Event Generation at Future Colliders: EW Corrections in Parton Showers

Rob Verheyen

Monte Carlo Challenges

Computational Challenges

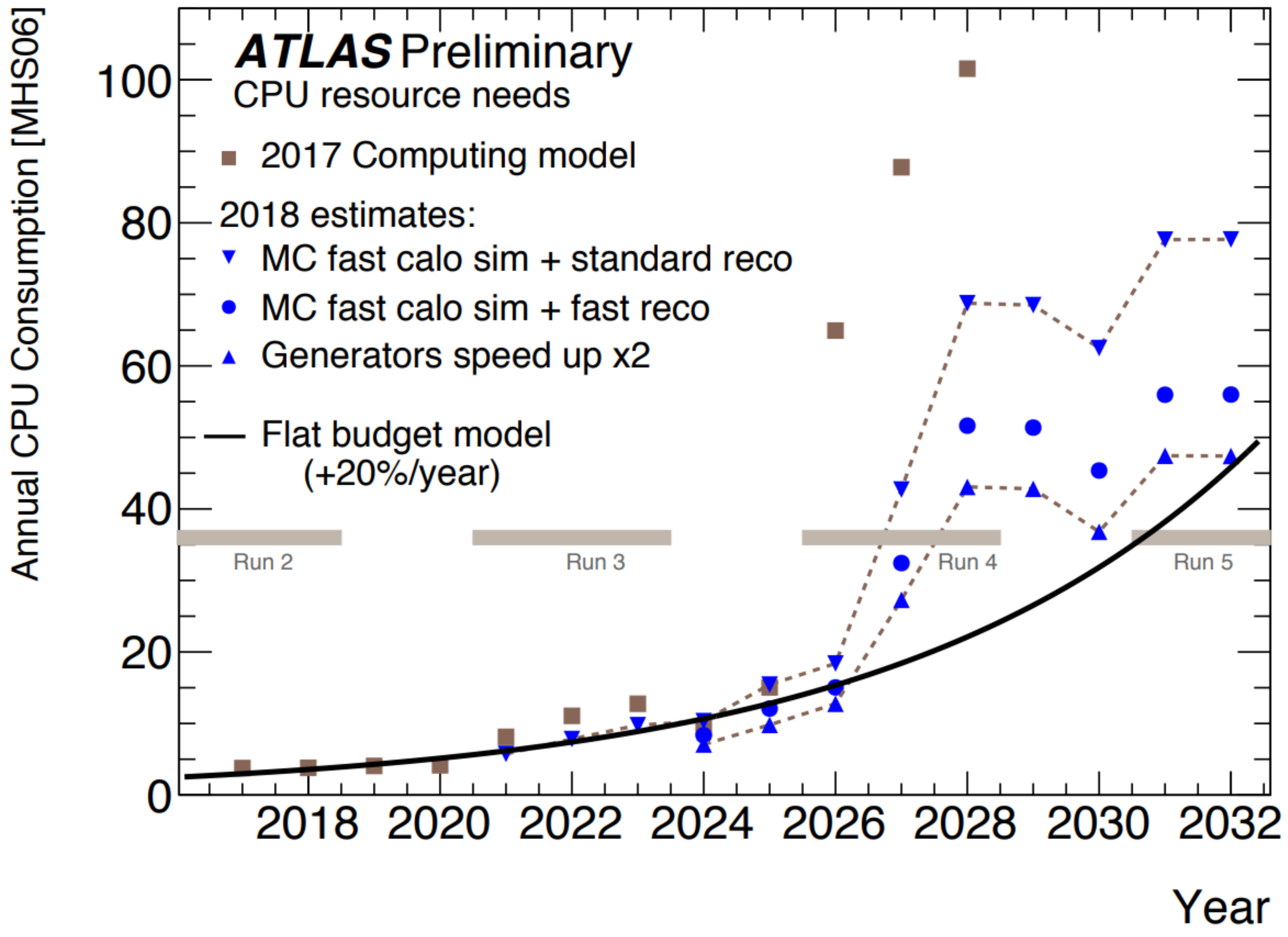
State of the art is now NLO/LO multileg merging

⟶ 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

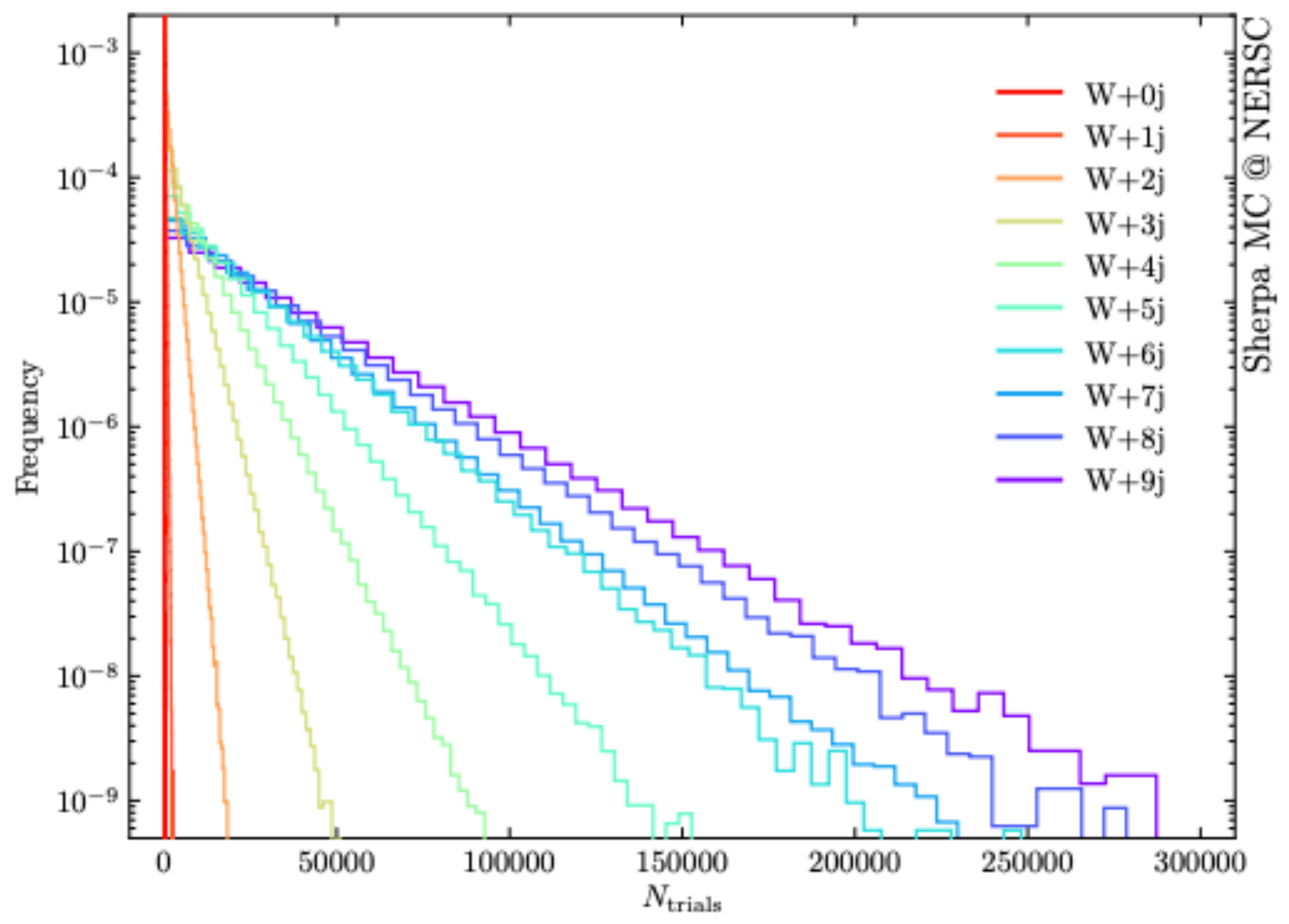


Matrix Element Sampling

Often still reliant on VEGAS + multi channeling

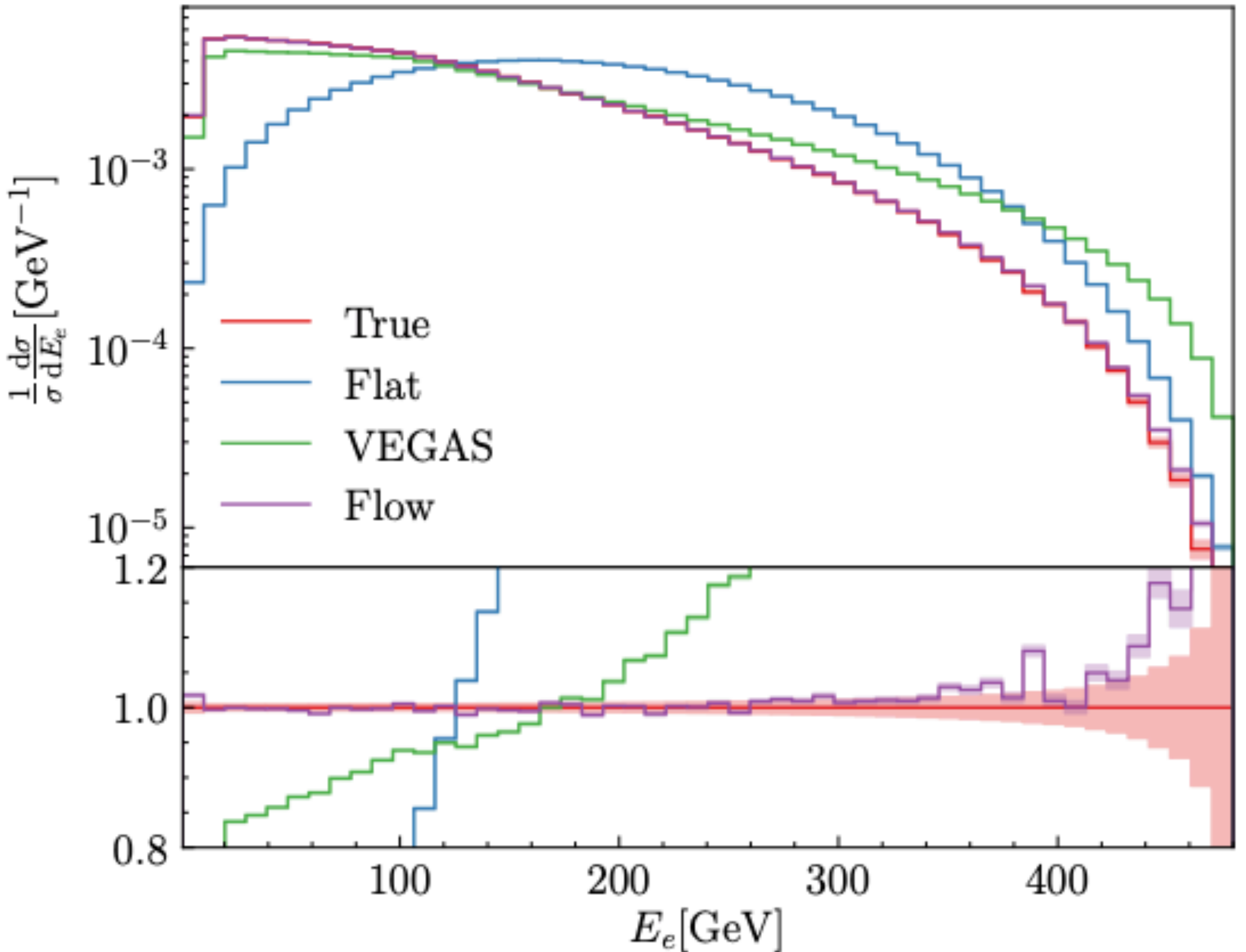
⟶ Many case-specific algorithms exist (FOAM, HAAG)

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



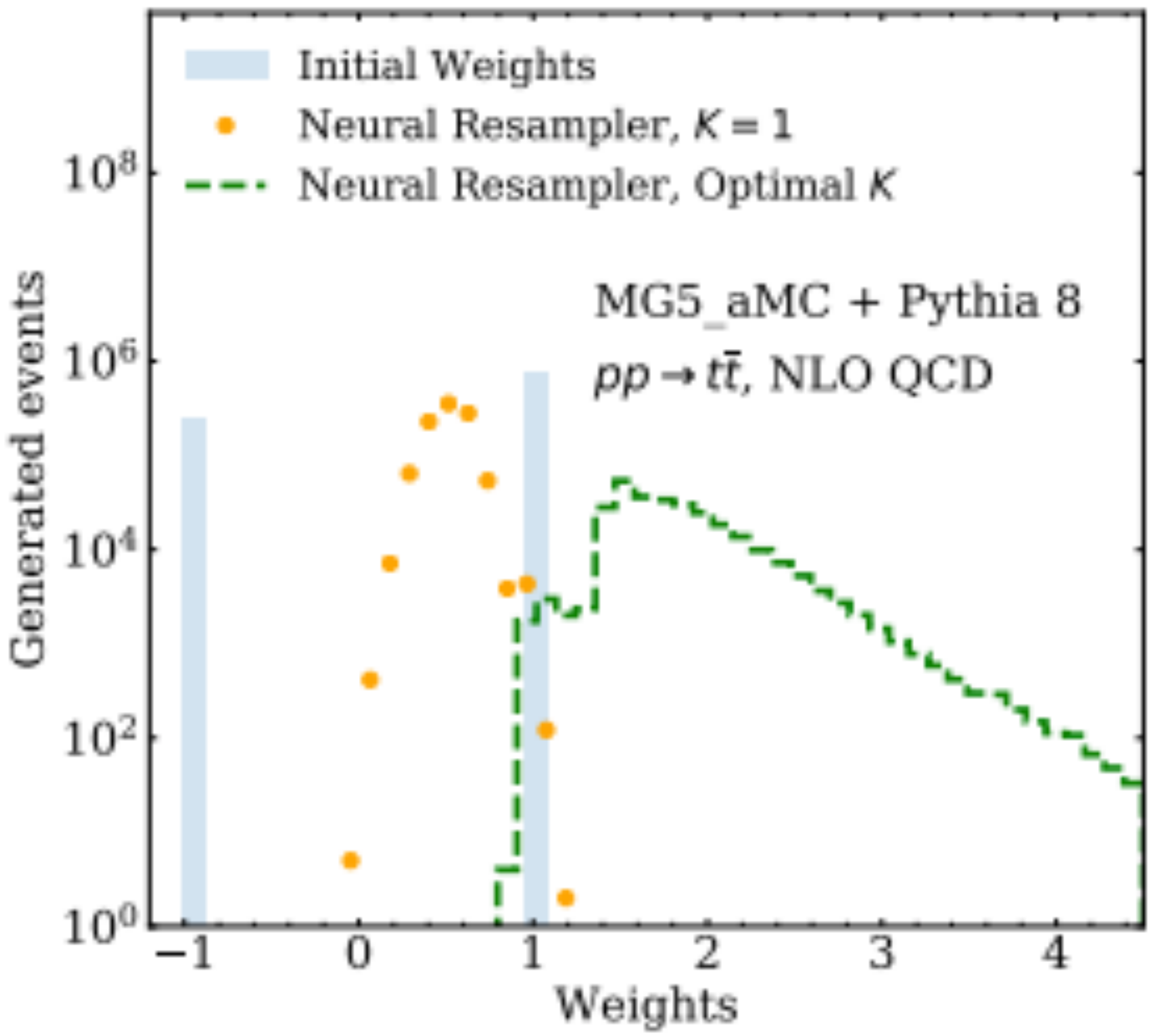
Negative Weights

NLO corrections often lead to negative weights

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

Several improvements being explored

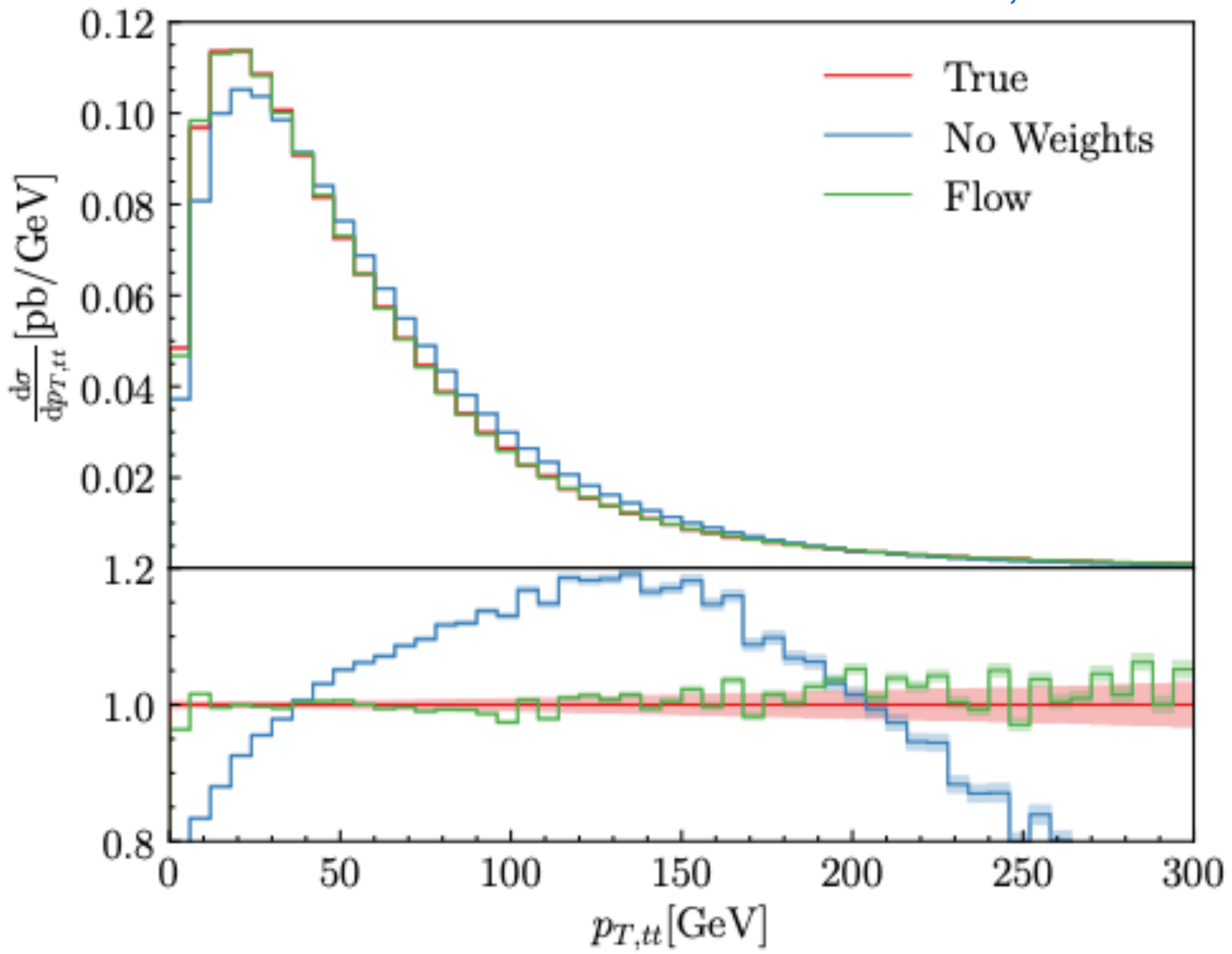
- Resampling — Andersen, Gutschow, Maier, Prestel 2005.09375; Nachman, Thaler 2007.11586



- 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



One-Slide Parton Shower Summary

Process-independent, fully differential resummation framework

Incorporates logarithms associated with soft and collinear branchings

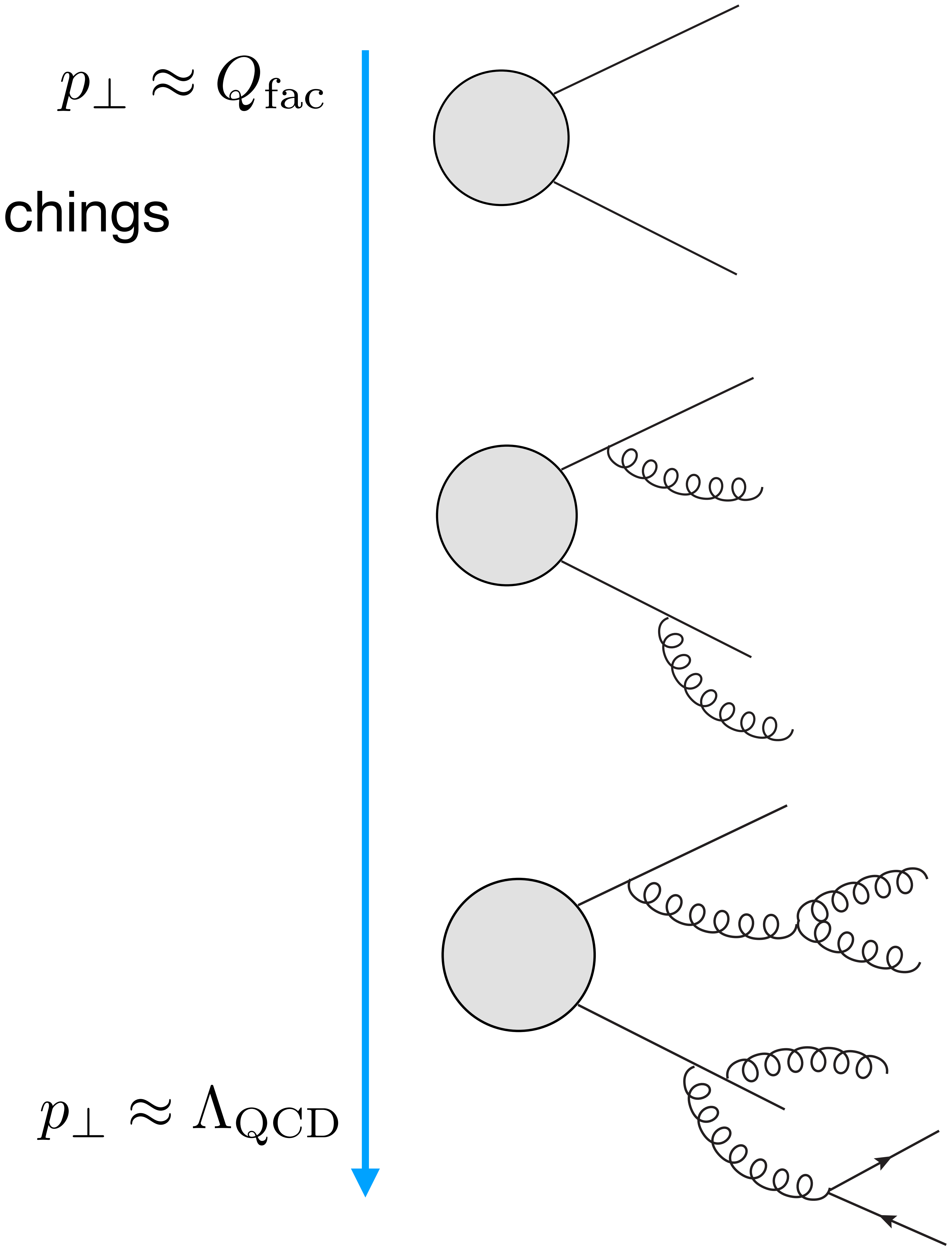
Repeatedly sample emissions from:

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)

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



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

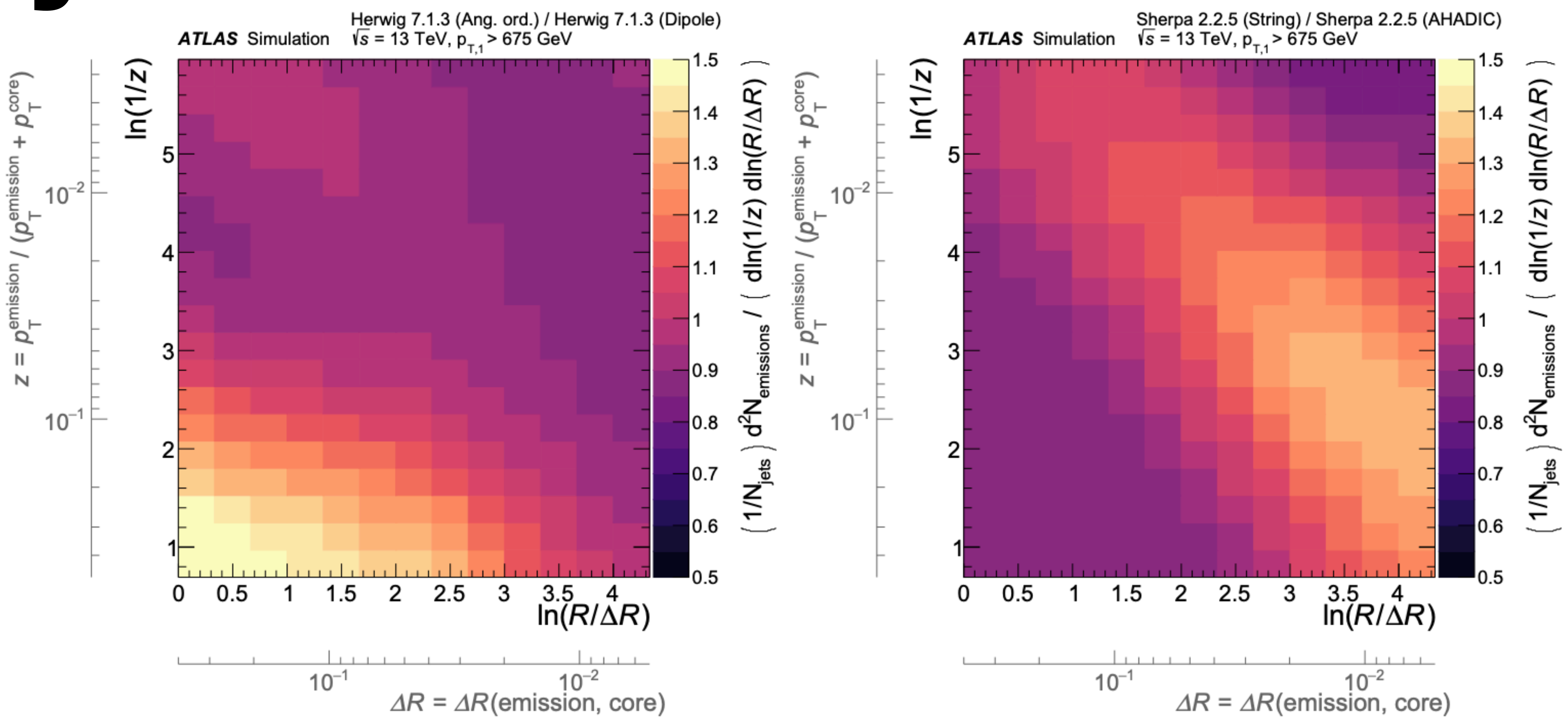
- Electroweak corrections $\alpha/\alpha_s \sim 10\%$

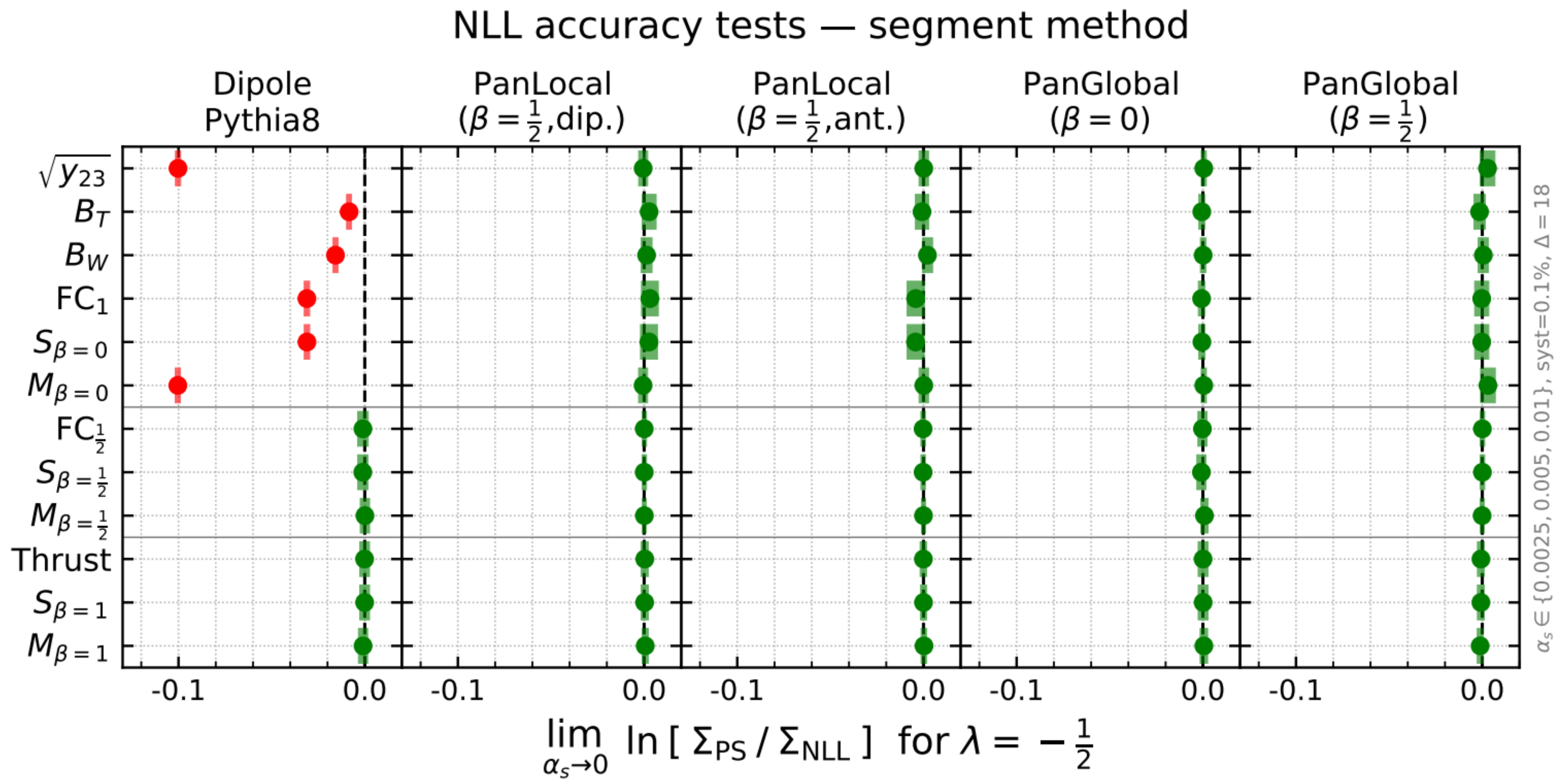
  Christiansen, Sjostrand arXiv:1401.5238

  Krauss, Petrov, Schoenherr, Spannowsky arXiv:1403.4788

  Chen, Han, Tweedie arXiv:1611.00788

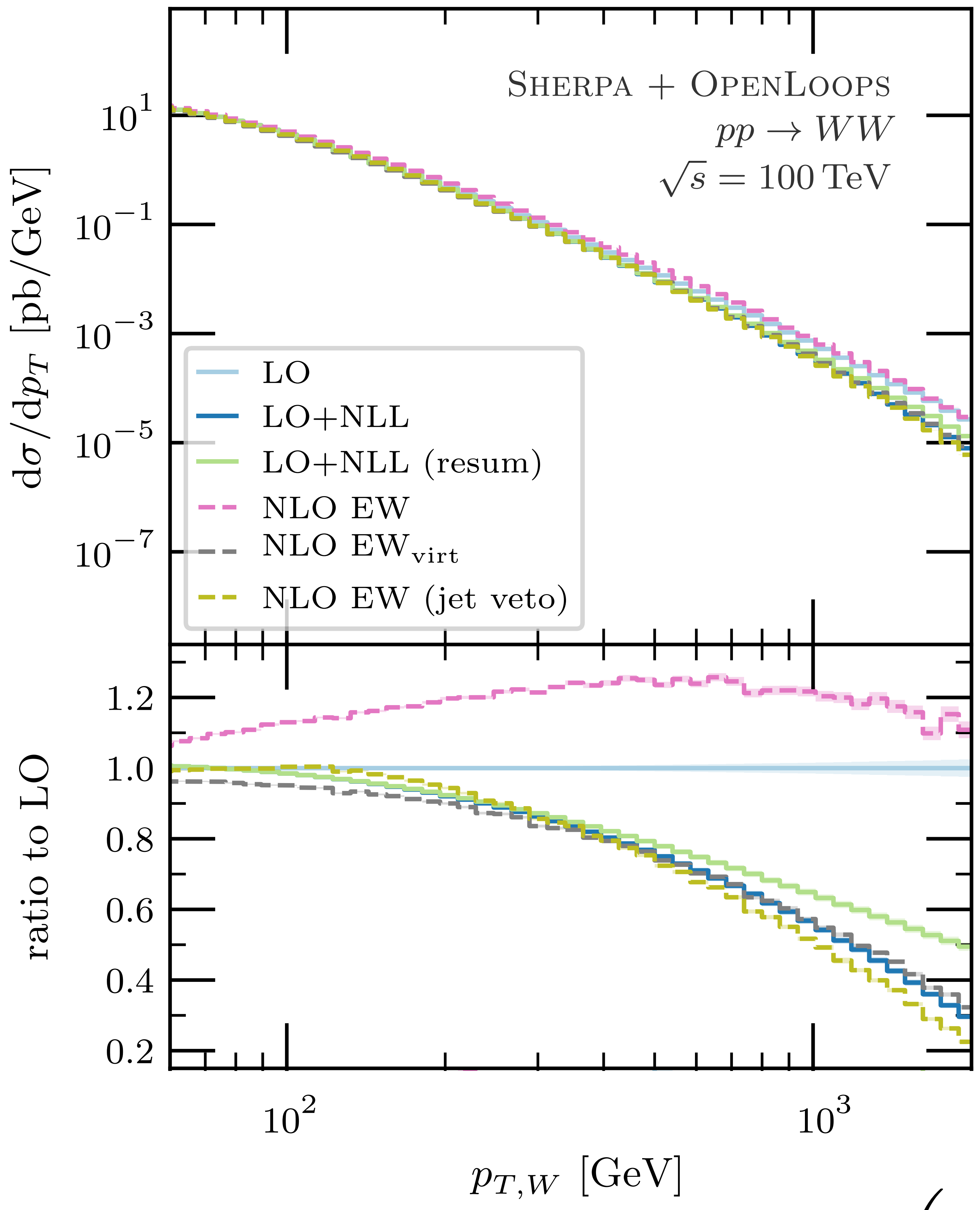
  Kleiss, RV 2002.09248





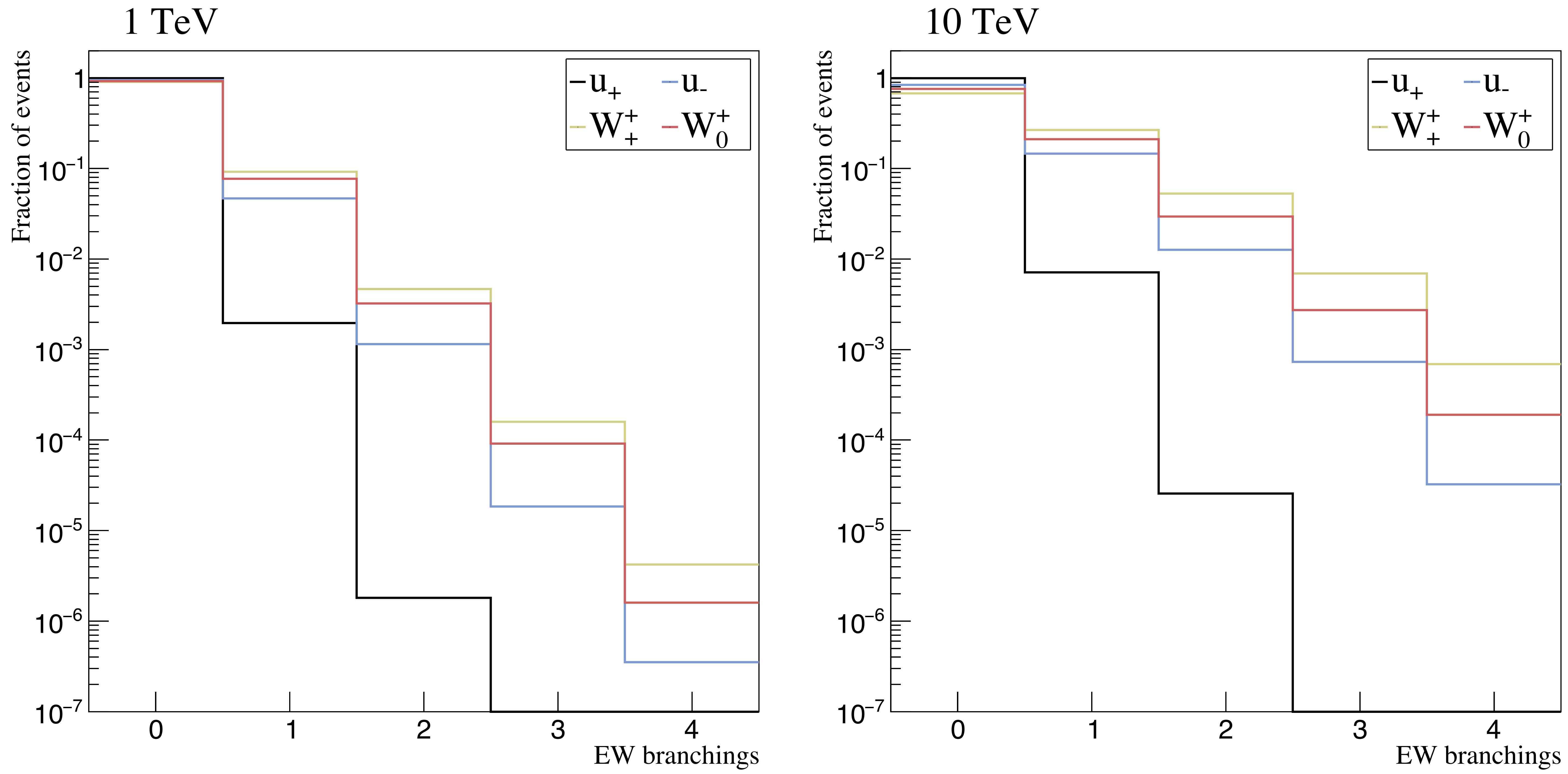
Electroweak Showers in Vincia

Why EW Showers?



Universal incorporation of EW virtual corrections $\propto \log\left(\frac{\hat{s}}{Q^2_{\mathrm{EW}}}\right)$

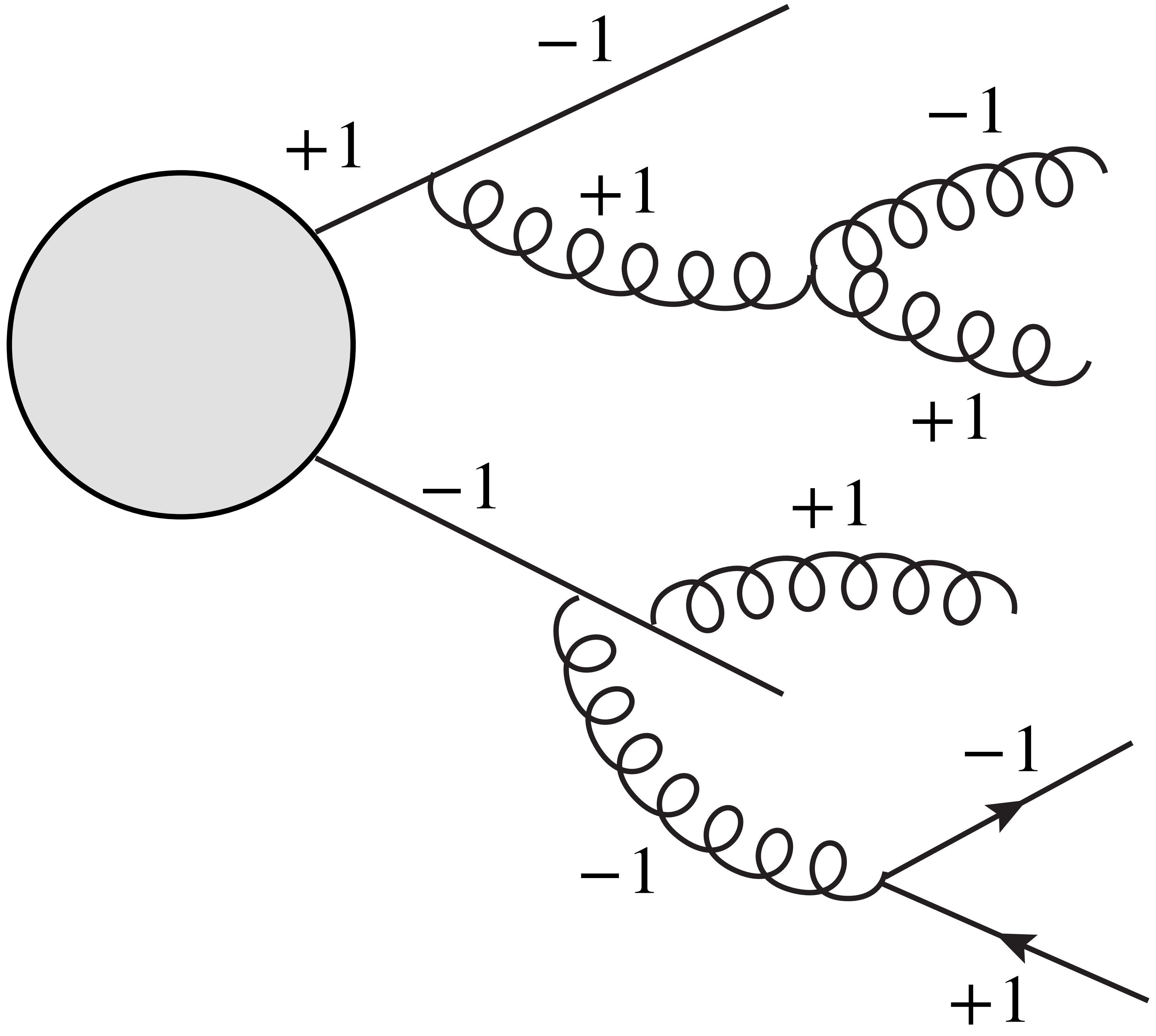
Bothmann, Napoletano 2006.14635
Many other papers



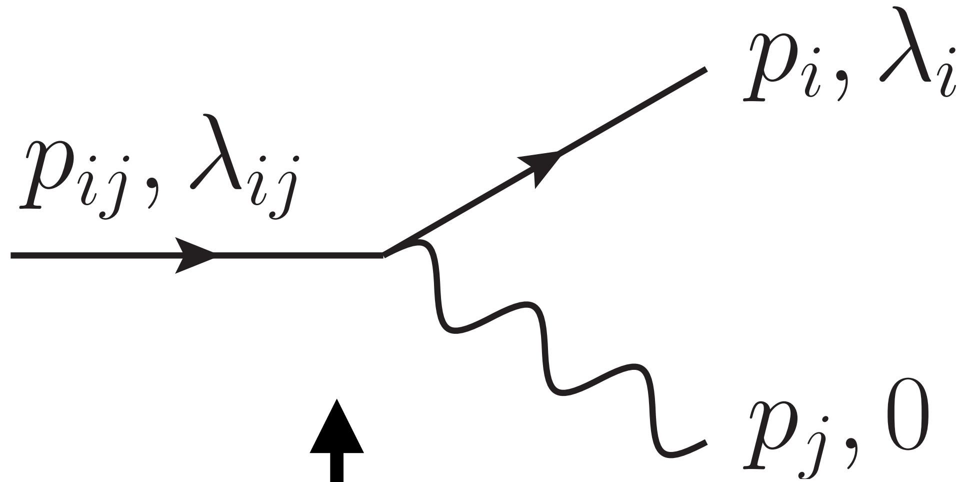
EW gauge bosons, top, Higgs part of jets

Unique Features of the EW Sector

- Chiral nature of the EW theory → helicity showers
- Consequences of EW symmetry breaking
- Shower vs. Resonance decays
- Neutral boson interference
- Double-counting Borns
- Bloch-Nordsieck violations



EW Symmetry Breaking & Goldstone Bosons

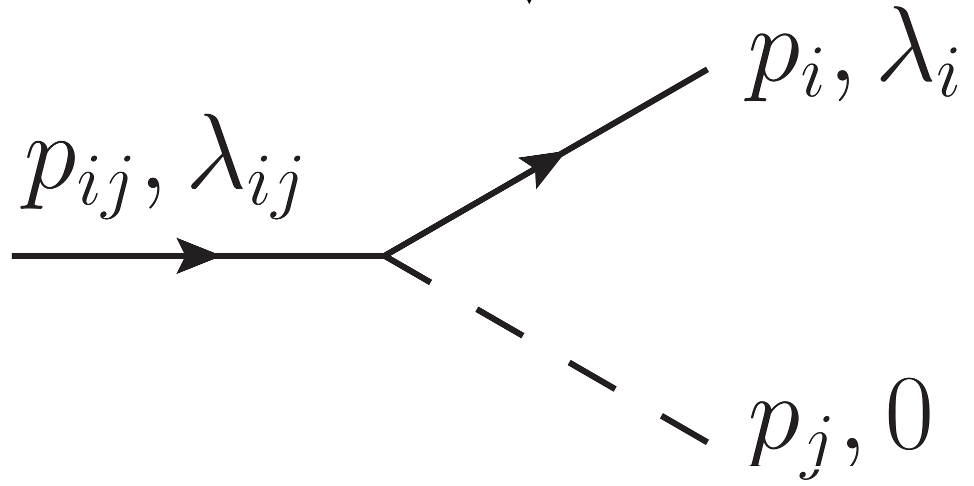


Naïve calculation of branching kernels

→ Unitarity violation

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

Consequence of gauge-dependence



Goldstone piece actually couples to Yukawa

Possible to solve with Goldstone equivalence and suitable gauge choice

Branching Kernels

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_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	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	$\frac{1}{2}\frac{m_{ij}^3}{m_i m_j}(2z-1)-\frac{m_i^3}{m_{ij}m_j}\left(\frac{1}{2}+\frac{1-z}{z}\right)+\frac{m_j^3}{m_{ij}m_i}\left(\frac{1}{2}+\frac{z}{1-z}\right)+\frac{m_i m_j}{m_{ij}}\left(\frac{1-z}{z}-\frac{z}{1-z}\right)+\frac{m_{ij}m_i}{m_j}(1-z)\left(2+\frac{1-z}{z}\right)-\frac{m_{ij}m_j}{m_i}z\left(2+\frac{z}{1-z}\right)$

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

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

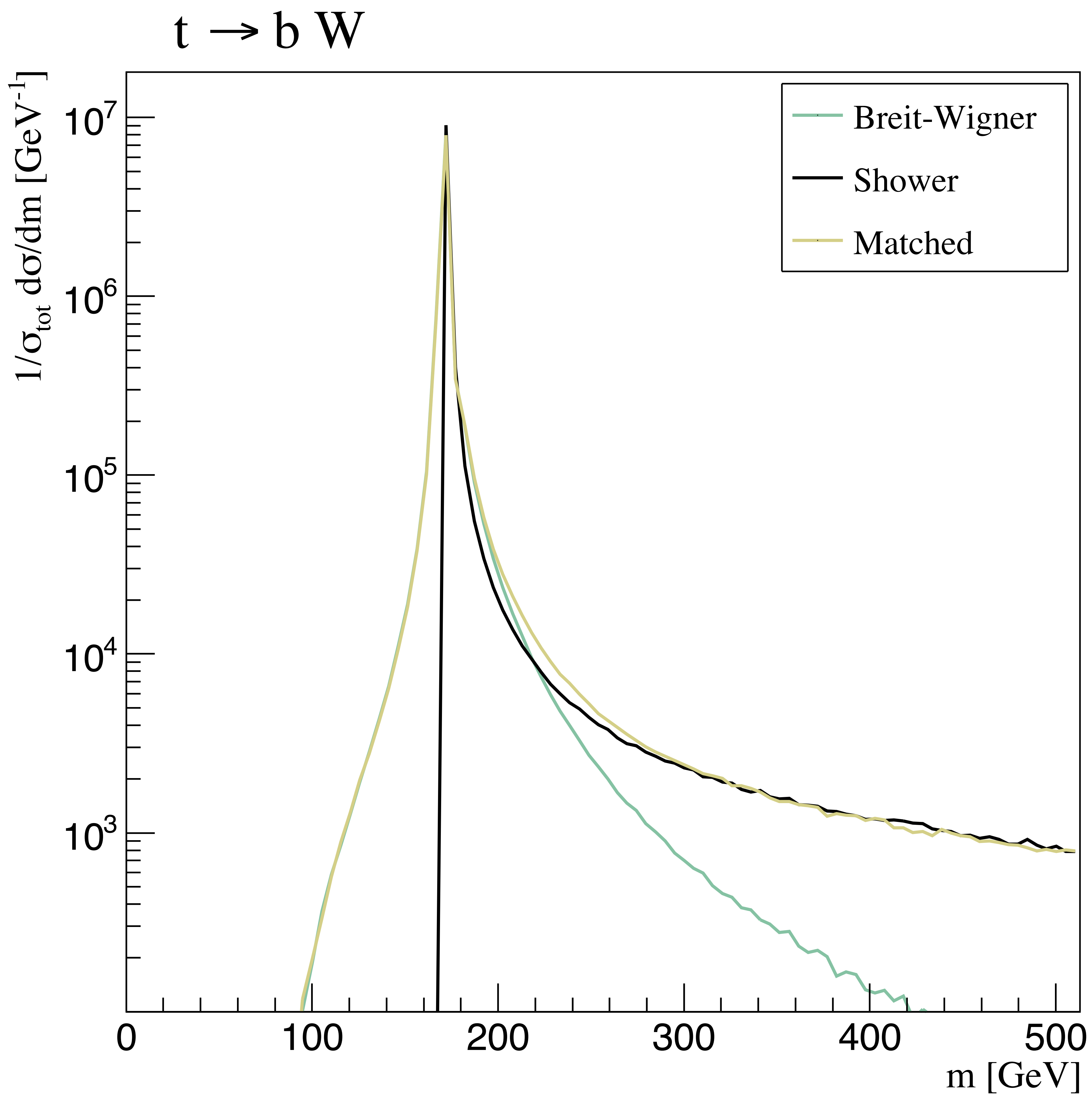
$$\mathrm{BW}(Q^2) \propto \frac{m_0 \Gamma(m)}{Q^4 + m_0^2 \Gamma(m)^2}$$

Matching:

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

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

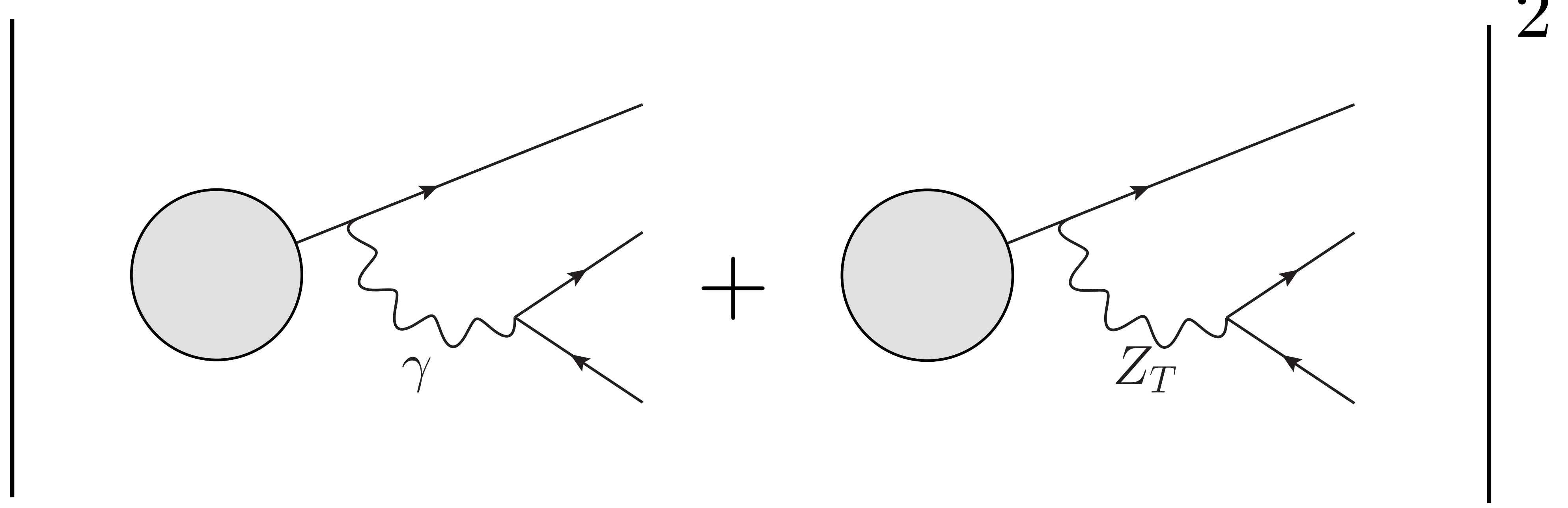
- Decay when shower hits off-shellness scale



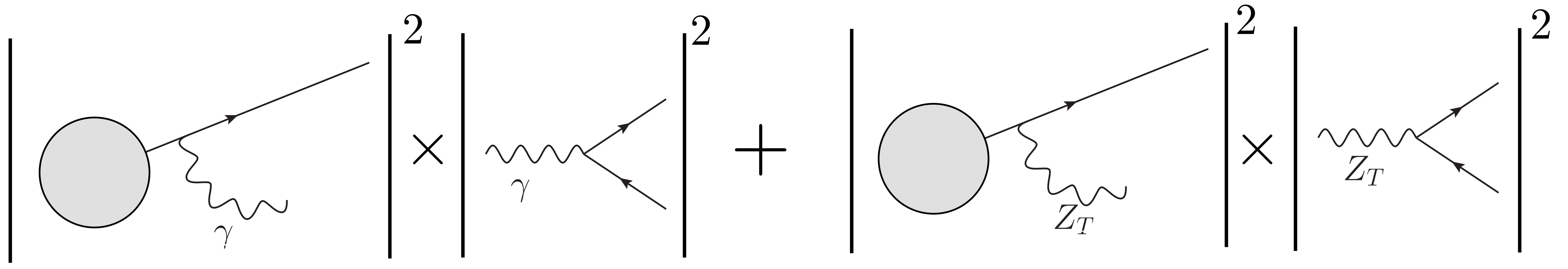
Neutral Boson Interference

Interference between γ, Z_T and h, Z_L

Physical contribution

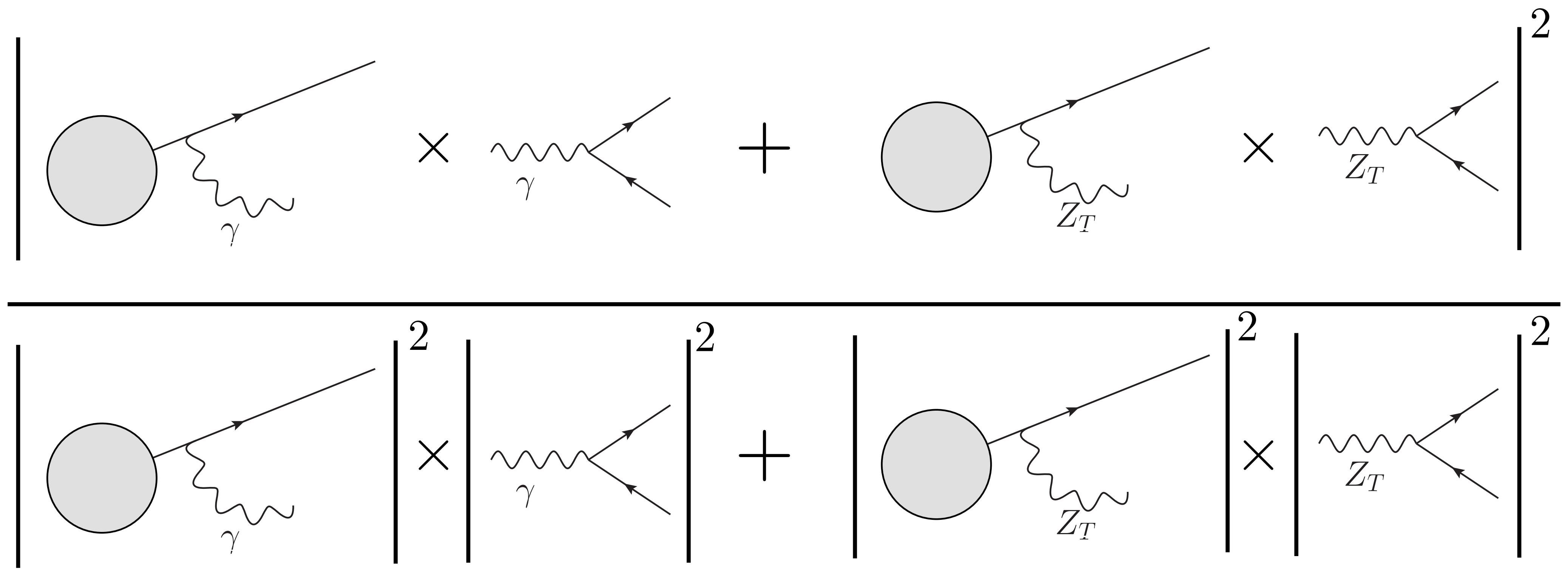


Shower approximation

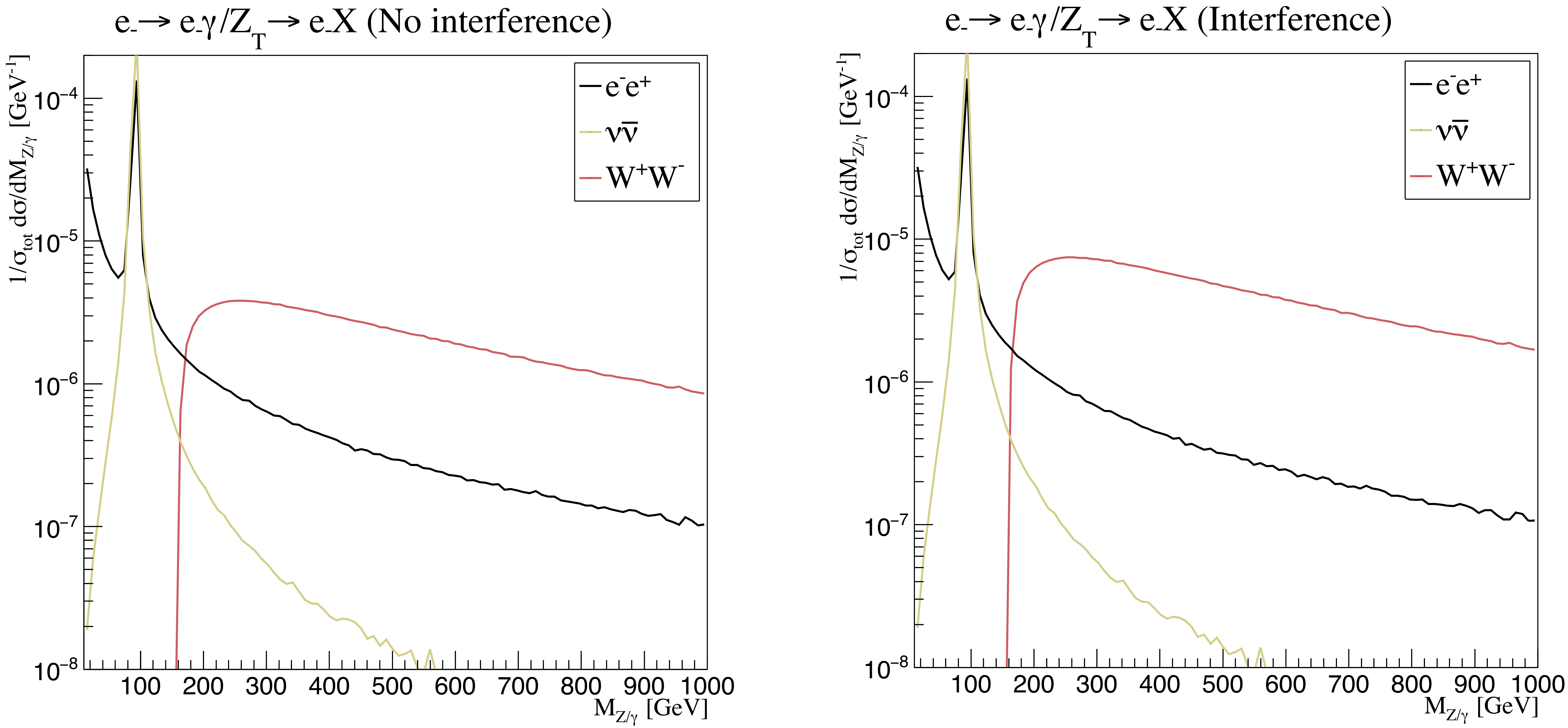


- Complicated solution: Evolve density matrices
  $\longrightarrow$ Very computationally expensive

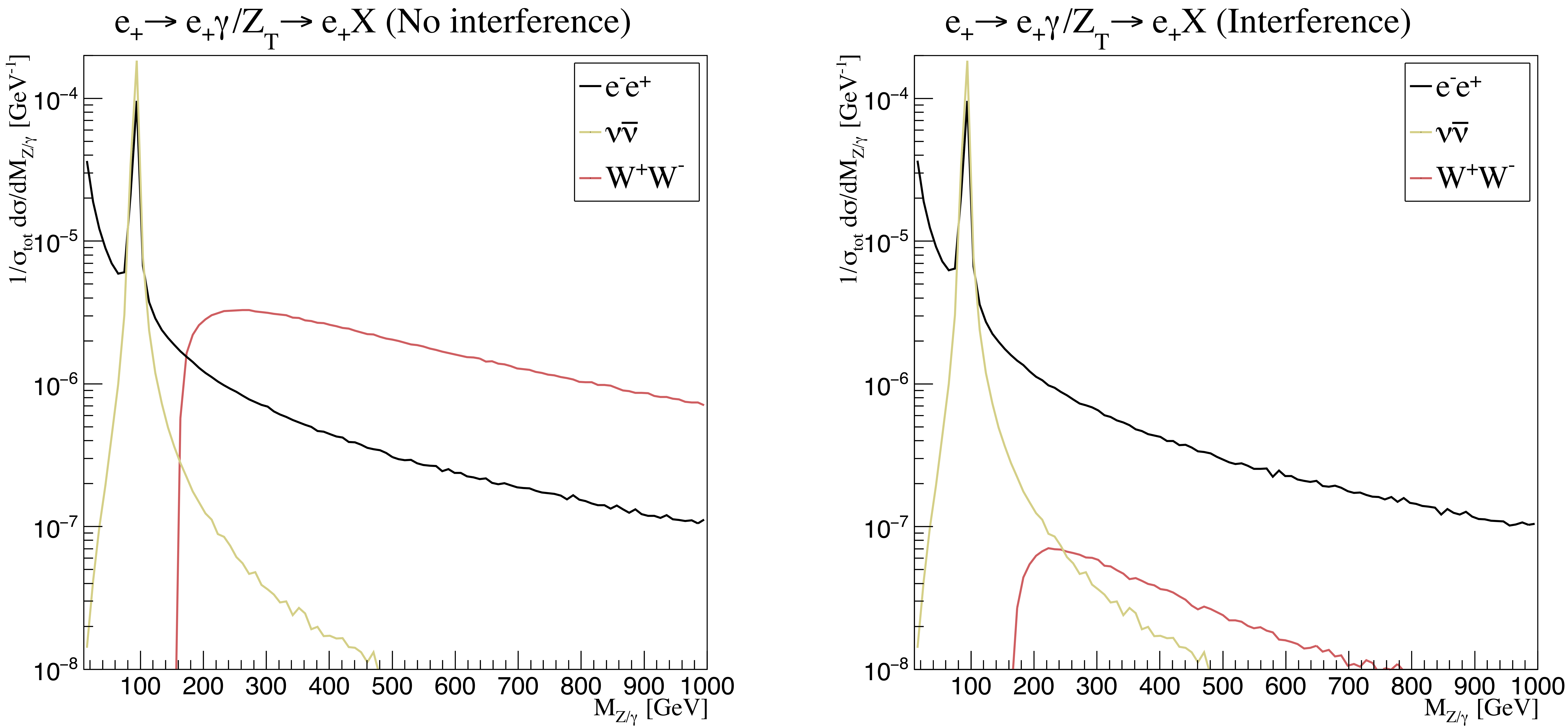
- Simple solution: Apply event weight
  $\longrightarrow$ Does not get Sudakov right

$w =$ 

Bosonic Interference

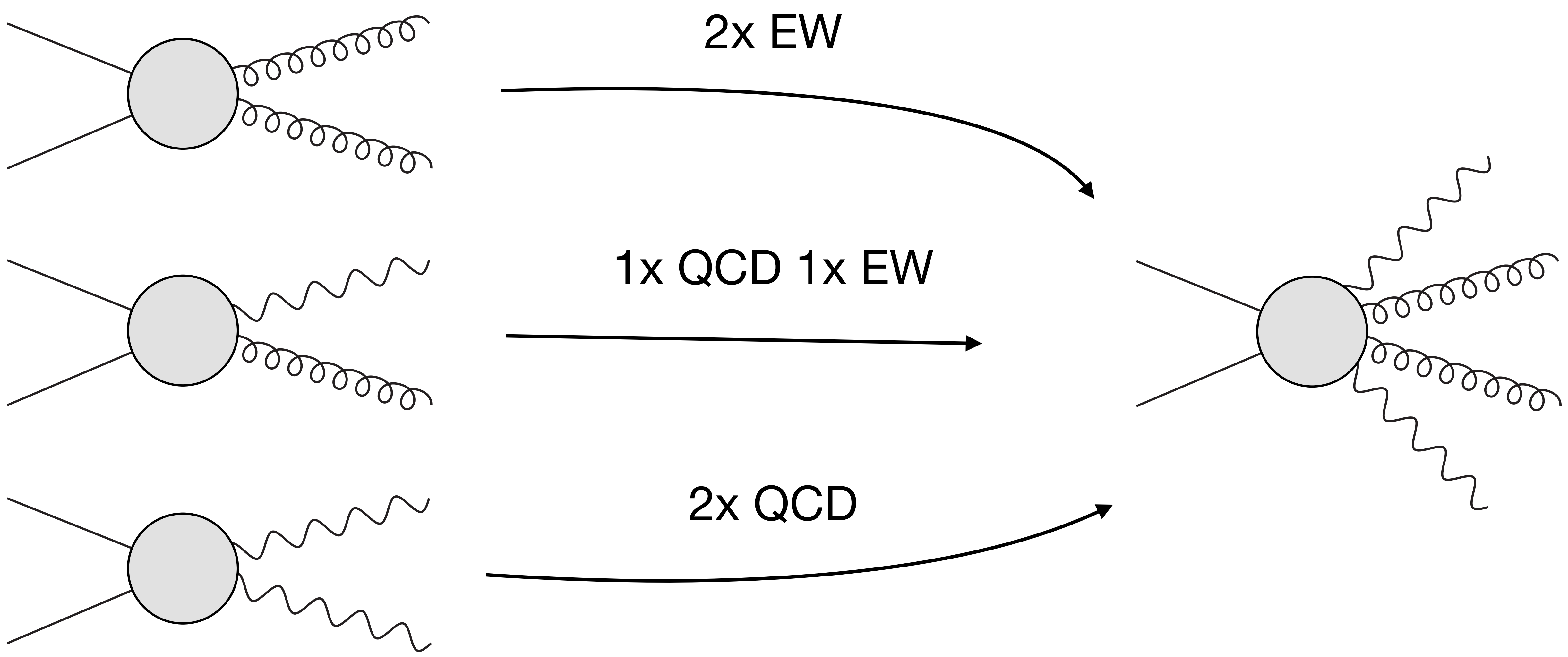


Bosonic Interference

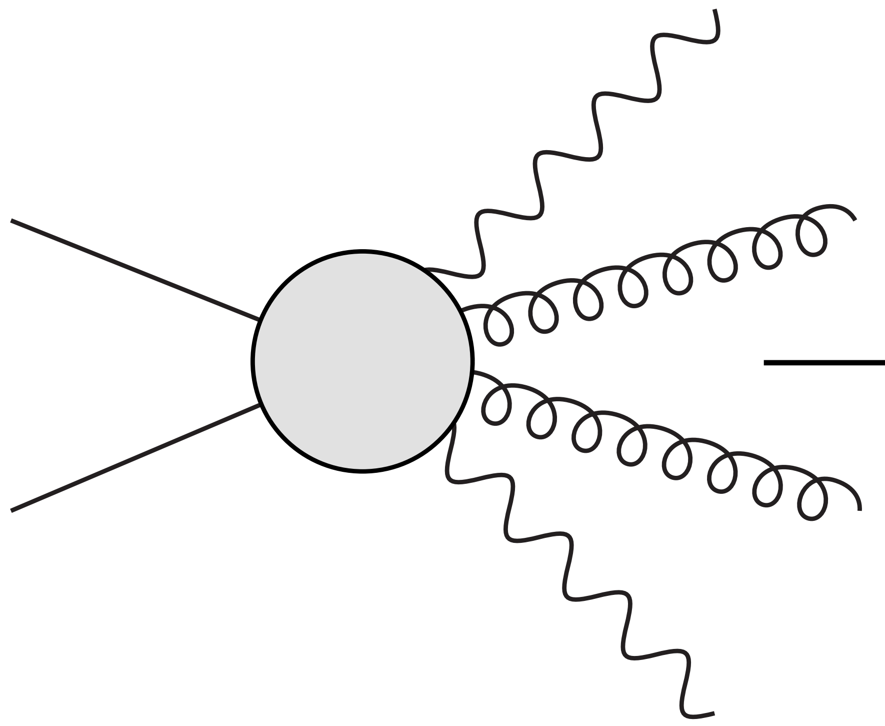


Overlap Veto

Double counting problem



Veto procedure

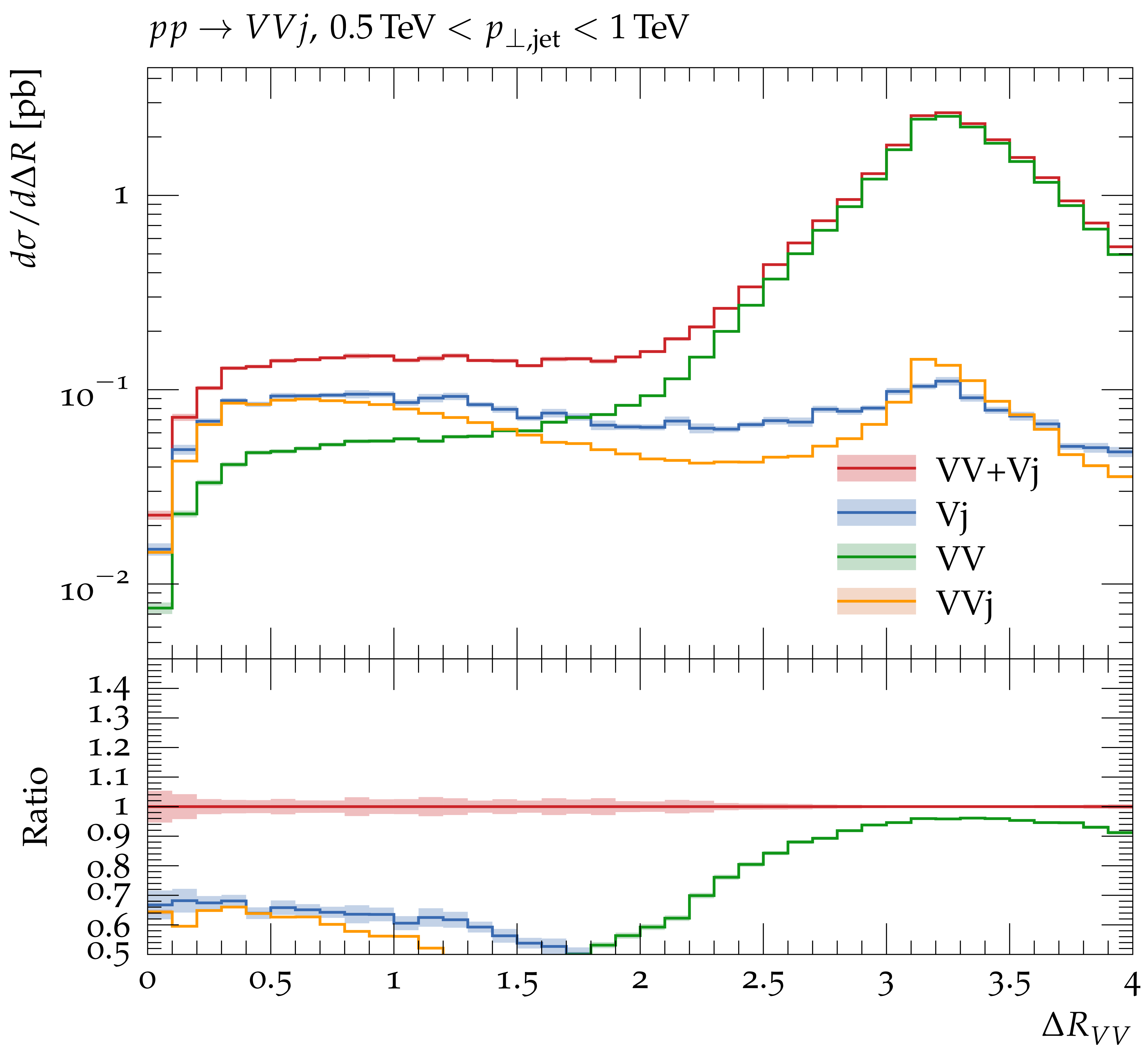


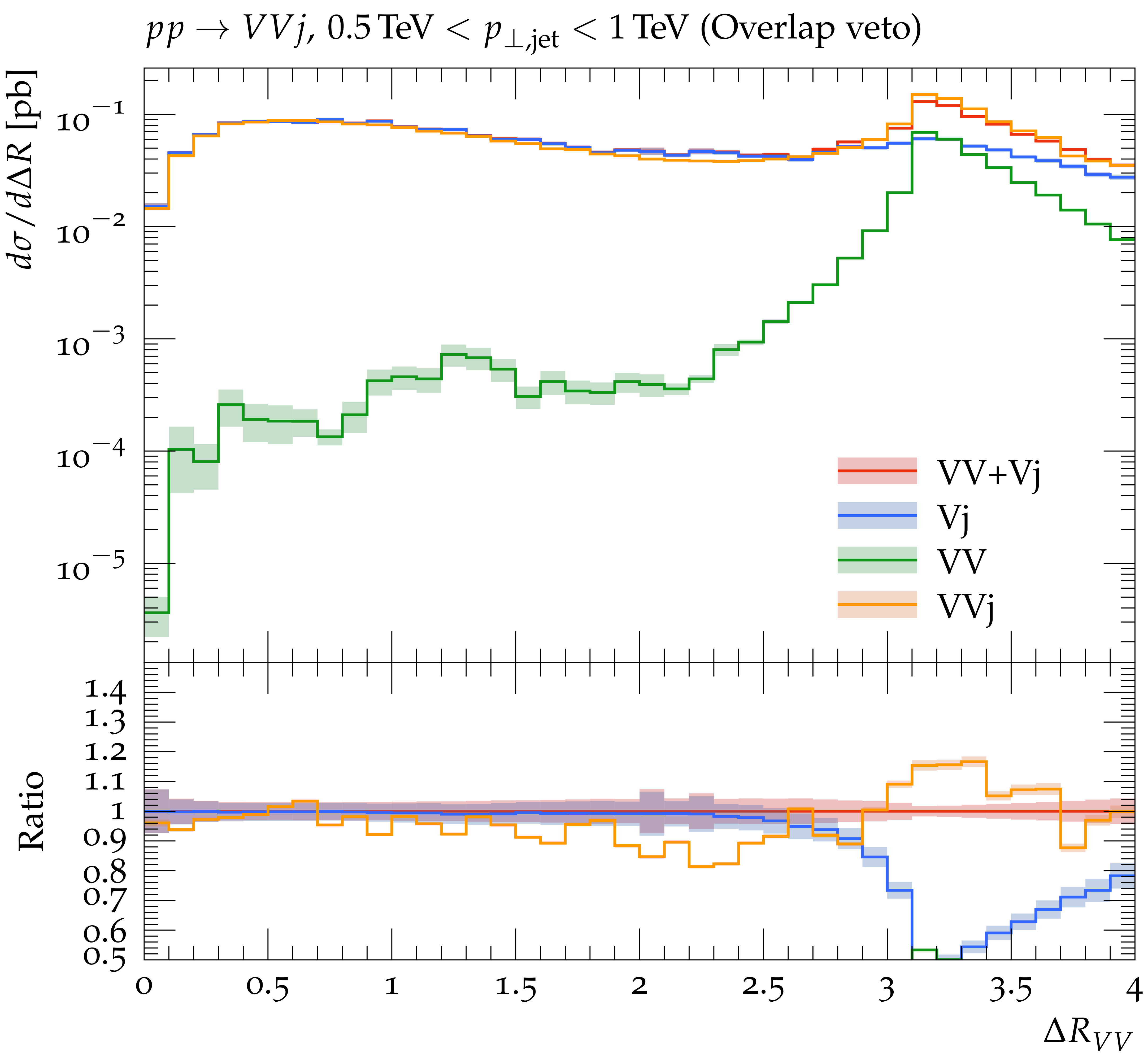
Last emission QCD? $\longrightarrow$ $d_{ij}^{\text{Last}} < \min\left(d_{ij}^{\text{EW}}\right)$ → Accept Branching

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



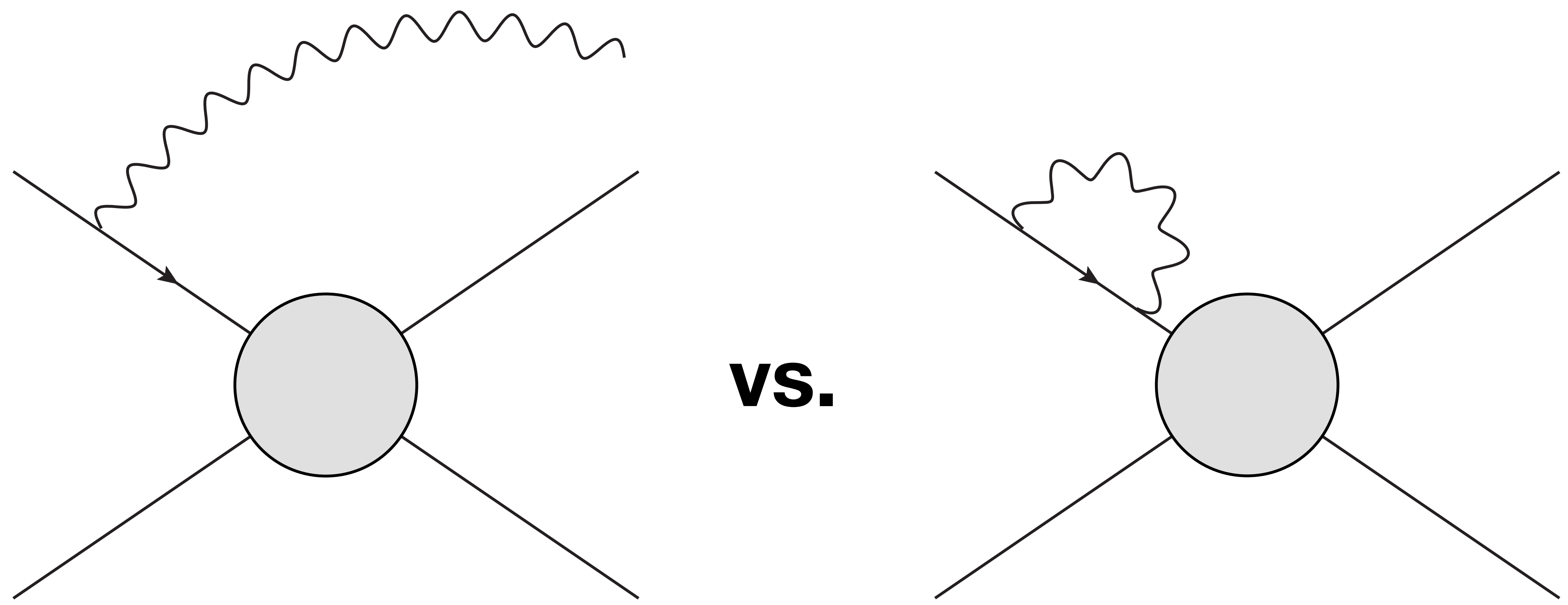


Bloch-Nordsieck Violations

BN / KLN Theorems: Real and virtual singularities cancel

Requirement: Summing over gauge indices

W radiation from 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

Many interesting challenges for the development of event generators

Electroweak corrections in parton showers come with unique challenges

- Chiral nature of the EW theory ✓
- Consequences of EW symmetry breaking ✓
- Shower vs. Resonance decays !
- Neutral boson interference !
- Double-counting Borns ✓
- Bloch-Nordsieck violations ✗

EW shower will be publicly available as part of Vincia in the upcoming Pythia 8.304 release

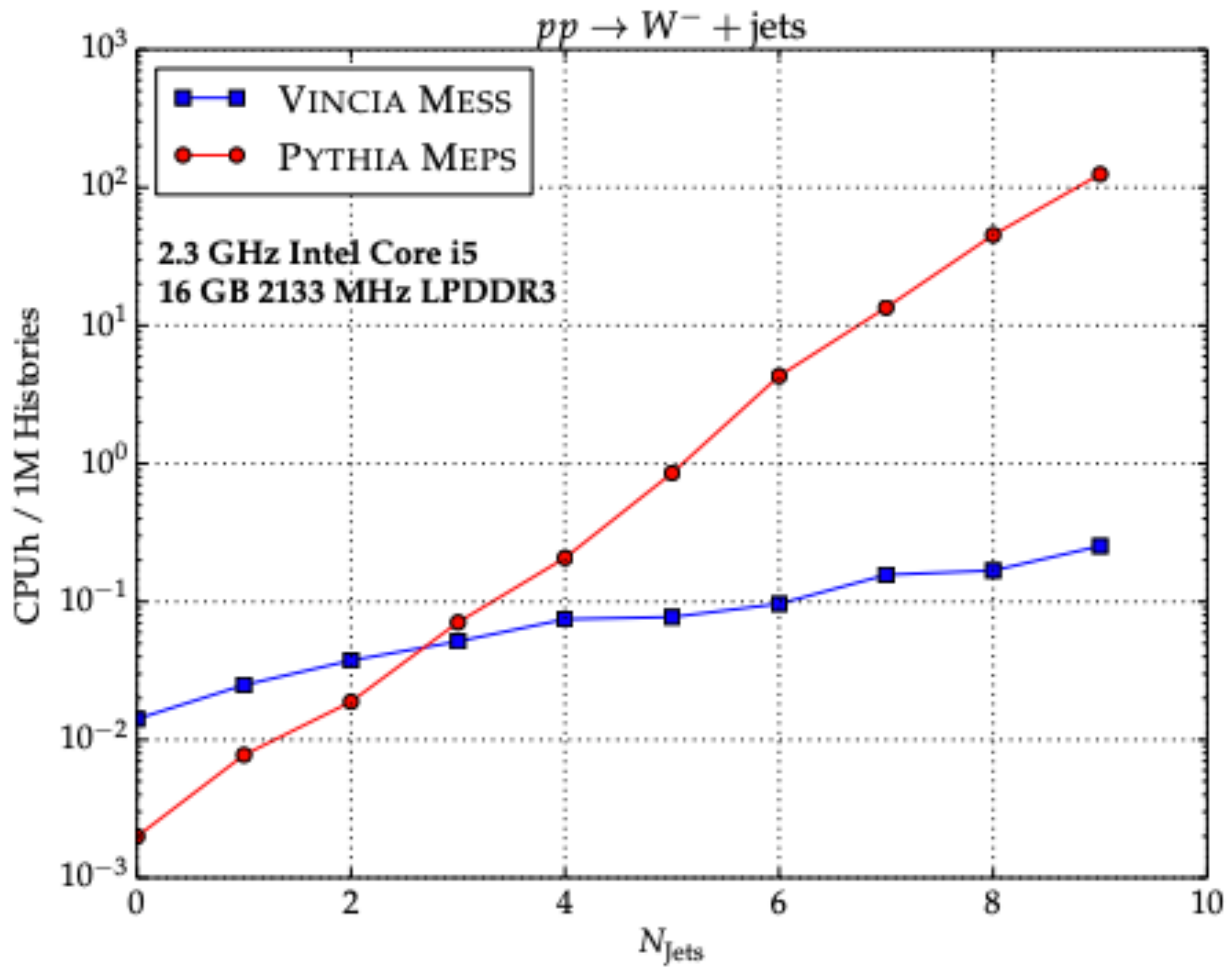
Backup

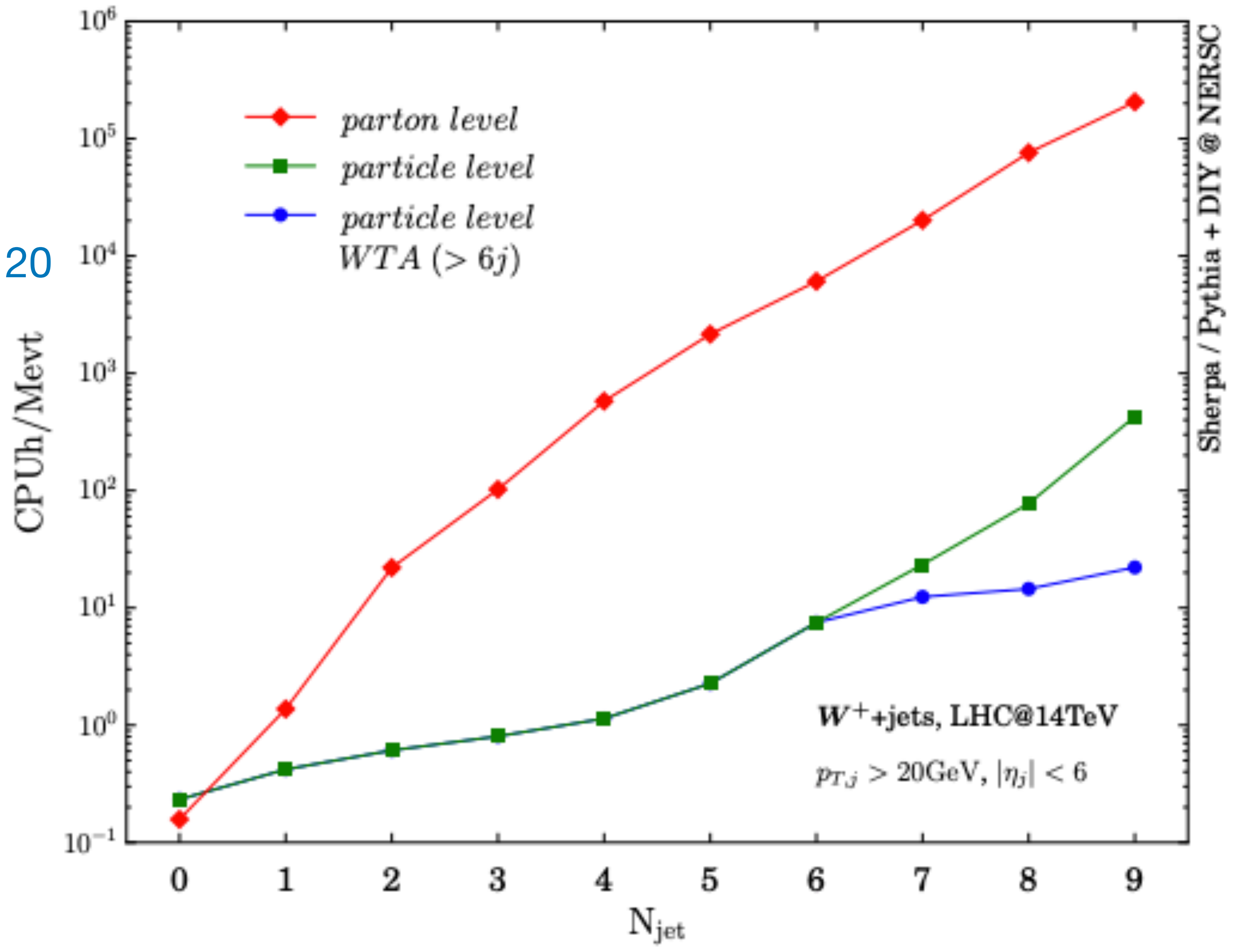
Efficient Multileg Merging

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

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

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

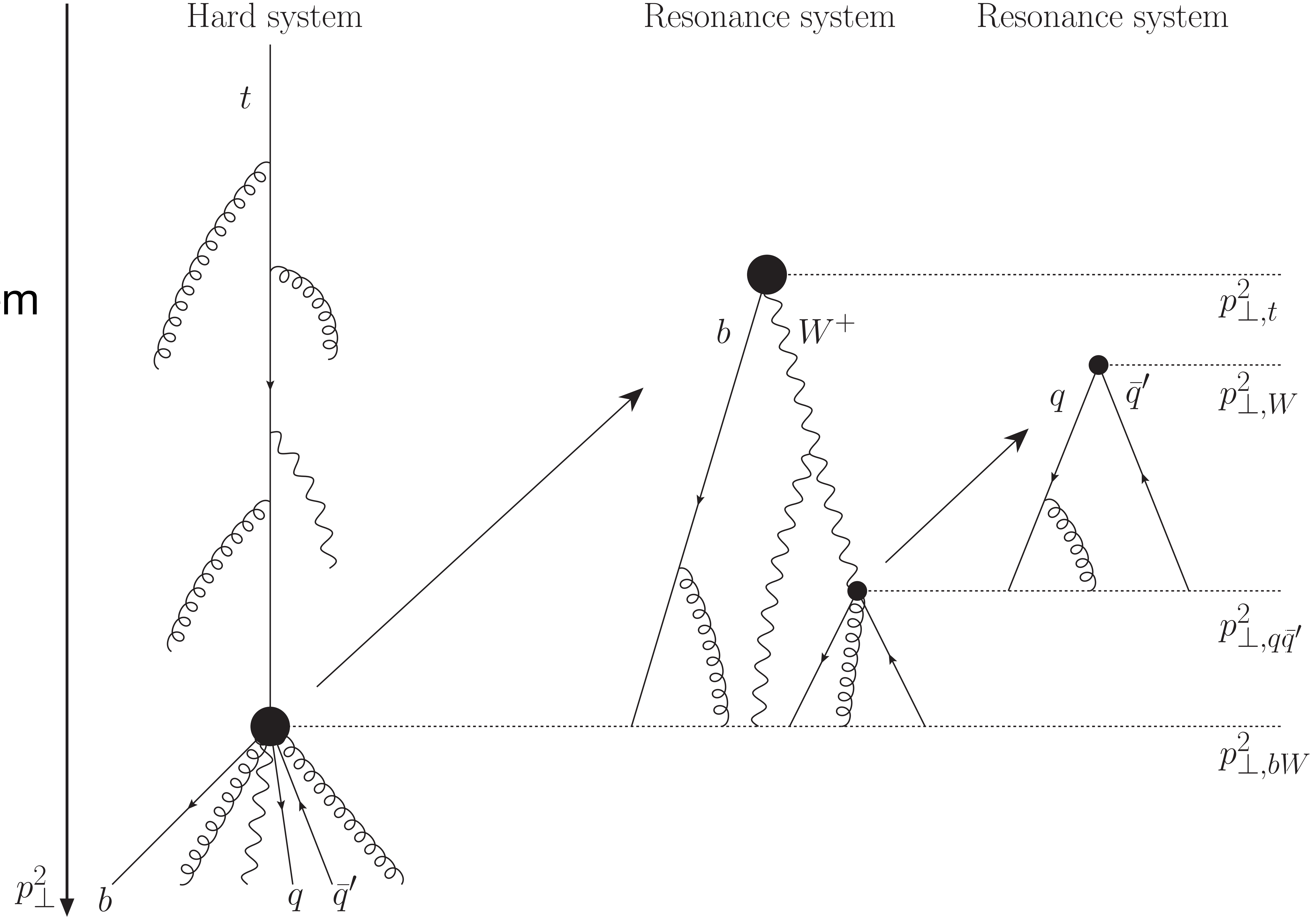
Resonance Matching

Pythia

- Narrow width approximation
- Decay showers after hard system

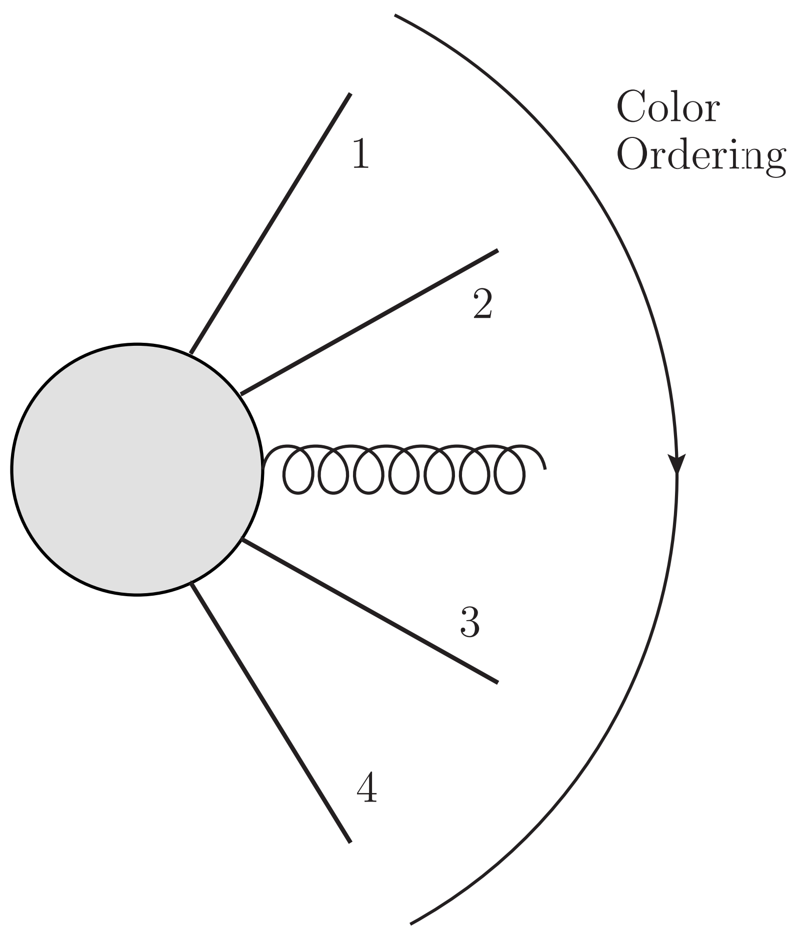
Vincia

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



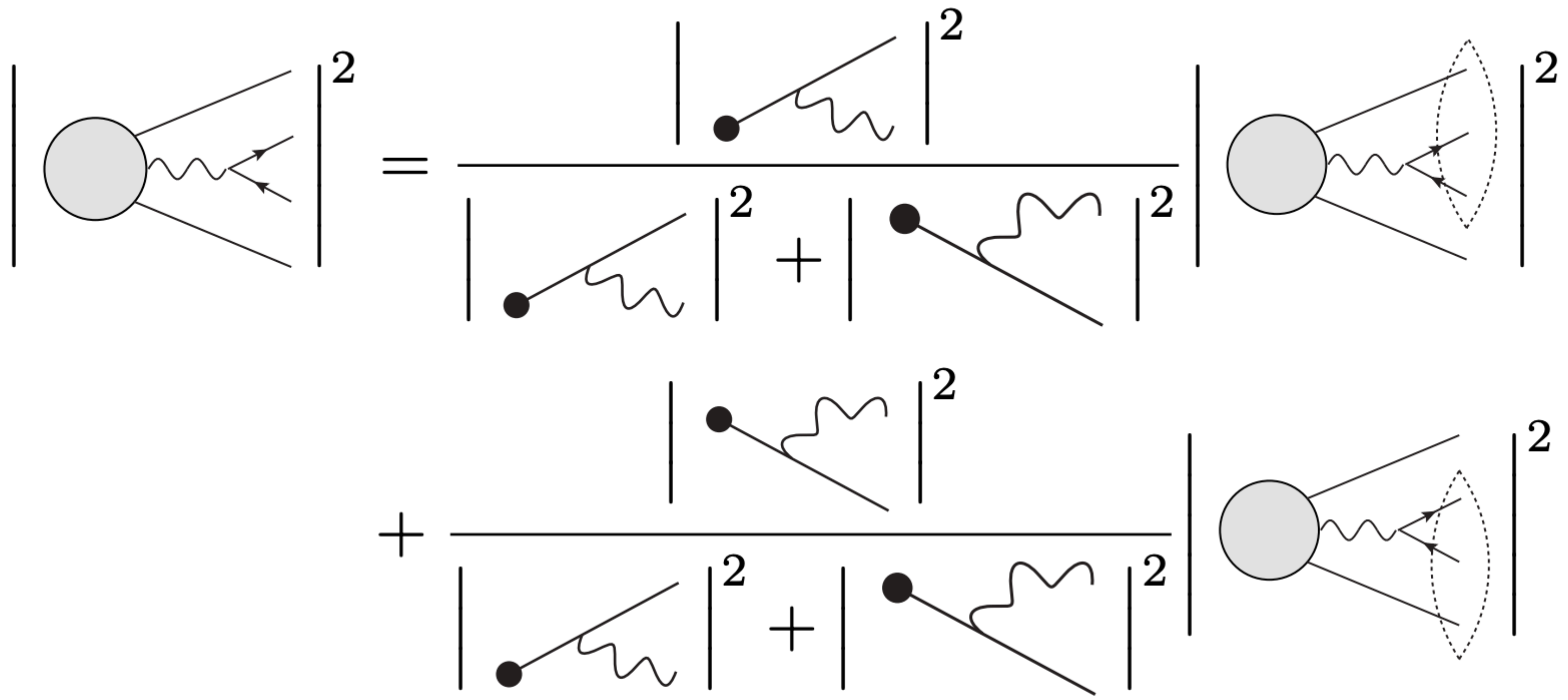
Recoiler Selection

In QCD recoiler determined by colour structure



Gluon splitting: recoiler ambiguous

In EW no such guidance exists



Probabilistic choice to avoid back reaction effects