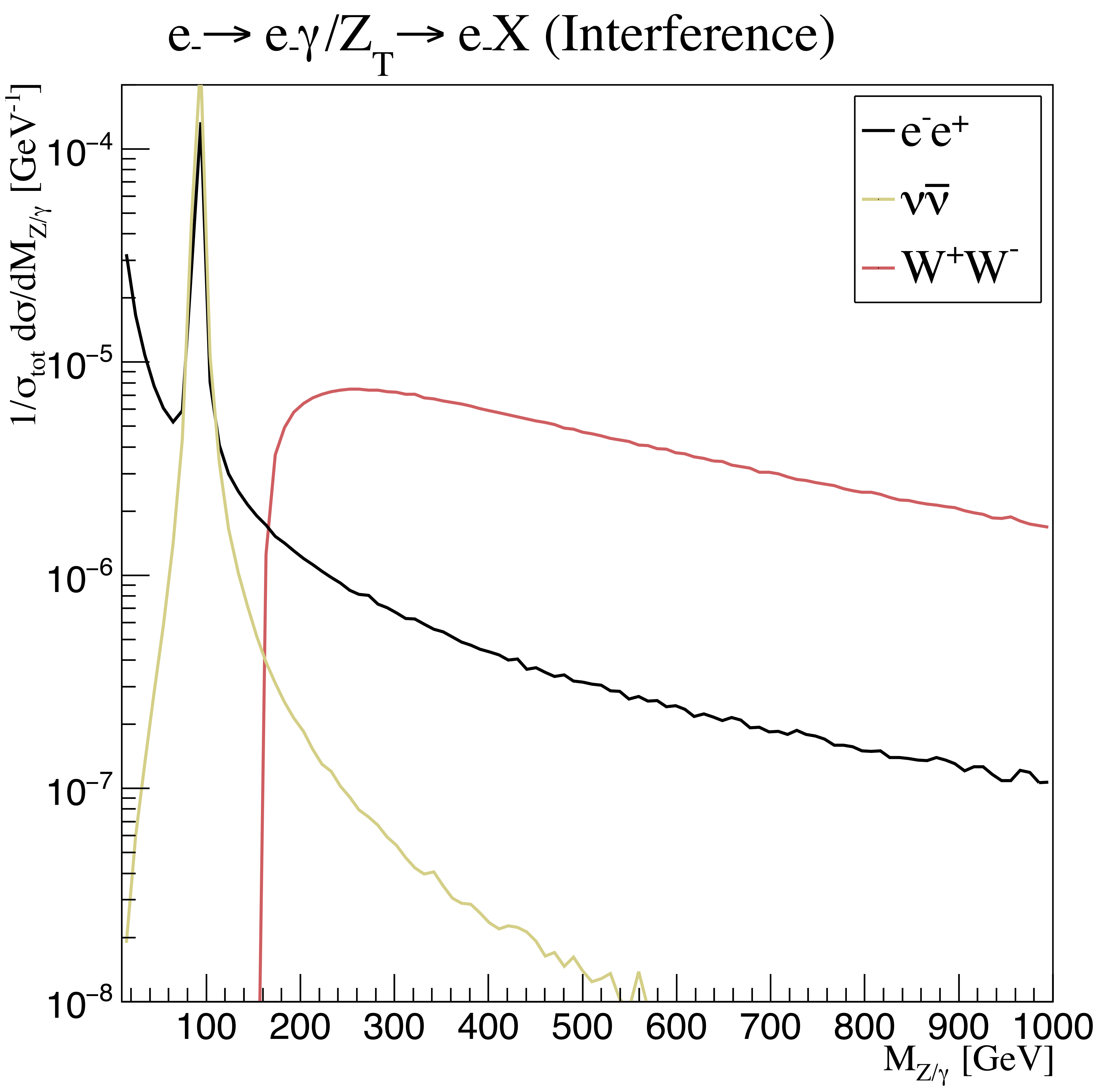
- Simple solution: Apply event weight
  $\longrightarrow$ Does not get Sudakov right

$w =$

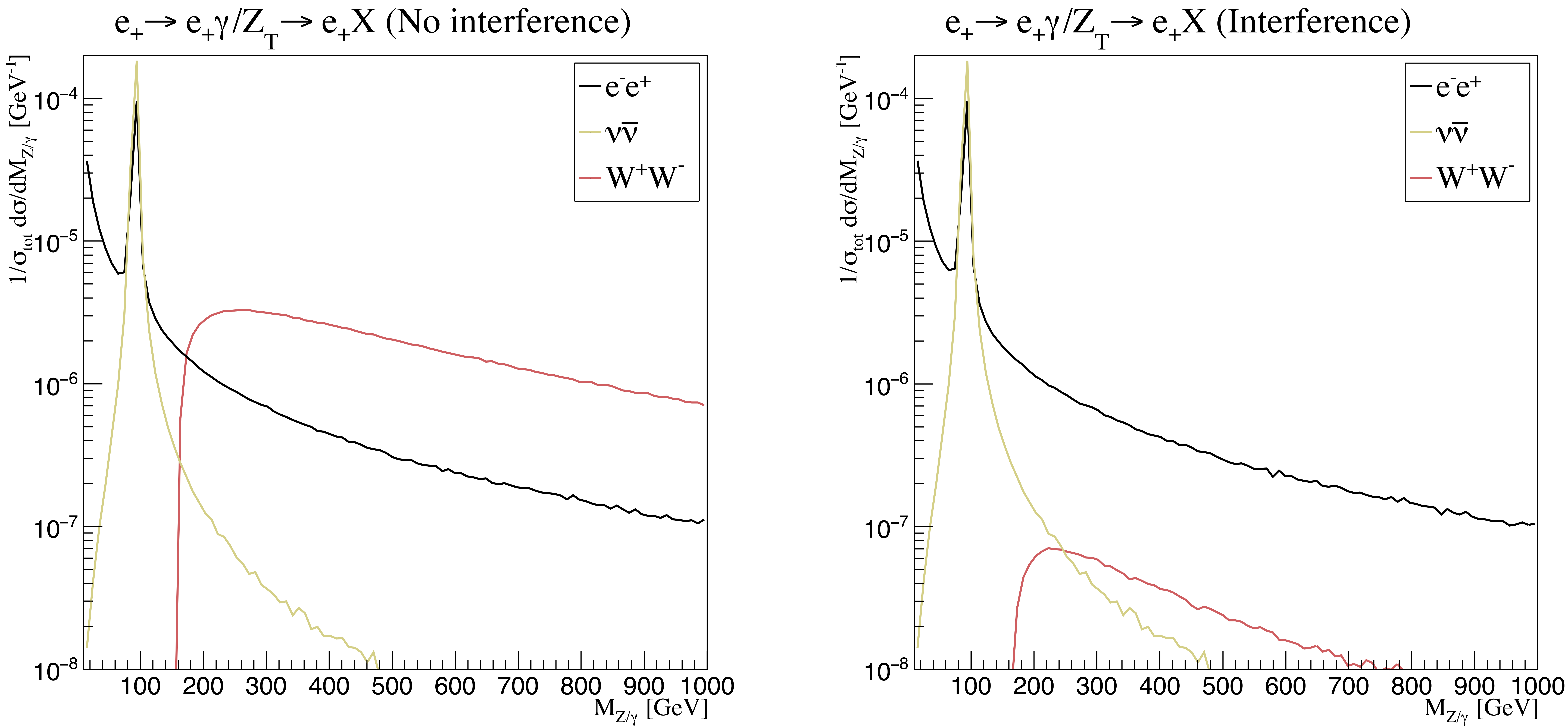


Bosonic Interference



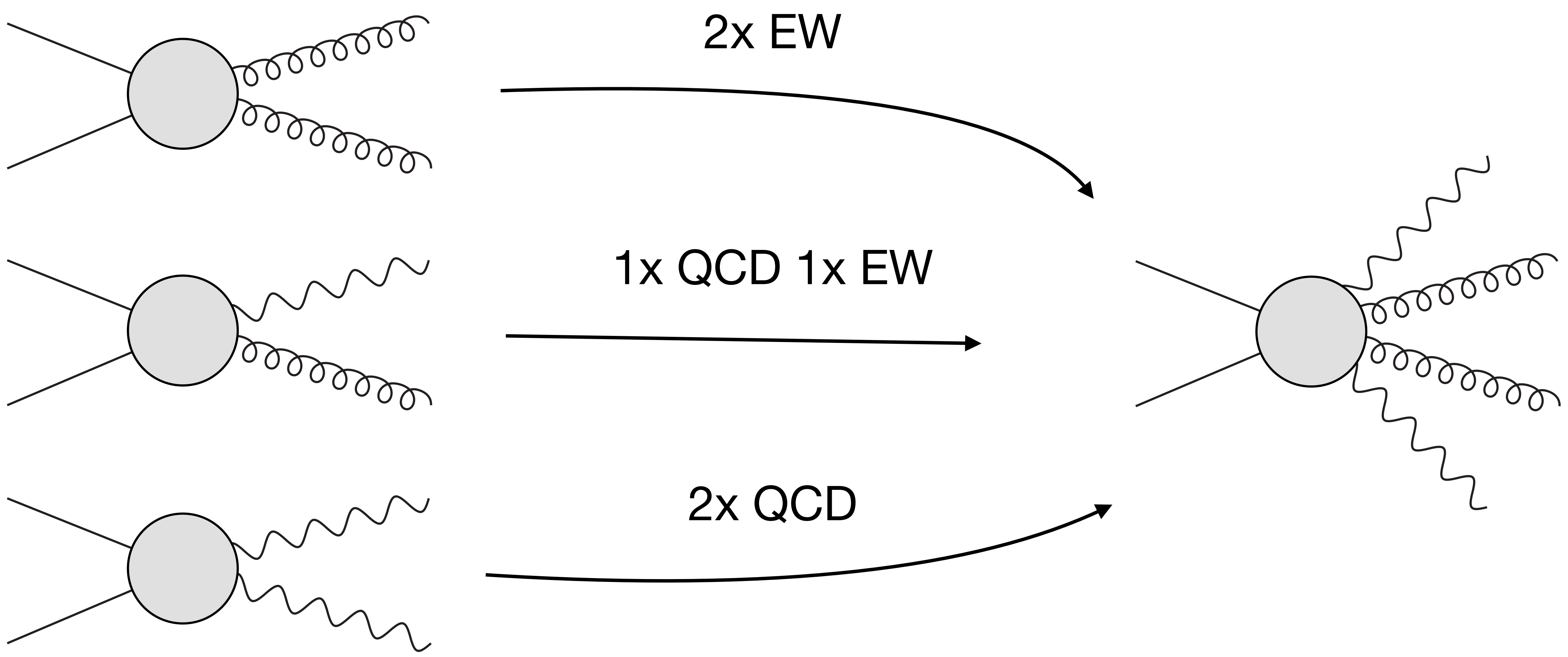


Bosonic Interference

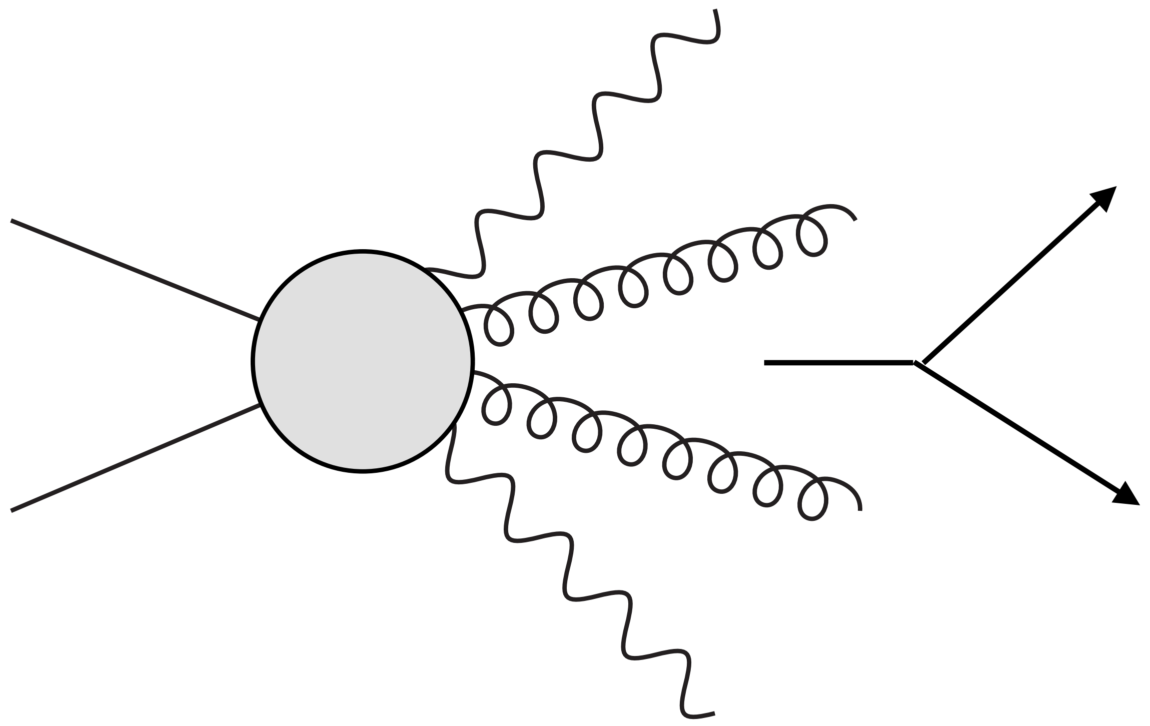


Overlap Veto

Double counting problem



Veto procedure

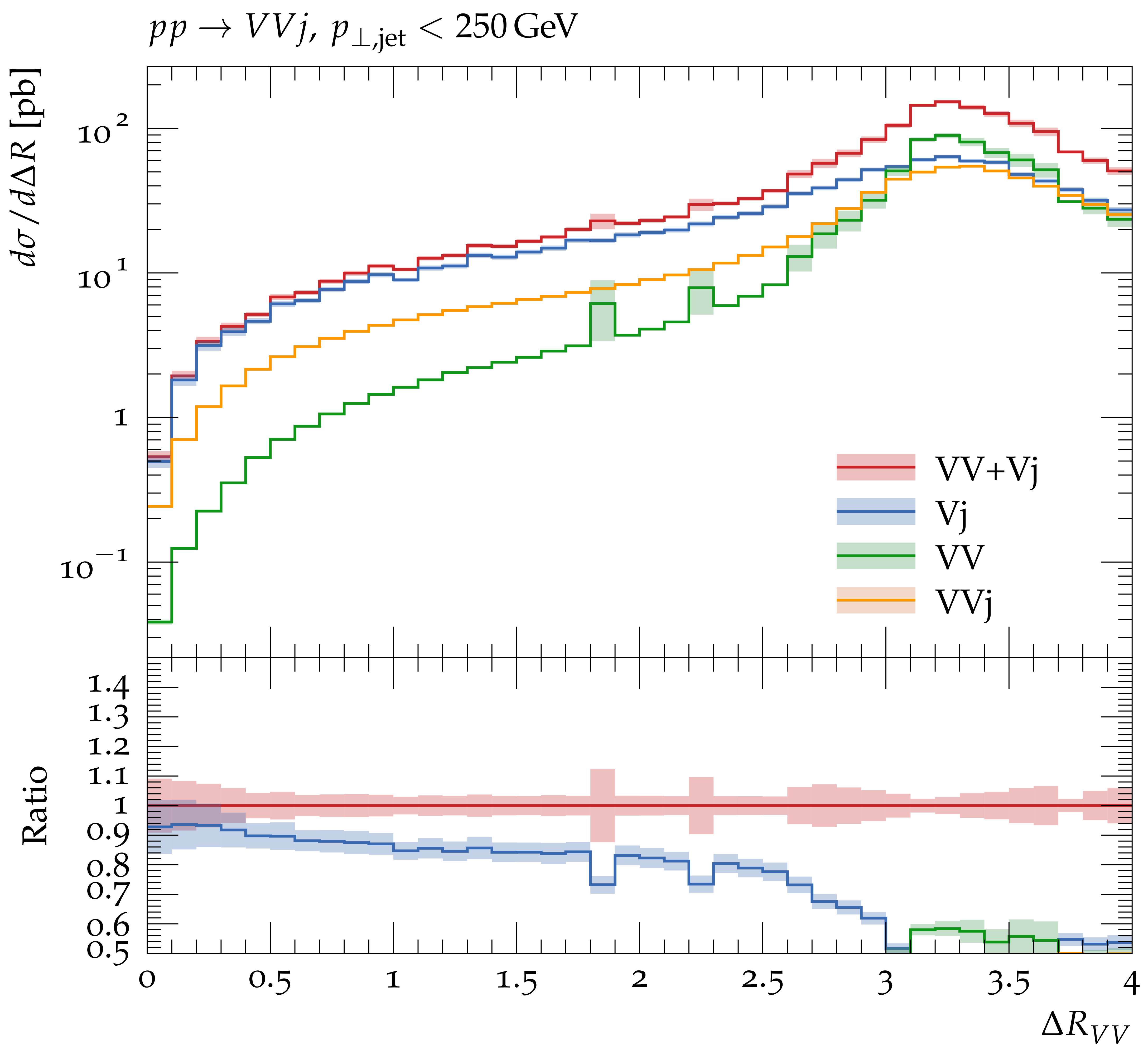


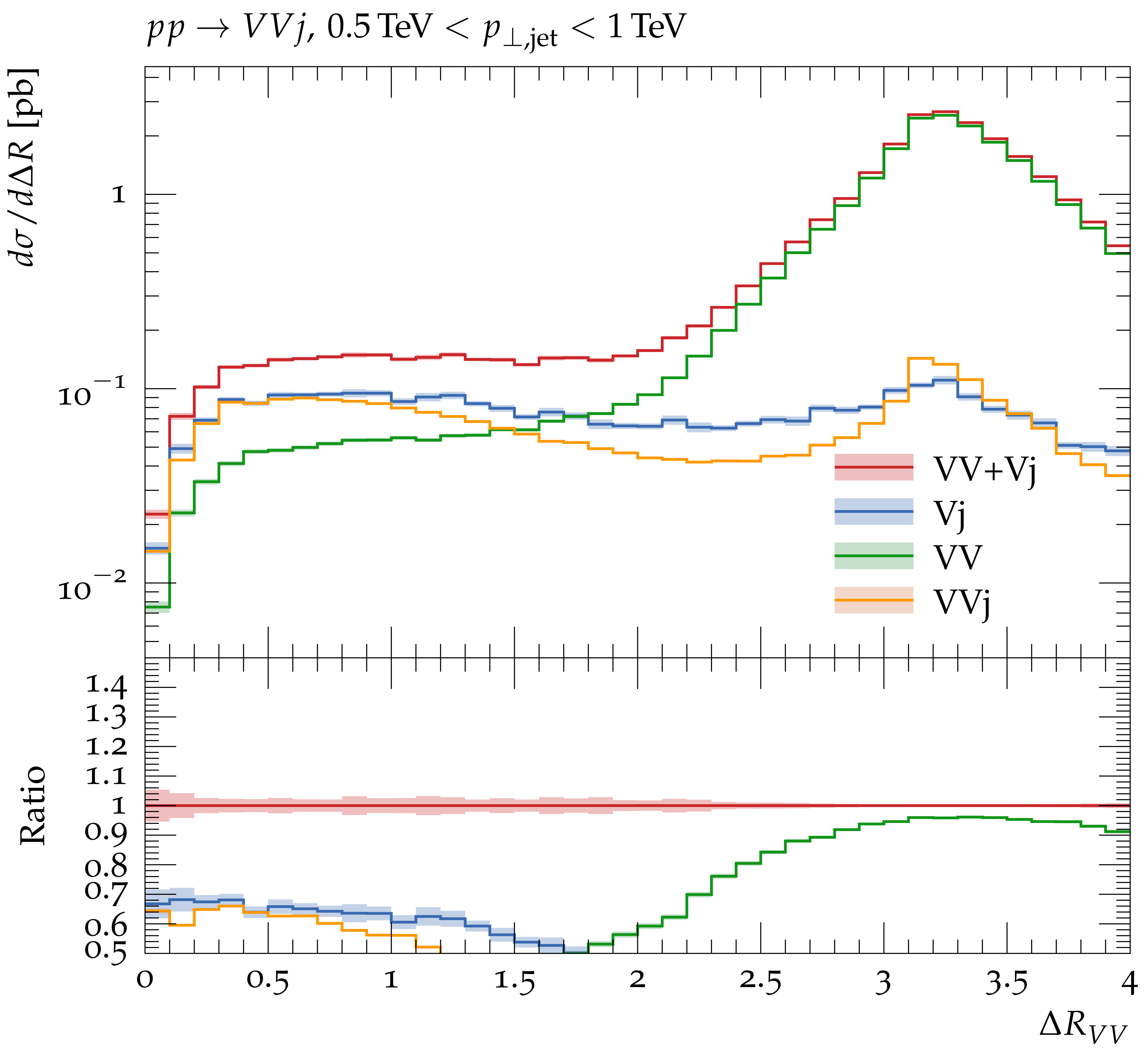
Last emission QCD? $\longrightarrow d_{ij}^{\text{Last}} < \min\left(d_{ij}^{\text{EW}}\right)$ → Accept Branching

Last emission EW? $\longrightarrow d_{ij}^{\text{Last}} < \min\left(d_{ij}^{\text{QCD}}\right)$ → Accept Branching

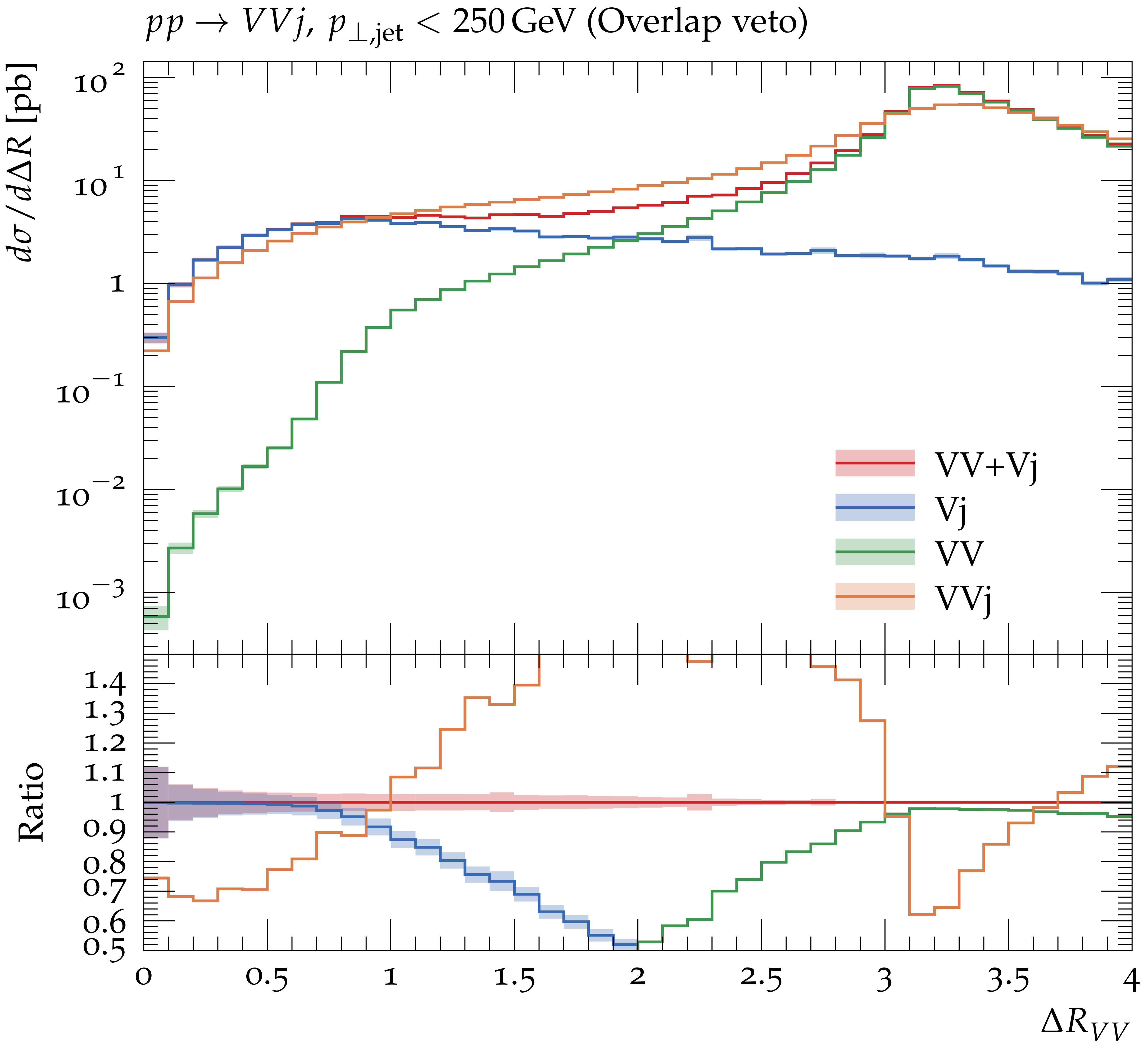
$$d_{ij} = \min\left(k_{T,i}^2, k_{T,j}^2\right)\frac{\Delta_{ij}}{R} + m_i^2 + m_j^2 - m^2$$

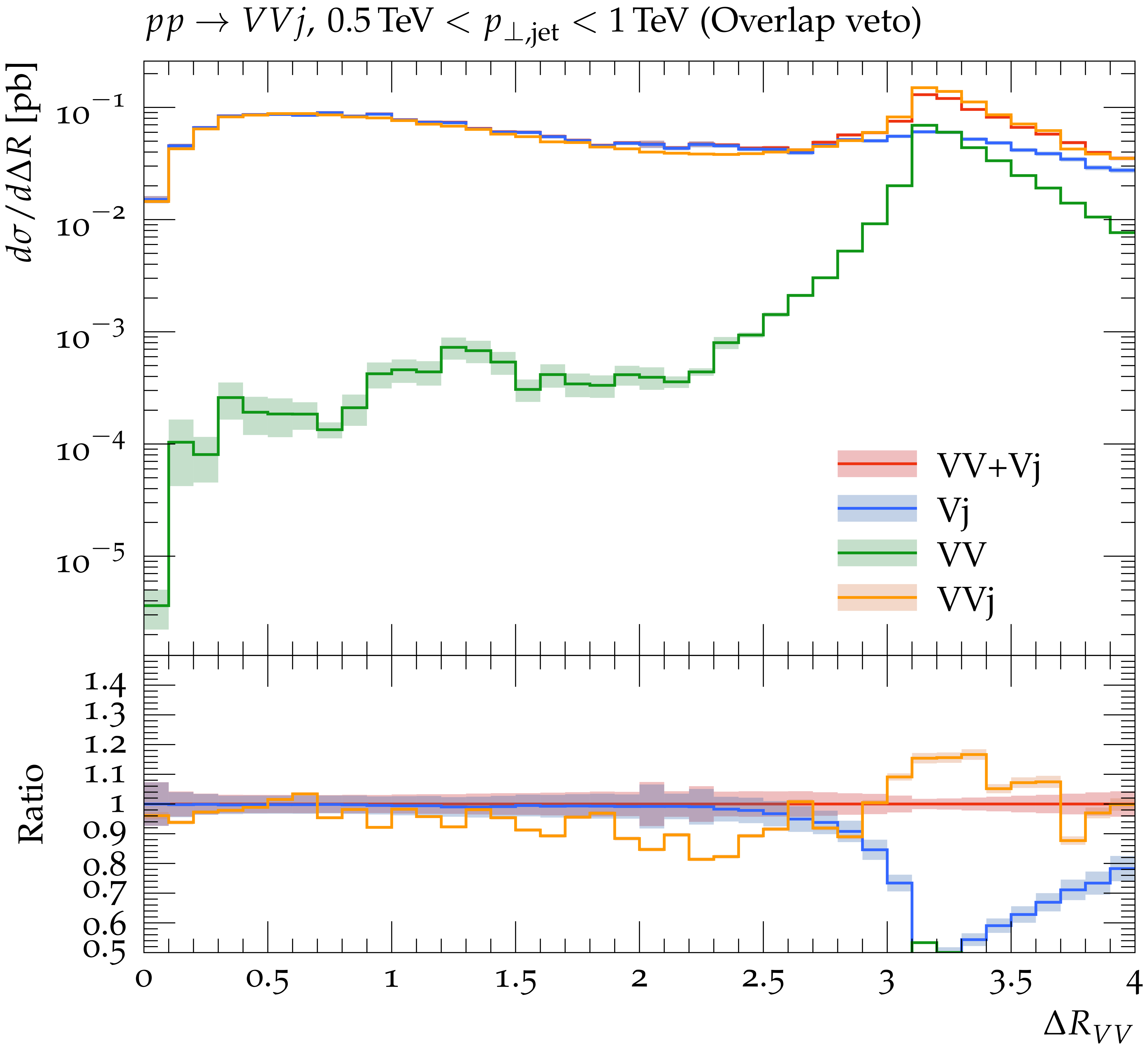
Overlap Veto





Overlap Veto



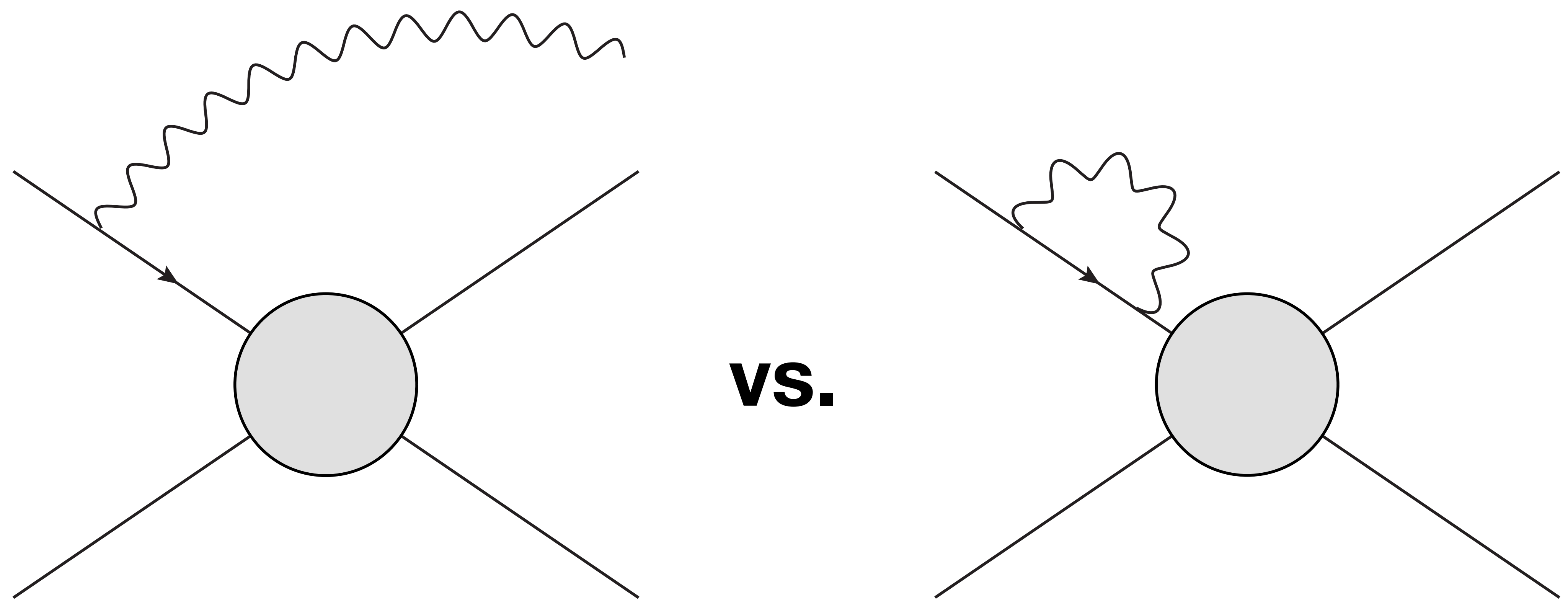


Bloch-Nordsieck Violations

BN / KLN Theorems: Real and virtual singularities cancel

Requirement: Summing over gauge indices

W radiation in the initial state:
PDFs are not isospin symmetric
$\longrightarrow$ Incomplete cancellation



Effects not large at LHC, but will be significant at higher energies

No straightforward solution in shower language

Conclusions

- Universal EW radiative corrections relevant at (HL)-LHC and future colliders
- EW sector offers rich physics, with lots of different collinear branchings
- Many features unique to the EW sector
  - Matching to resonance decays ✓
  - Neutral boson interference ✓
  - Overlap between hard scatterings ✓
  - Bloch-Nordsieck violations ✗
- EW shower will be publicly available as part of the Vincia shower
  Will be included in Pythia 8.3 out of the box

Backup

Spinor-Helicity formalism

Fermion

$$u_\pm(p) = \frac{1}{\sqrt{2p\cdot k}}(\not{p} + m)u_\mp(k)$$

$$v_\pm(p) = \frac{1}{\sqrt{2p\cdot k}}(\not{p} - m)u_\mp(k)$$

$k \longrightarrow$ helicity for massive fermions

Spin points in direction of motion

Gauge boson

$$\epsilon^\mu_\pm(p) = \pm\frac{1}{\sqrt{2}}\frac{1}{2p\cdot k}\bar{u}_\mp(k)\not{p}\gamma^\mu u_\pm(k)$$

$$\epsilon^\mu_0(p) = \frac{1}{m}\left(p^\mu - \frac{m^2}{p\cdot k}k^\mu\right)$$

$k \longrightarrow$ gauge choice

Purely transverse & longitudinal

$$k = (1, -\vec{e}_p)$$

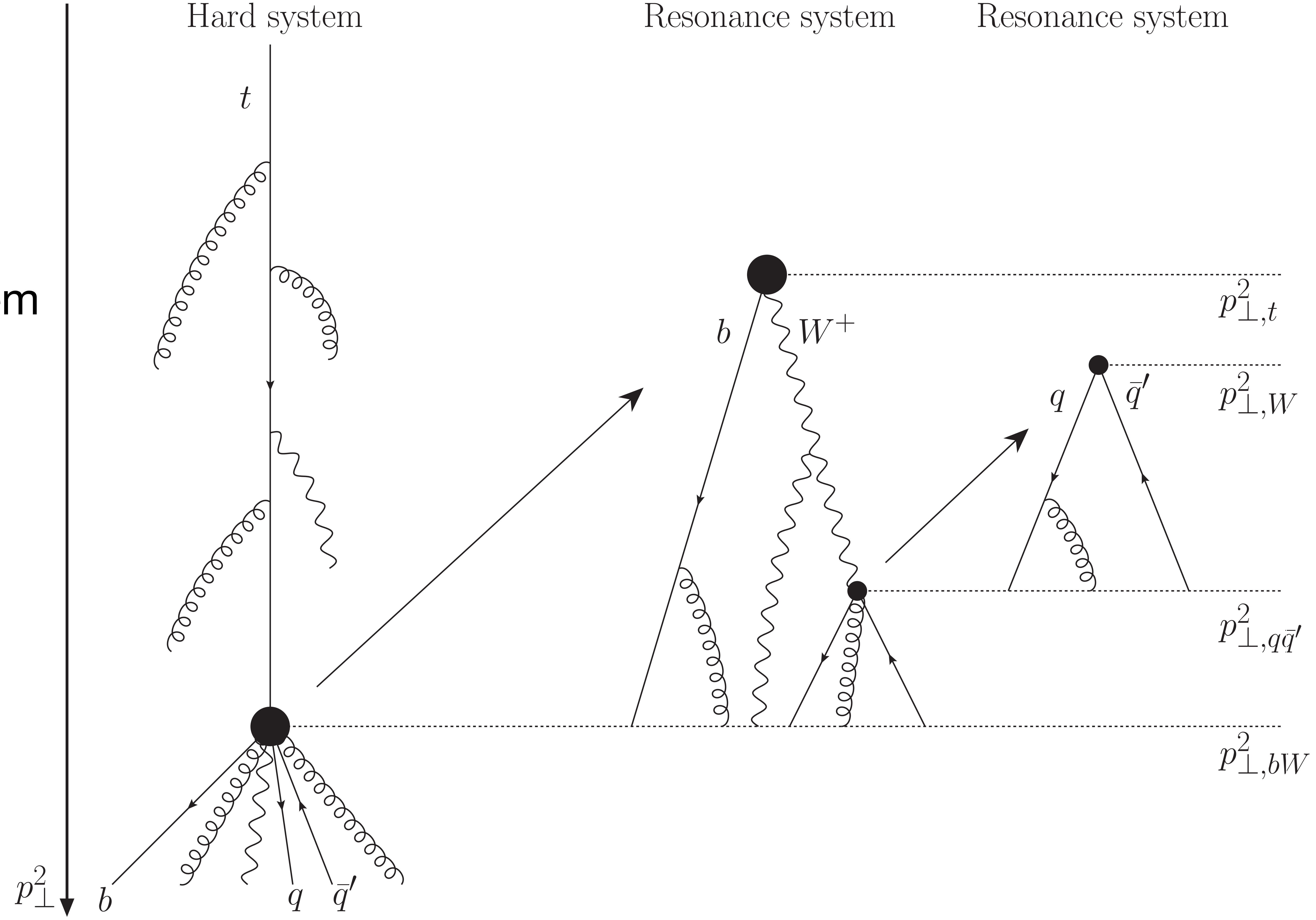
Resonance Matching

Pythia

- Narrow width approximation
- Decay showers after hard system

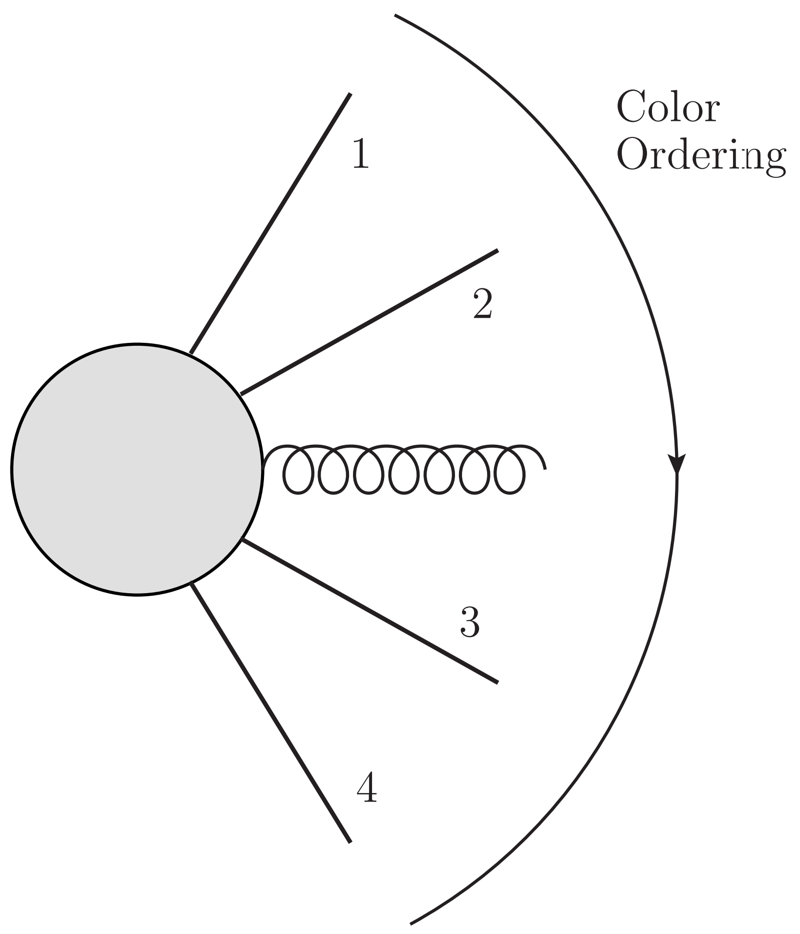
Vincia

- Decays part of hard system
- Natural treatment of finite width effects



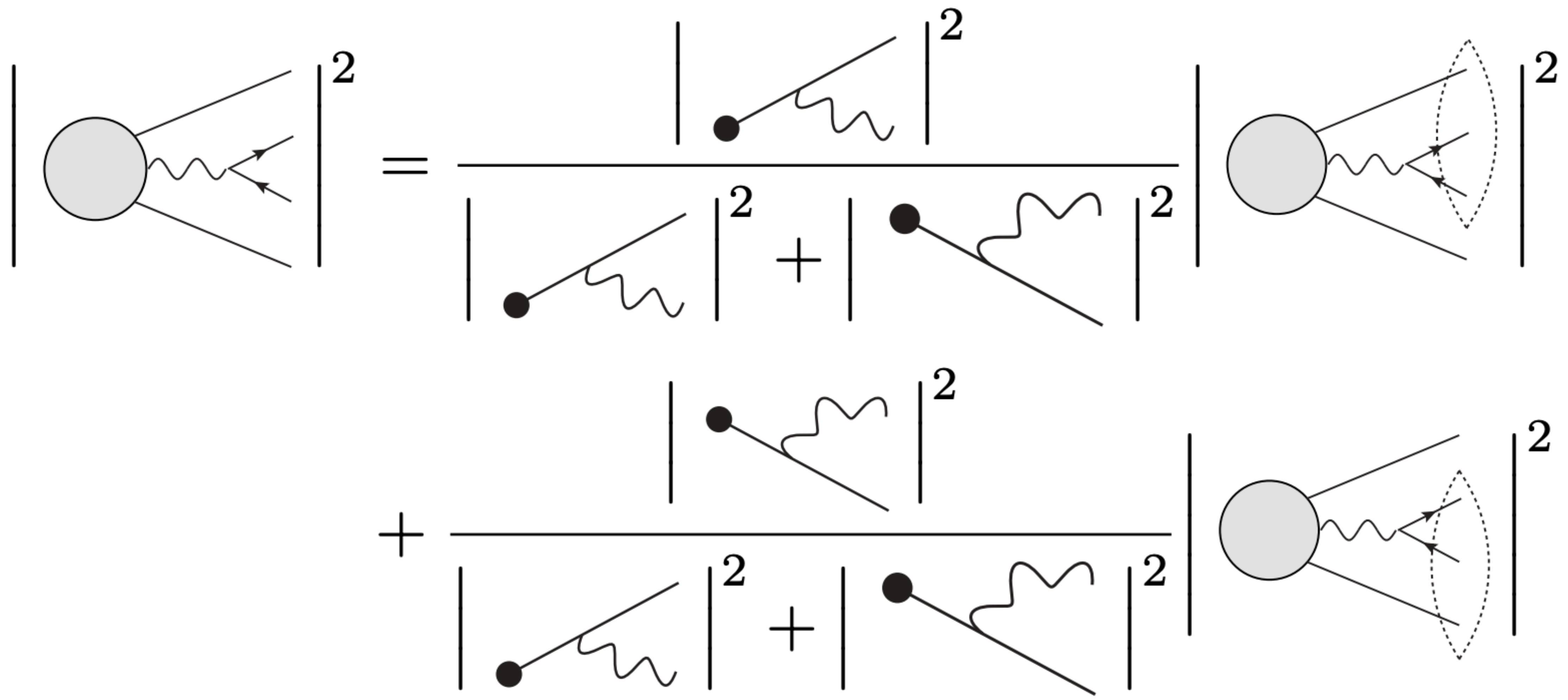
Recoiler Selection

In QCD recoiler determined by colour structure



Gluon splitting: recoiler ambiguous

In EW no such guidance exists



Probabilistic choice to avoid back reaction effects