Electroweak Parton Showers

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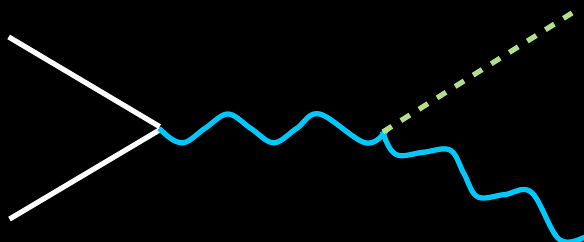
PITT PACC, University of Pittsburgh
@ QCD, EW and Tools at 100 TeV
08 October 2015

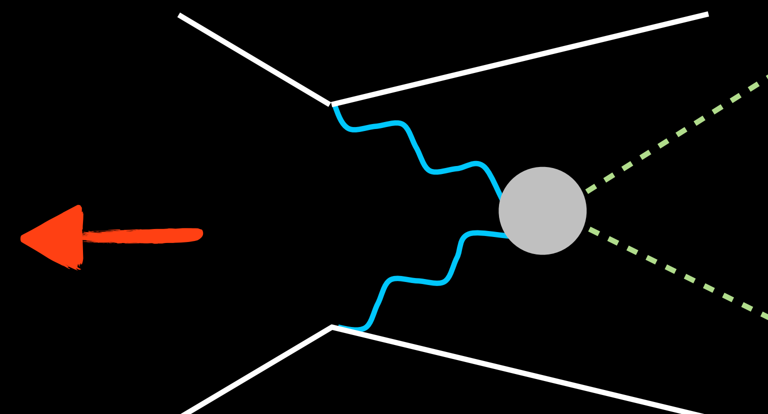
* Including work in progress with J Chen & T Han

How EW-Scale Objects are Made

At the hard process scale

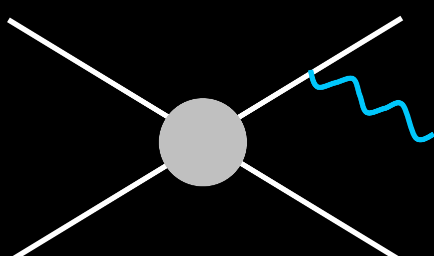
More beam energy ⇒ more parton lumi

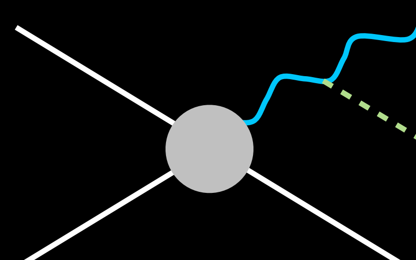




Hierarchically below the hard process scale...EW parton shower

More beam energy ⇒ easier access to extreme event kinematics



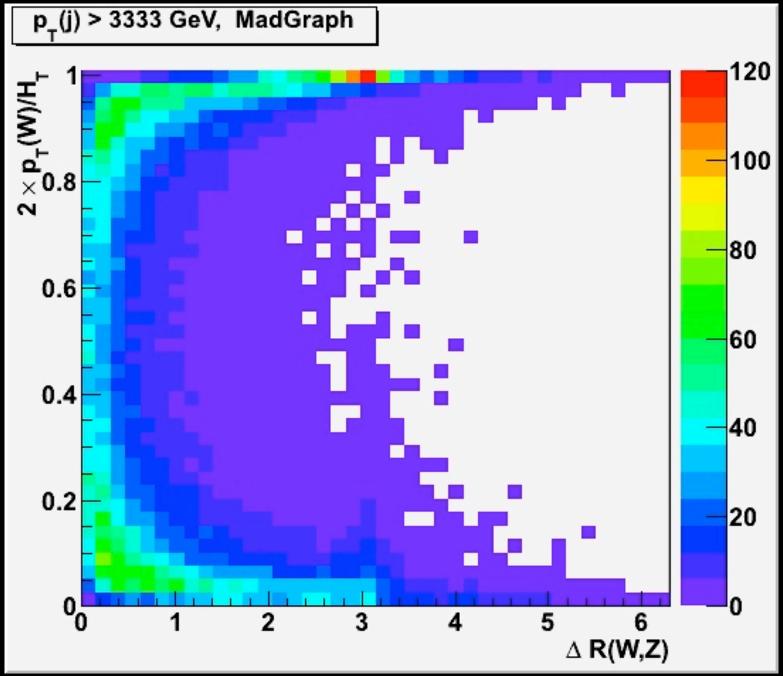


Why Think About EW Parton Showering?

- No choice
  - impacts almost all physics at E > TeV (SM or BSM), especially processes containing hard EW gauge bosons
  - effect on exclusive kinematic selections can grow quickly (exceeding 10%), and not a priori obvious
- Easy to implement
  - logarithmically-enhanced behavior is process-independent
  - collinear piece in particular factorizes leg-by-leg
  - LL Sudakov and real radiation contributions from a single algorithm (plus trivial to interleave with QCD)
- New regime to measure behavior of full EW/Higgs theory, BSM
  - different systematics, different (smaller?) backgrounds
  - EW-showered BSM topologies give new kinematic/coupling info

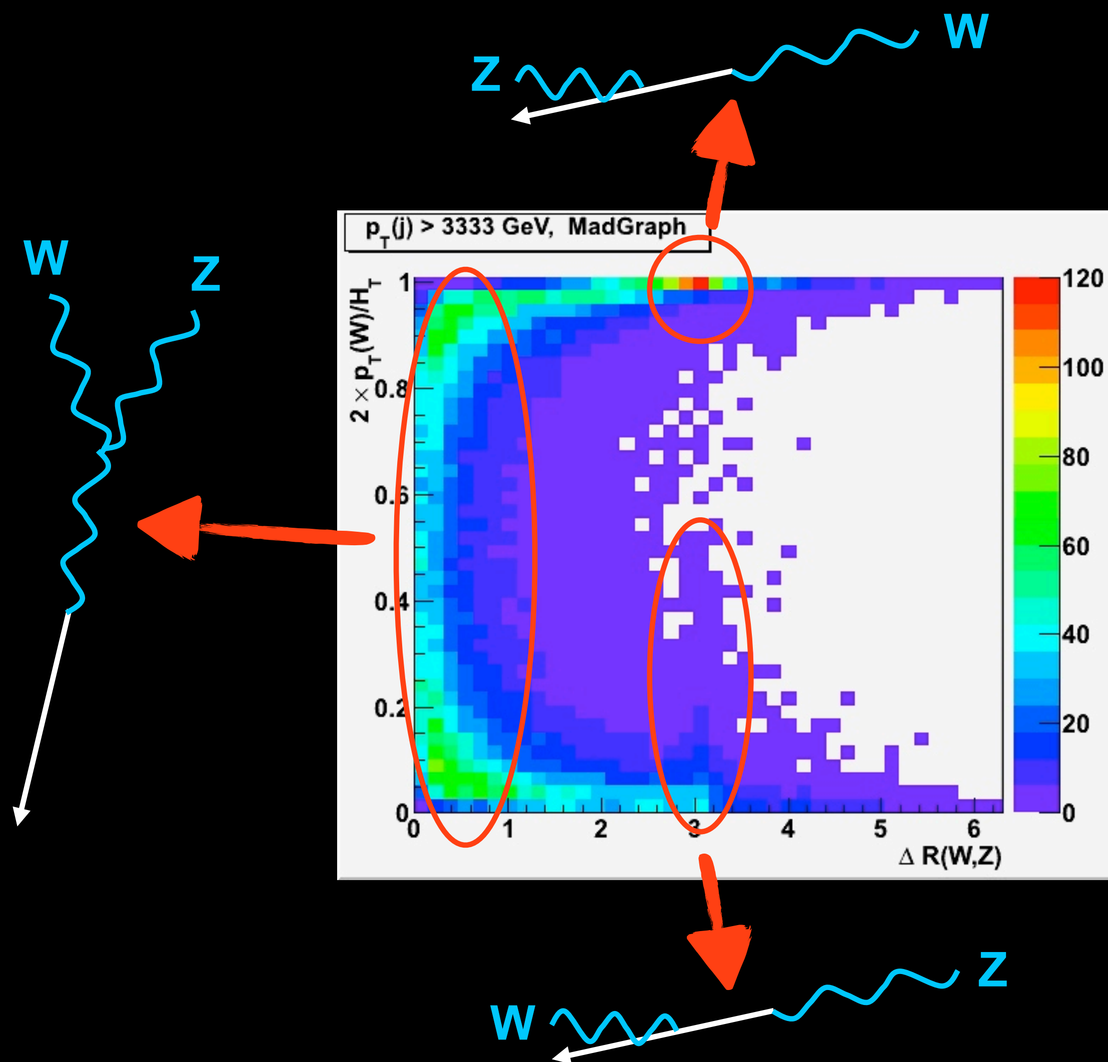
Example: WZ+Jet @ 100 TeV

MadGraph
$p_T(j) > 3300$ GeV



*** using lumi = 1 ab^{-1}**

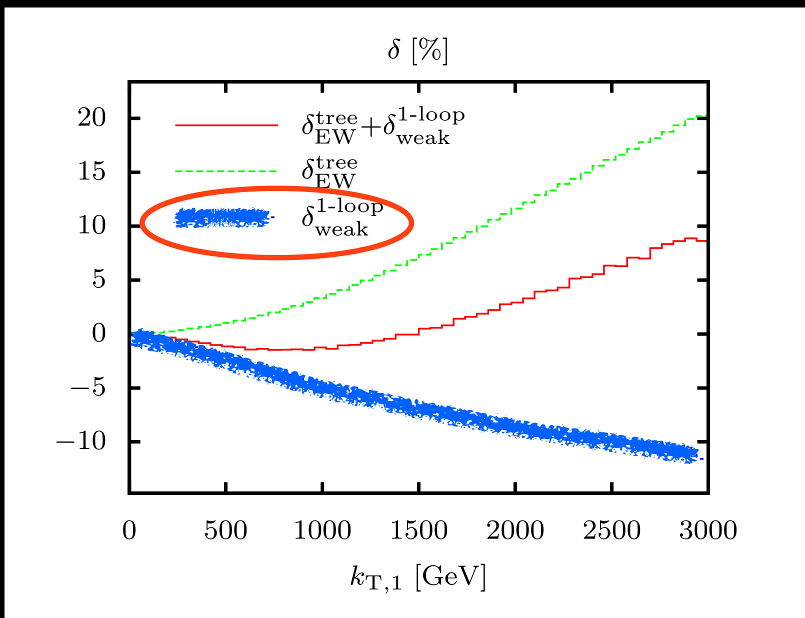
Example: WZ+Jet @ 100 TeV



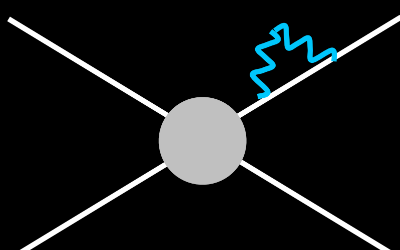
also **Denner & Pozzorini (hep-ph/0010202,0104127)**, **Manohar, et al** (SCET resummation, ~10 papers), many other related works

Electroweak Sudakovs

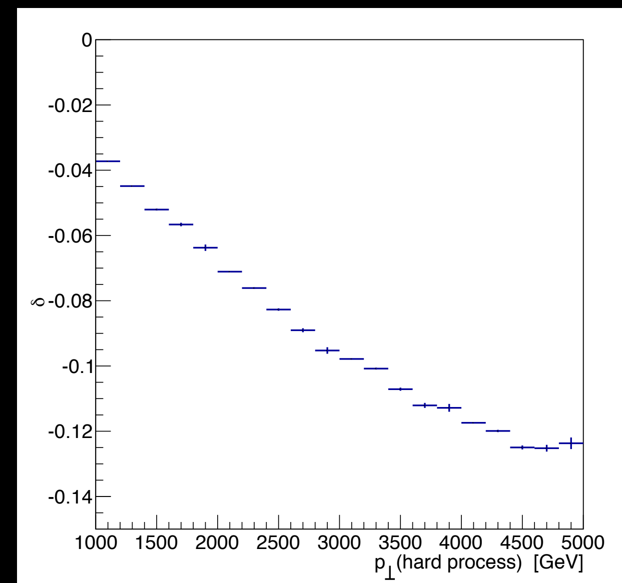
Dittmaier, Huss, Speckner (1210.0438)



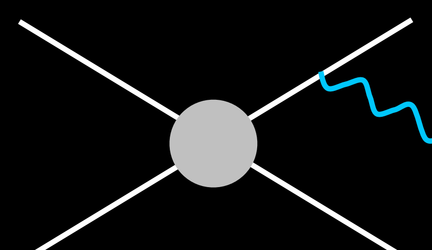
Virtual weak corrections to exclusive dijets at LHC14



Christiansen & Sjöstrand (1401.5238)



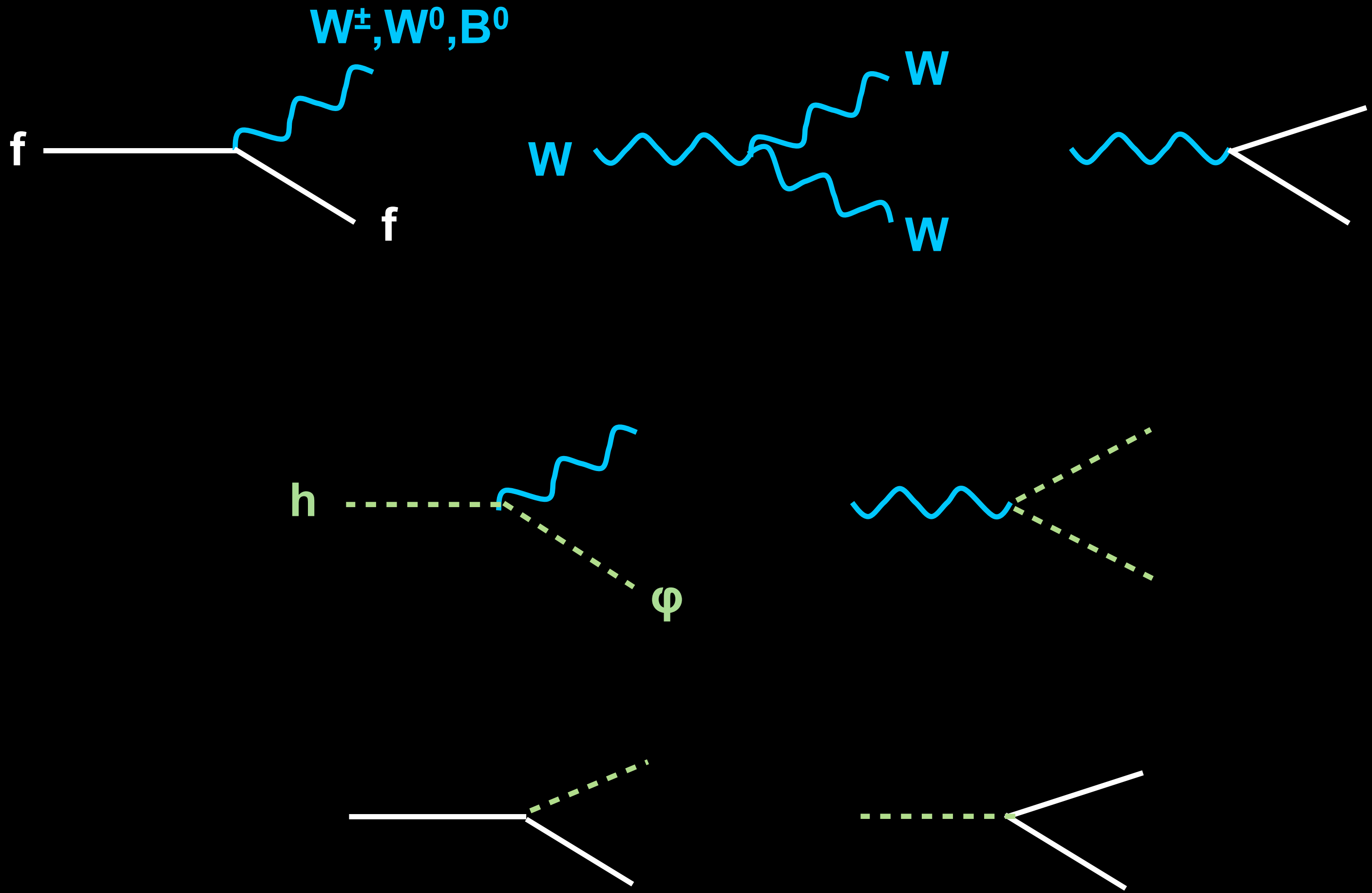
LO rate minus real W/Z emission events (PYTHIA)



Novelties wrt QCD/QED Parton Showering

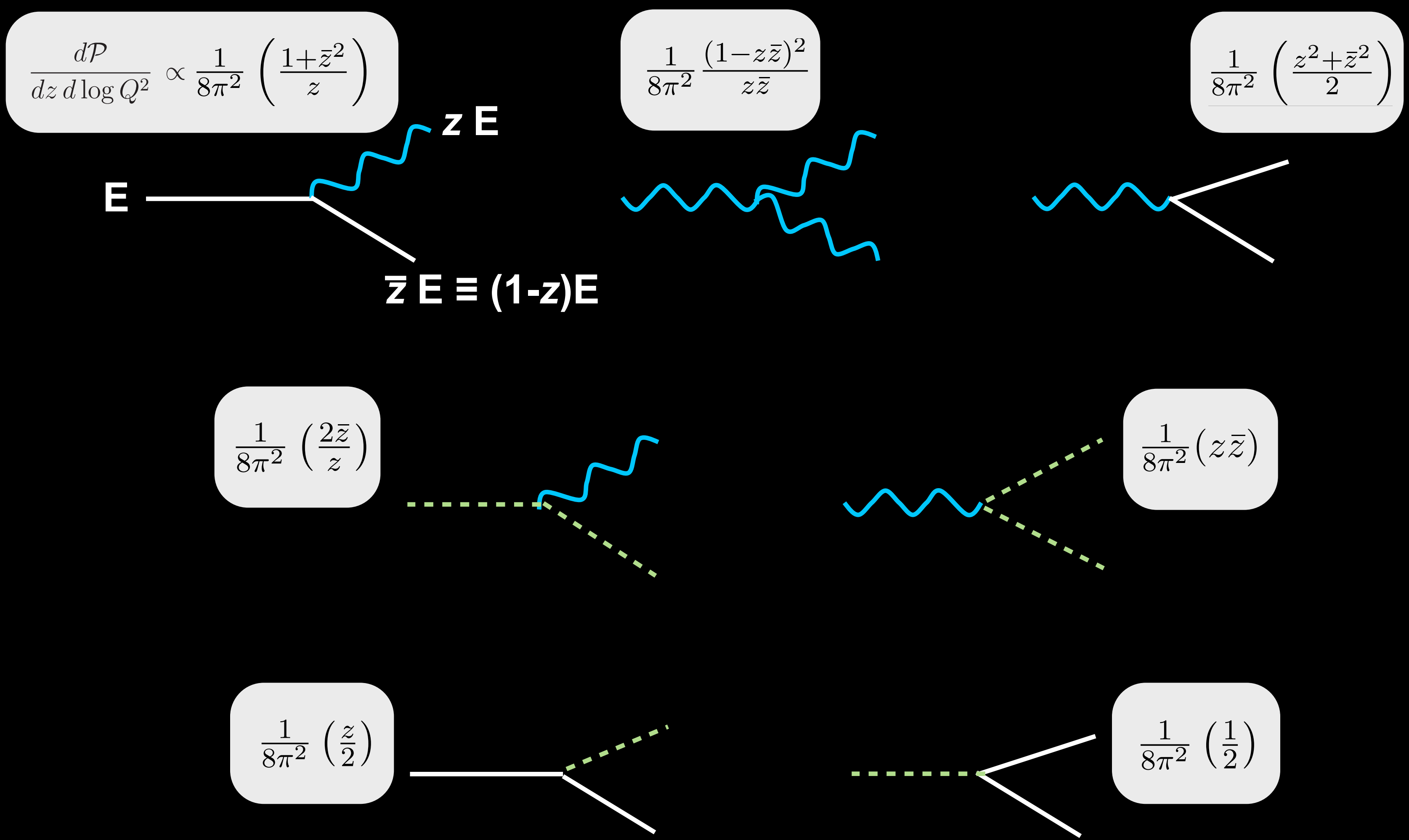
- Perturbative cutoff via SSB
- Longitudinals/scalars
- Chirality
- Yukawa showers
- Neutral boson interference
- Weak isospin self-averaging

Electroweak Splittings



+ 1→3 splittings

Electroweak Splittings

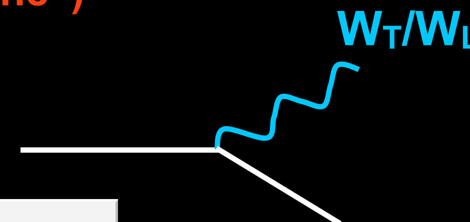


+ 1→3 splittings

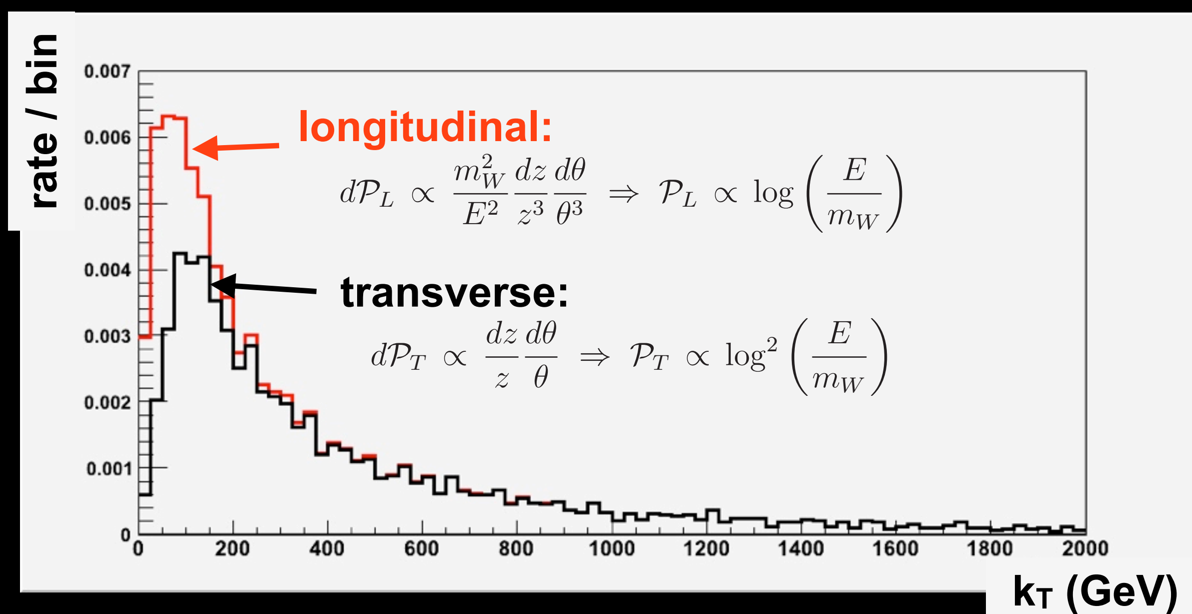
Massive Splitting Functions

$$\frac{d\mathcal{P}(a \to bc)}{dz\, dk_T^2} \simeq \frac{1}{16\pi^2} \frac{z_b z_c}{(k_T^2 + z_c m_b^2 + z_b m_c^2 - z_b z_c m_a^2)^2} |\mathcal{M}(a \to bc)|^2$$

shower shuts off at $k_T \sim m$ (“dead cone”)



W-boson FSR within 10 TeV quark-jet



* E.g., ISR ⇒ polarized W/Z PDFs: **Kane, Repko, Rolnik (1984), Dawson (1985), Chanowitz & Gaillard (1985)**

Light Quark Total Splitting Rates

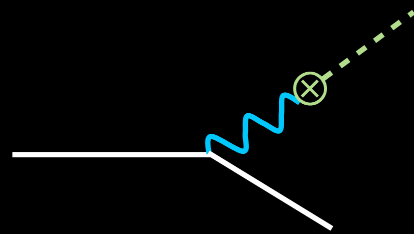
Averaged over flavors & helicities, summed over W & Z

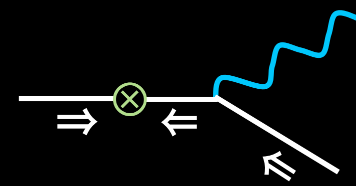
$$\mathcal{P}(q \to V_T q) \simeq (3 \times 10^{-3}) \left[\log \frac{E}{m_{\rm EW}}\right]^2 \quad \Rightarrow \quad \mathcal{P}(1 \text{ TeV}) \simeq 1.7\%, \quad \mathcal{P}(10 \text{ TeV}) \simeq 7\%$$

$$\mathcal{P}(q \to V_L q) \simeq (2 \times 10^{-3}) \log \frac{E}{m_{\rm EW}} \quad \Rightarrow \quad \mathcal{P}(1 \text{ TeV}) \simeq 0.5\%, \quad \mathcal{P}(10 \text{ TeV}) \simeq 1\%$$

"Broken" Showering at O(v)

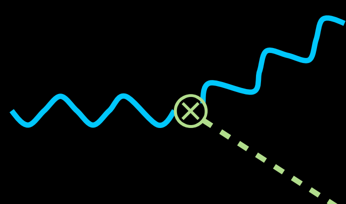
⇒ log(E/m)

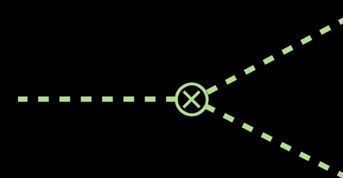




⇒ constant*

⇒ constant*





⇒ constant*

(~0.001)

* All beamed into a cone of size ~m/E

Gauging to Manifest Goldstone Equivalence

E.g., rotating lightcone gauge

$$n(k)\cdot A(k) = 0$$

$$n^0(k) \equiv 1\,, \quad \vec{n}(k) \equiv -\frac{k^0}{|k^0|}\frac{\vec{k}}{|\vec{k}|}$$

$$\text{long. polarization } \epsilon^\mu_\phi(k) \equiv \frac{\sqrt{|k^2|}}{n(k)\cdot k} n^\mu(k) = \epsilon^\mu_L(k) - k^\mu/m$$

$$\langle A_T(k)A_T(-k)\rangle = \frac{i}{k^2-m^2}$$

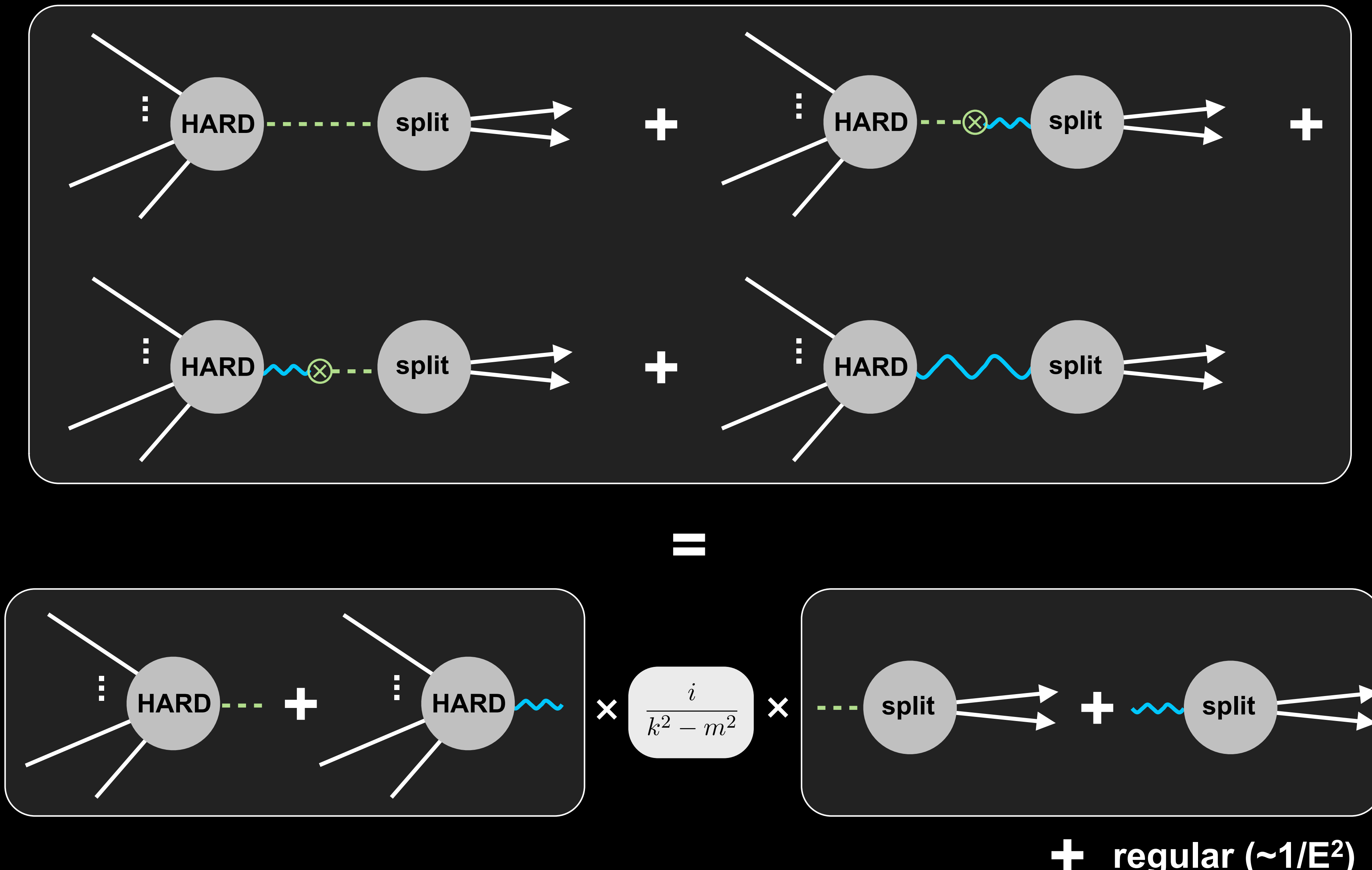
$$\langle A_\phi(k)A_\phi(-k)\rangle = \frac{i}{k^2-m^2}\,\mathrm{sign}(k^2)$$

$$\langle \phi(k)\phi(-k)\rangle = \frac{i}{k^2-m^2}$$

$$\langle A_\phi(k)\phi(-k)\rangle = \frac{i}{k^2-m^2}\frac{-im}{\sqrt{|k^2|}}\,.$$

- Delete problematic k^μ/m part of longitudinal polarization
  - fully replaced in Feynman rules by Goldstone field
  - amplitude to create on-shell longitudinal from $A^\mu \sim m/E$
- Keep mixed basis: Two fields, one particle
  - unlike R_ξ, Goldstone field interpolates physical longitudinal bosons (amplitude ~ i)
- Similar story in other "physical" gauges
  - **Kunszt & Soper (1987), Beenakker & Werthenbach (hep-ph/0112030)**

Factorization for Longitudinals



Transverse Vector (W^0,$W^\pm$) Total Splitting Rates

$$\mathcal{P}(V_T \to V_T V_T) \simeq (0.01)\left[\log\frac{E}{m_{\rm EW}}\right]^2 \quad \Rightarrow \quad \mathcal{P}(1\ {\rm TeV}) \simeq 6\%, \quad \mathcal{P}(10\ {\rm TeV}) \simeq 22\%$$

$$\mathcal{P}(V_T \to V_T V_L) \simeq (0.01)\log\frac{E}{m_{\rm EW}} \quad \Rightarrow \quad \mathcal{P}(1\ {\rm TeV}) \simeq 2\%, \quad \mathcal{P}(10\ {\rm TeV}) \simeq 5\%$$

$$\mathcal{P}(V_T \to V_L V_L) \simeq (4\times 10^{-4})\log\frac{E}{m_{\rm EW}} \quad \Rightarrow \quad \mathcal{P}(1\ {\rm TeV}) \simeq 0.1\%, \quad \mathcal{P}(10\ {\rm TeV}) \simeq 0.2\%$$

$$\mathcal{P}(V_T \to f\bar{f}) \simeq (0.02)\log\frac{E}{m_{\rm EW}} \quad \Rightarrow \quad \mathcal{P}(1\ {\rm TeV}) \simeq 5\%, \quad \mathcal{P}(10\ {\rm TeV}) \simeq 10\%$$

$$\mathcal{P}(V_T \to V_L h) \simeq (4\times 10^{-4})\log\frac{E}{m_{\rm EW}} \quad \Rightarrow \quad \mathcal{P}(1\ {\rm TeV}) \simeq 0.1\%, \quad \mathcal{P}(10\ {\rm TeV}) \simeq 0.2\%$$

$$\mathcal{P}(V_T \to V_T h) \simeq (3\times 10^{-4}) \quad \Rightarrow \quad \mathcal{P}(1\ {\rm TeV}) \simeq 0.03\%, \quad \mathcal{P}(10\ {\rm TeV}) \simeq 0.03\%$$

Longitudinal Vector Total Splitting Rates

$$\mathcal{P}(V_L \to V_T V_L) \sim (2 \times 10^{-3}) \left[\log \frac{E}{m_{\rm EW}}\right]^2 \quad \Rightarrow \quad \mathcal{P}(1\ \text{TeV}) \sim 1\%, \quad \mathcal{P}(10\ \text{TeV}) \sim 4\%$$

$$\mathcal{P}(V_L \to V_T h) \sim (2 \times 10^{-3}) \left[\log \frac{E}{m_{\rm EW}}\right]^2 \quad \Rightarrow \quad \mathcal{P}(1\ \text{TeV}) \sim 1\%, \quad \mathcal{P}(10\ \text{TeV}) \sim 4\%$$

Plus others.....

Comment on Neutral Bosons

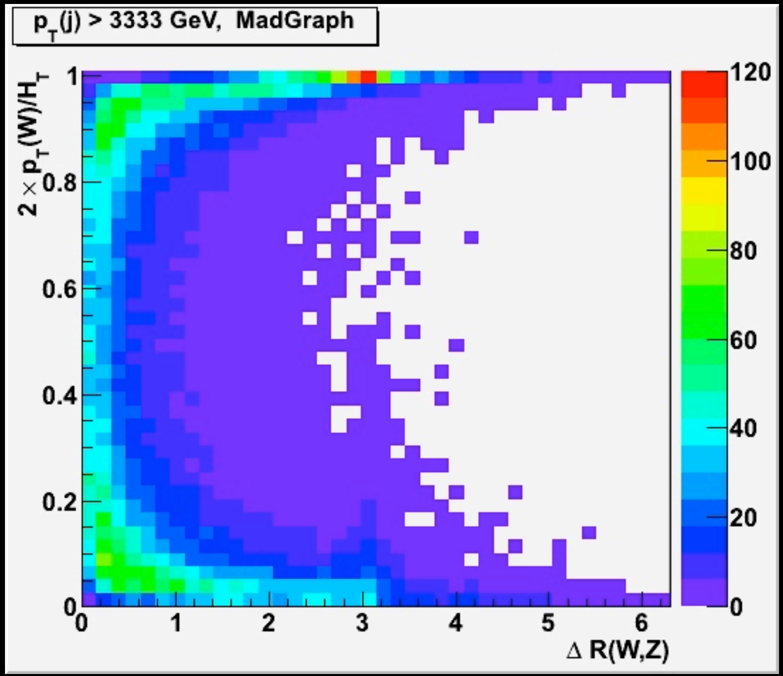
- Wrong prescription
  - run shower on "hard" γ and Z according to gauge 3-points
  - misses high-energy restoration of SU(2)xU(1), doesn't factorize
  - e.g., γ/Z produced in annihilation of RH fermions is pure hypercharge, cannot split to W^+W^- (also different fermion splittings)
- Better prescription
  - use B^0/W^0 basis in shower down to Q ~ m_Z, then project out γ and Z states, continue showering if γ (decay if Z)
  - would need B^0/W^0 content from hard event generators, kinematics adjusted in shower
- Unified prescription
  - describe mixed neutral boson state with density matrix (similar to coherent shower of **Nagy & Soper (0706.0017)**)
  - matrix-valued splitting functions, would need matrix-valued γ/Z content from hard event generators

Our Shower Program

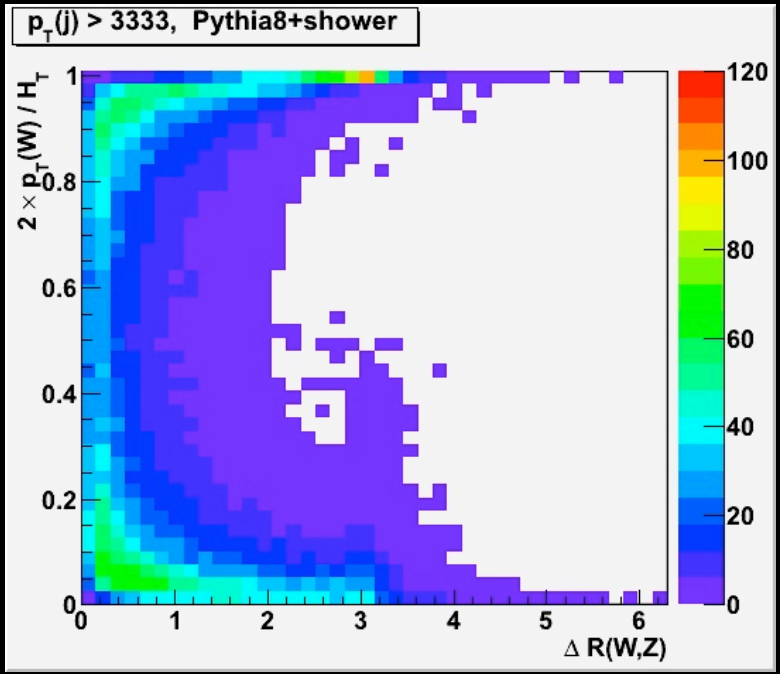
- Currently PYTHIA6-like virtuality-ordered
  - collinear approximation, no coherence between dipoles
- Polarized splittings
- Massive splitting functions
  - amplitudes and phase space
- Reweighting of secondary splittings
- Interleaved with QCD & QED
- Only FSR (so far)
- Built in C++...ideally adapt to run within existing shower frameworks

WZ+Jet Revisited

MadGraph



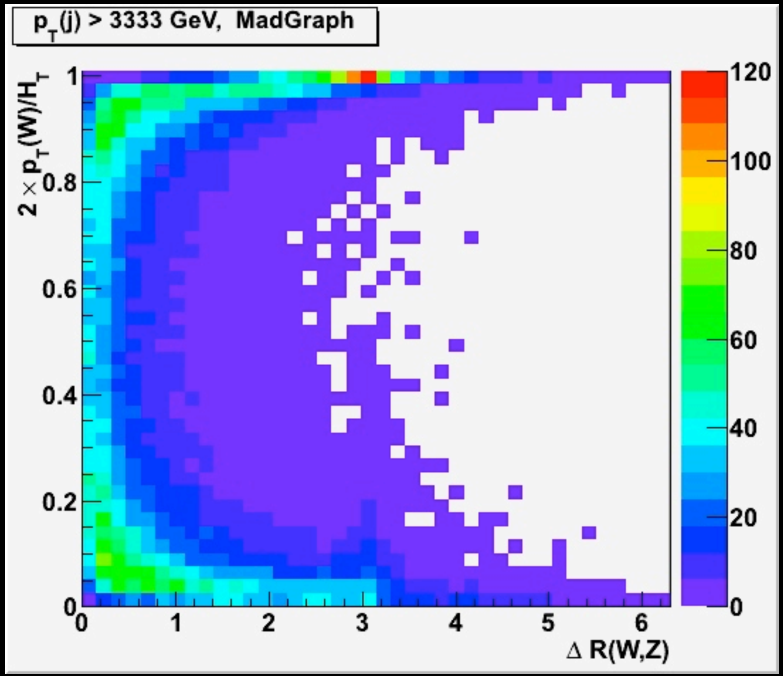
Pythia8 W/Z+jet + EW-Shower



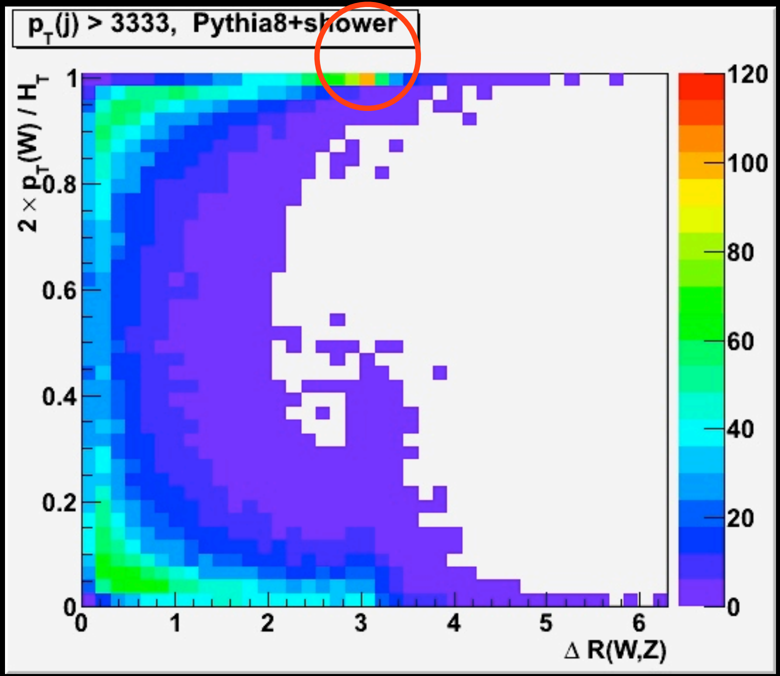
WZ+Jet Revisited

~10% loss from further showering

MadGraph



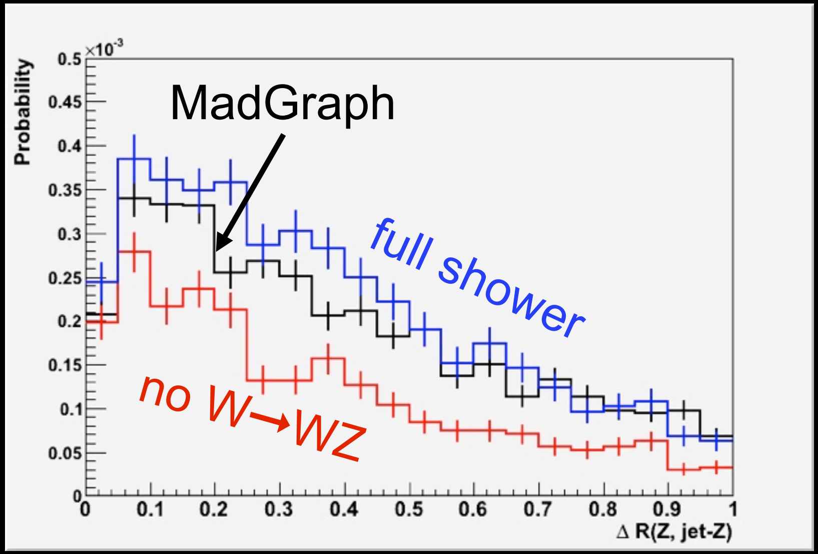
Pythia8 W/Z+jet + EW-Shower



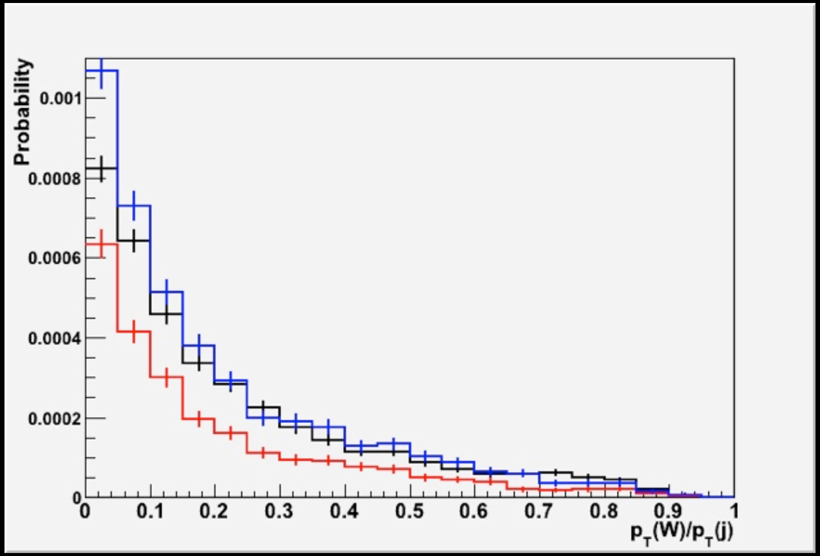
Multiple Weak Emissions Inside One Jet

u_L(10 TeV) → $d_L W^+ Z$

* R=1.0 anti-kT jet, W/Z as partons



ΔR(Z, rest of jet)

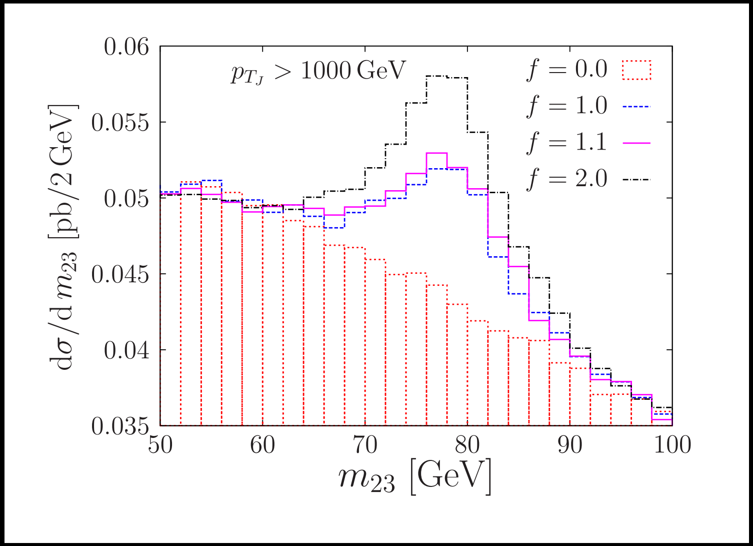


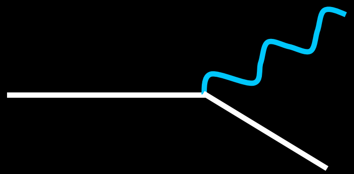
$p_T(W)$ / $p_T(j)$

Will become much more relevant for pure W/Z/γ "jets"
(analogous to gluon-jets)

Measurement of Weakstrahlung Rate (LHC)

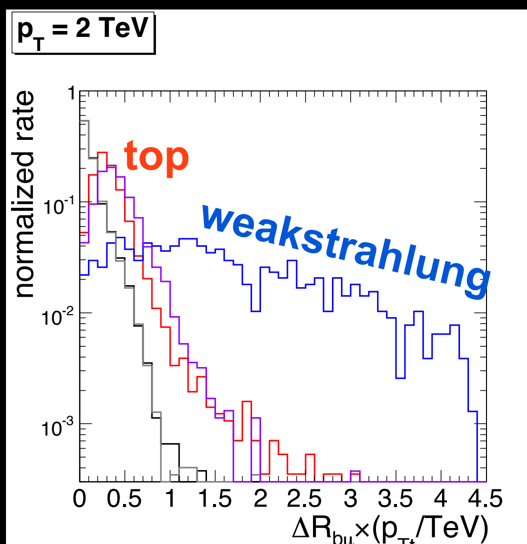
Krauss, Petrov, Schönherr, Spannowsky (1403.4788)





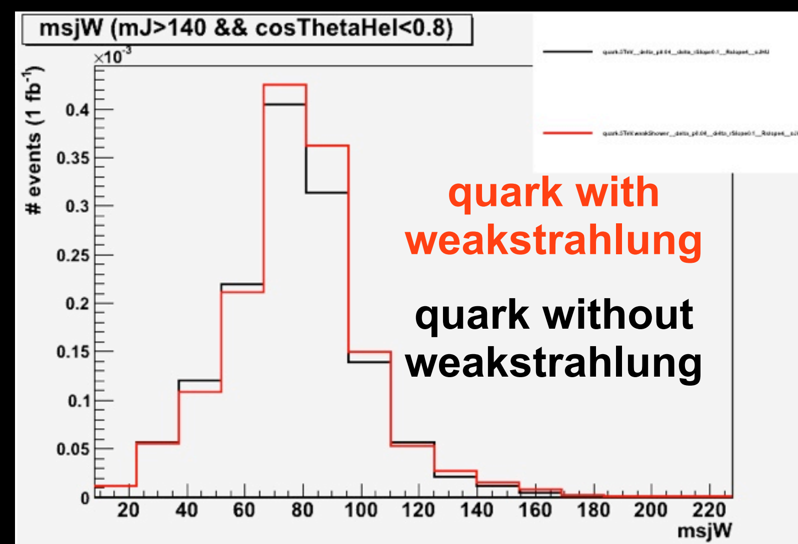
Effect on Top-Tagging (Any p_T > TeV)

Leptonic top-jets:
main background (~10^{-3} quark-mistag)



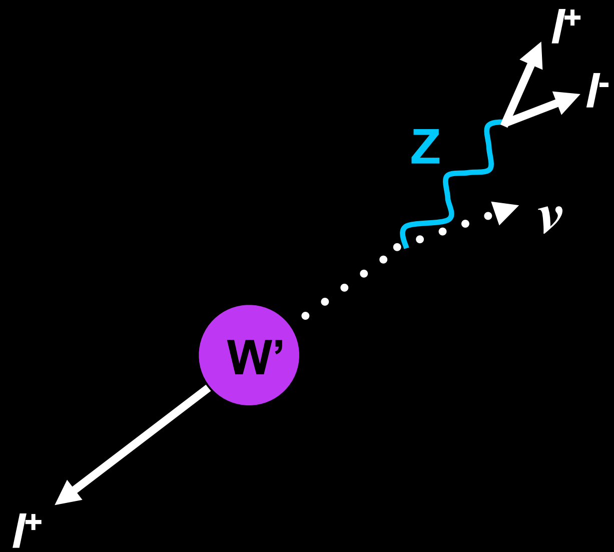
Rehermann & Tweedie (1007.2221)

Hadronic top-jets:
5-10% perturbation to quark mistag

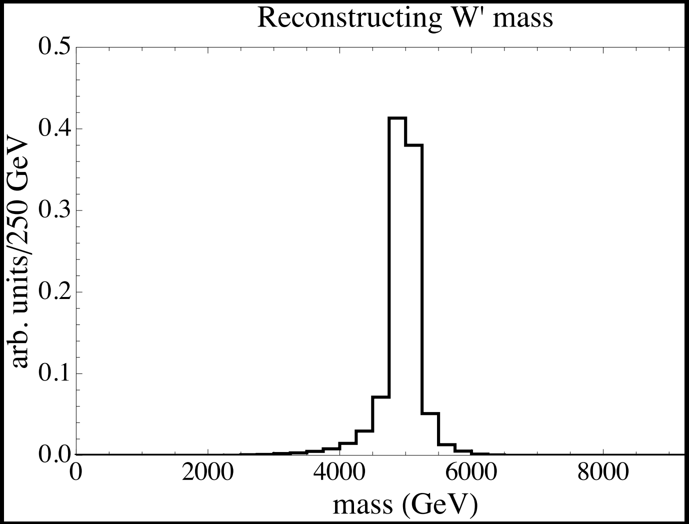


with Z Han & M Son

As a Handle on Heavy New Physics



Hook & Katz (1407.2607)
also **Rizzo (1403.5465)**



Radiated Z-boson traces neutrino's 3-vector direction (and probes W' chirality)

Some Other Back-of-the Envelope Applications

- $W_T W_T$ production at O(10 TeV)
  - $W_T W_T \rightarrow W_T W_T$ scattering: O(1) showering probability
  - KK graviton decay: corrections up to O(50%)
- $W_L W_L$ production at O(10 TeV)
  - $W_L W_L \rightarrow W_L W_L$/hh, $Z' \rightarrow Z_L h$, $W' \rightarrow W_L h / W_L Z_L$: O(10%) showering probability

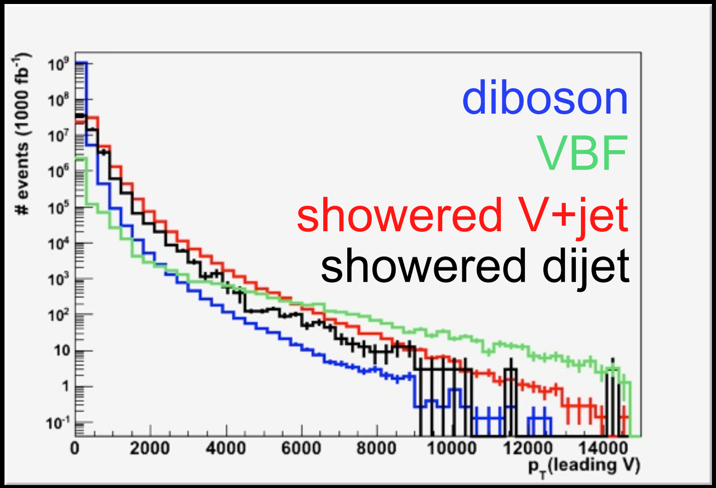
Summary

- EW splitting processes quickly grow/asymptote in rate
  - range from totally negligible to O(1), depending on what you're looking at; potentially large accumulations of small effects
  - Sudakovs studied+resummed over the past years
- Several MC tools coming online recently/soon
  - e.g., PYTHIA8 has f→fW, but only one of 7 shower processes
  - very little work done so far with BSM
- We're working on a multipurpose EW shower program
  - "quick and dirty" way to capture universal collinear physics
  - main addition is W→WW, V→fermions, lots of other Higgs and Goldstone-equivalent processes, systematic accounting of "broken" ultracollinear processes
  - in principle extendable to dipole formalism, matching (with more theory input)
  - more validations and 14/100 TeV examples forthcoming

More…

"Shower" Vs "Prompt" Diboson

p_T(leading V)



H_T(jets + V's)