Electroweak-Scale Objects at a 100 TeV Collider

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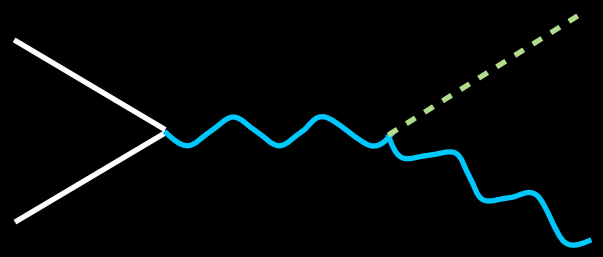
PITT PACC, University of Pittsburgh
@ ACFI Workshop
19 September 2015

*** Including work in progress with J Chen, T Han, and R Ruiz**

How EW-Scale Objects are Made

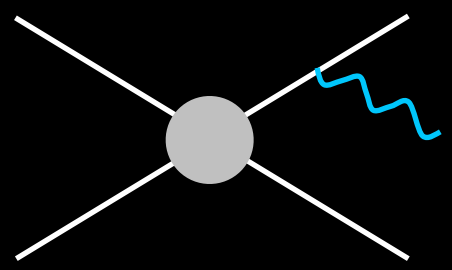
At the hard process scale

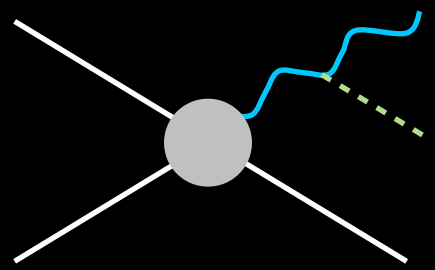
More beam energy ⇒ more parton lumi



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

More beam energy ⇒ easier access to extreme event kinematics





How EW-Scale Objects are Made

At the hard process scale

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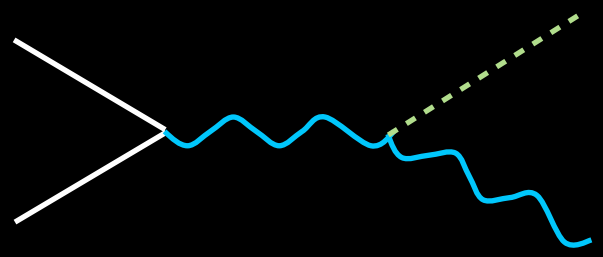
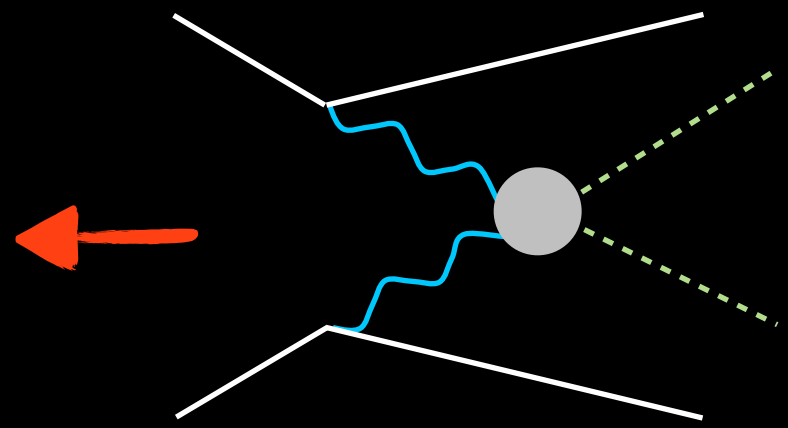
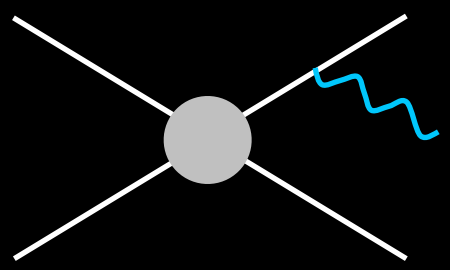
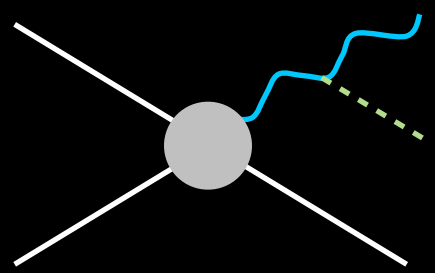




Hierarchically below the hard process scale...EW parton shower

More beam energy ⇒ easier access to extreme event kinematics



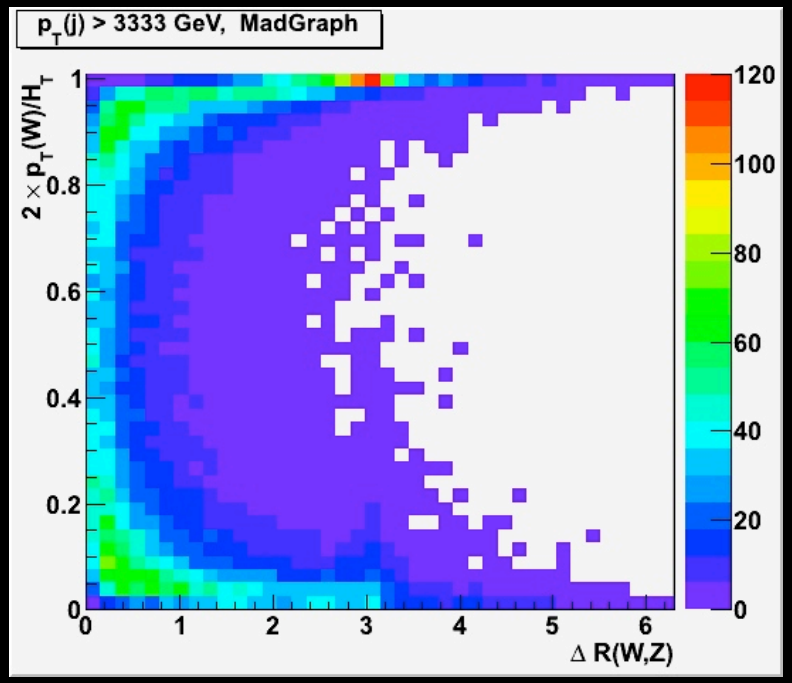


Why Think About EW Parton Showering?

- No choice
  - impacts almost all physics at E > TeV
- New regime to measure couplings of full EW/Higgs theory
  - different systematics
  - different (smaller?) backgrounds
- New leverage against new physics
  - opportunities for new “light” particle states associated with EWPT?

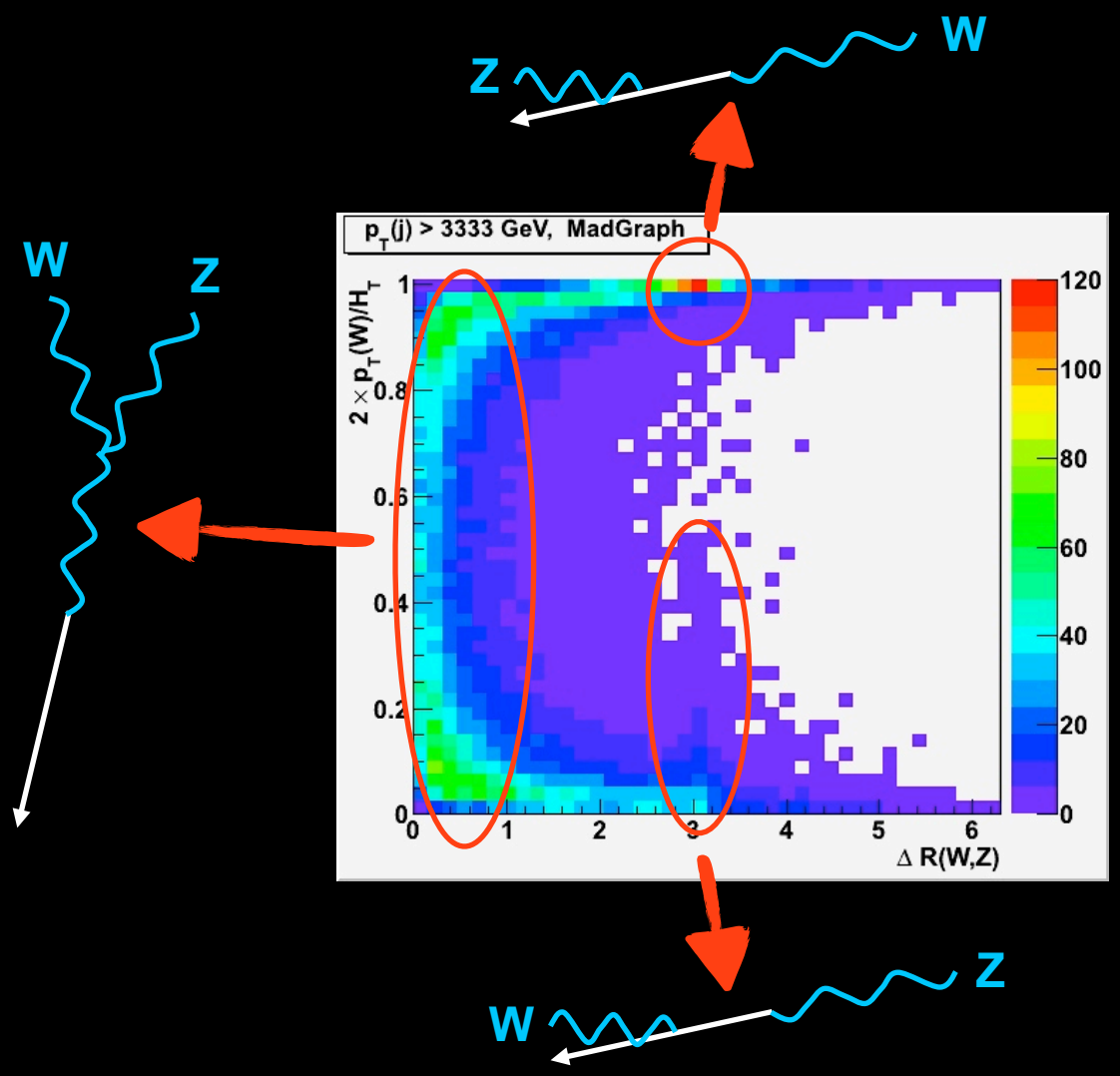
Example: WZ+Jet @ 100 TeV

$p_T(j)$ > 3300 GeV



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

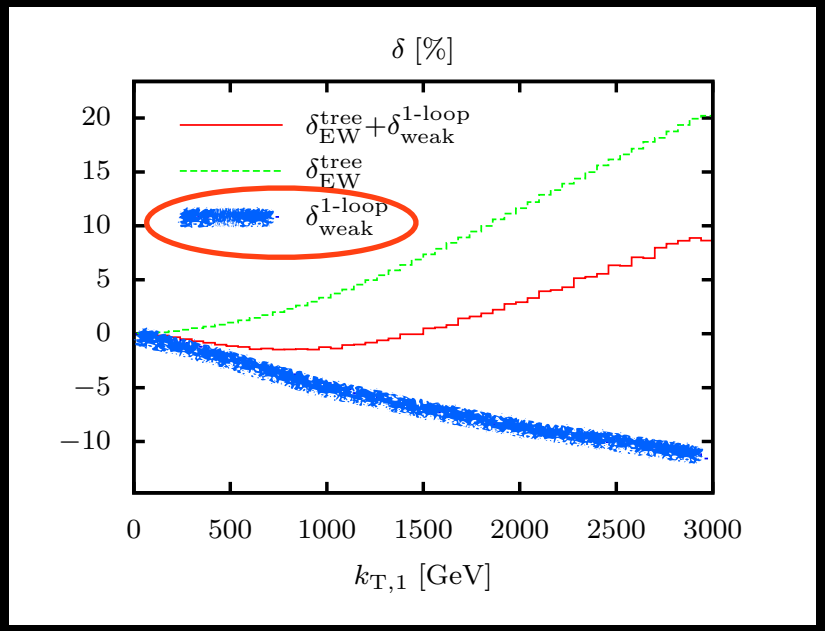
Example: WZ+Jet @ 100 TeV



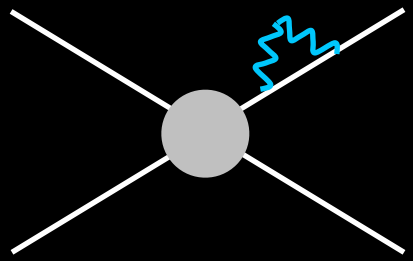
also **Moretti, Nolten, Ross (hep-ph/0606201), Denner & Pozzorini (hep-ph/0010202,0104127),** many Manohar papers, many other related works

Electroweak Sudakovs

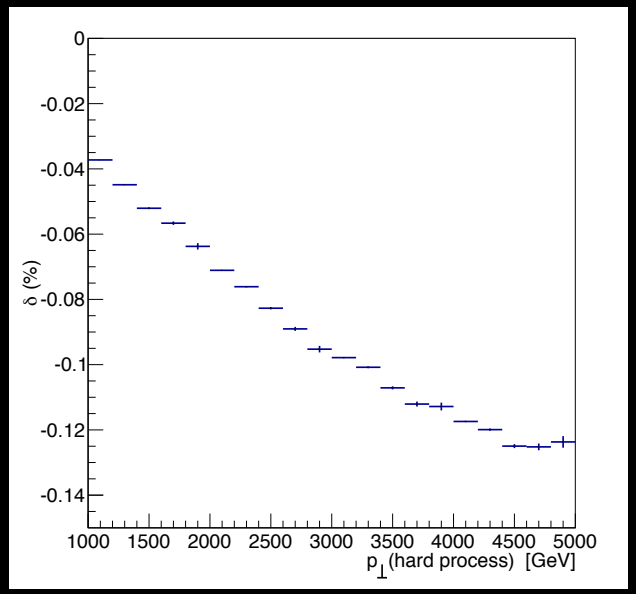
Dittmaier, Huss, Speckner (1210.0438)



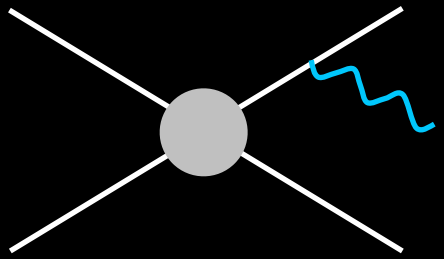
Virtual weak corrections to exclusive dijets at LHC14



Christiansen & Sjöstrand (1401.5238)



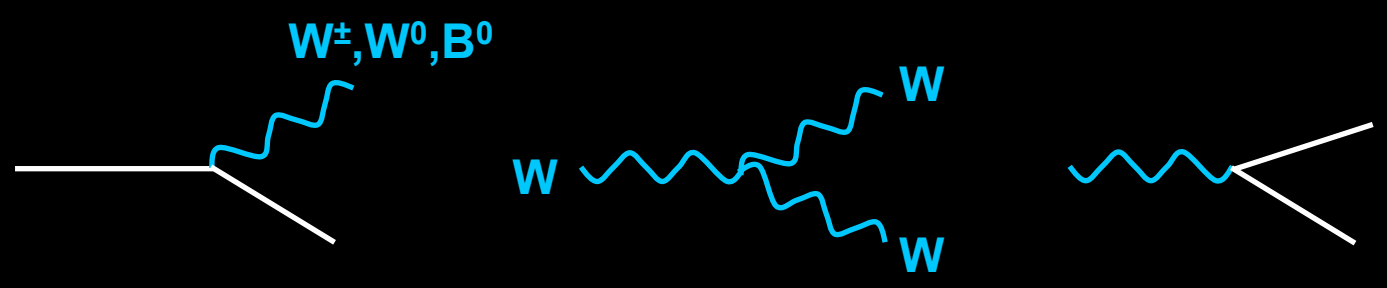
LO rate minus real W/Z emission events



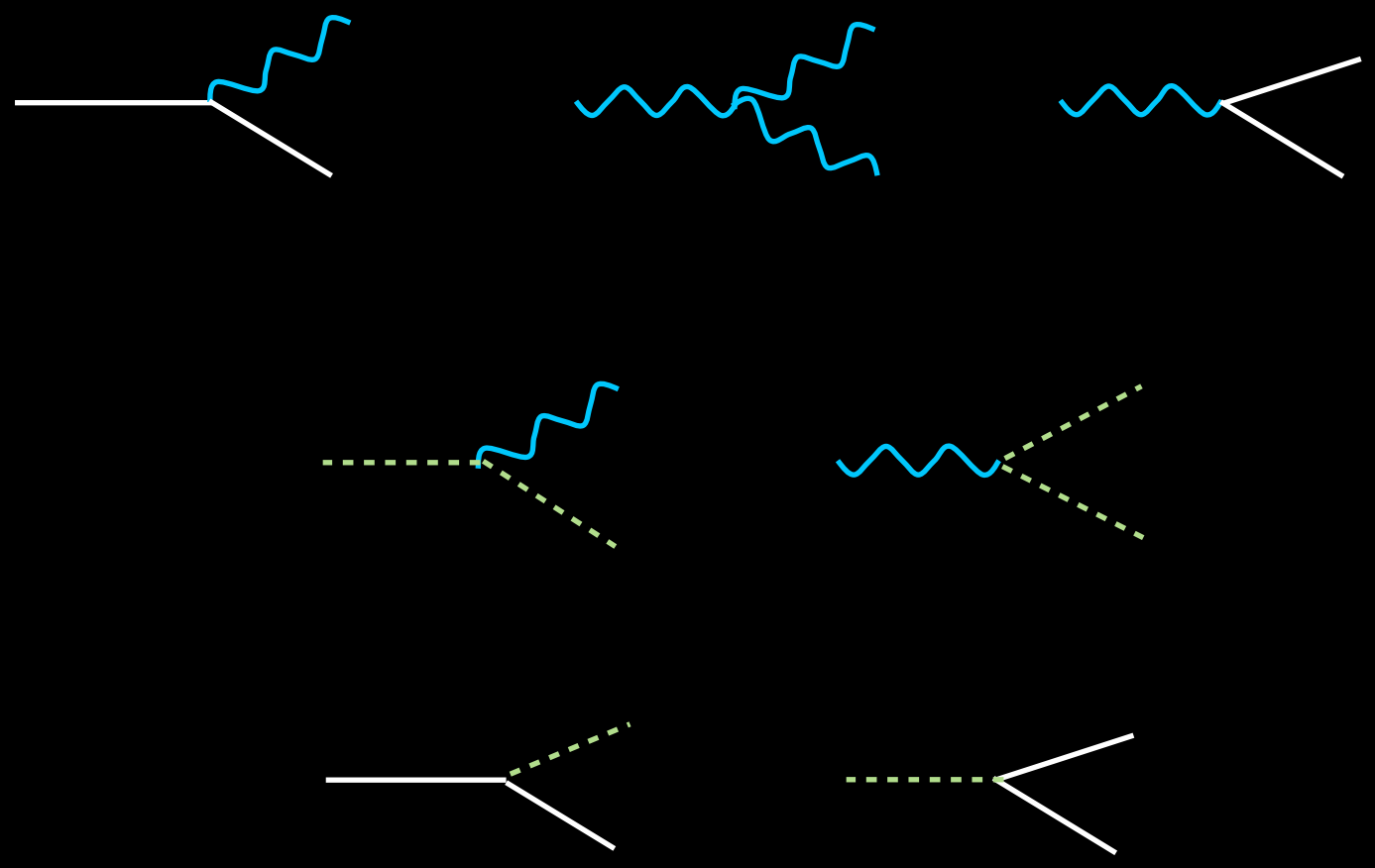
Novelties wrt QCD/QED Parton Showering

- Perturbative cutoff via SSB
  - physically-measurable soft/collinear emissions
- Longitudinals/scalars
- Chirality
- Yukawa showers
- Neutral boson interference
  - correct basis is W^0/B^0, not γ/Z
- Weak isospin self-averaging
  - $u(x) > d(x) \rightarrow u_R(x) > Q_L(x) > d_R(x)$

Electroweak Splittings



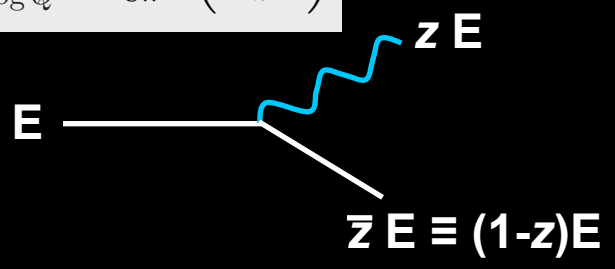
Electroweak Splittings



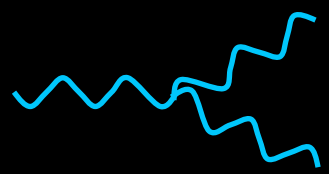
+ 1→3 splittings

Electroweak Splittings

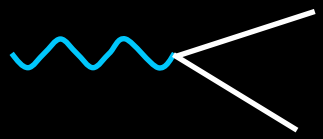
$$\frac{d\mathcal{P}}{dz\, d\log Q^2} \propto \frac{1}{8\pi^2}\left(\frac{1+\bar{z}^2}{z}\right)$$



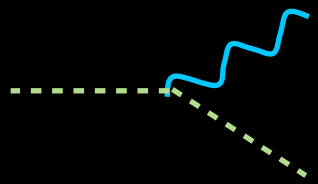
$$\frac{1}{8\pi^2}\frac{(1-z\bar{z})^2}{z\bar{z}}$$

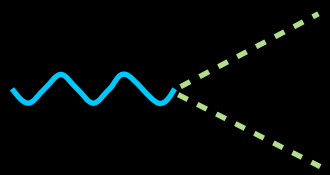


$$\frac{1}{8\pi^2}\left(\frac{z^2+\bar{z}^2}{2}\right)$$



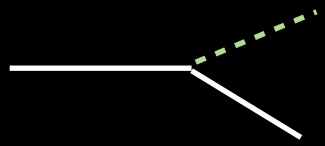
$$\frac{1}{8\pi^2}\left(\frac{2\bar{z}}{z}\right)$$

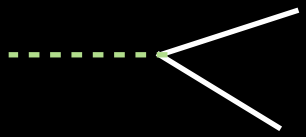




$$\frac{1}{8\pi^2}\left(z\bar{z}\right)$$

$$\frac{1}{8\pi^2}\left(\frac{z}{2}\right)$$





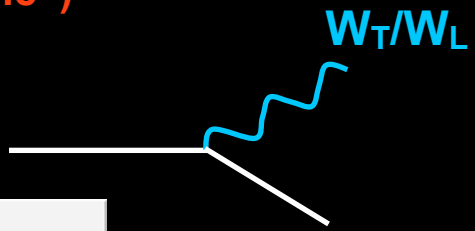
$$\frac{1}{8\pi^2}\left(\frac{1}{2}\right)$$

+ 1→3 splittings

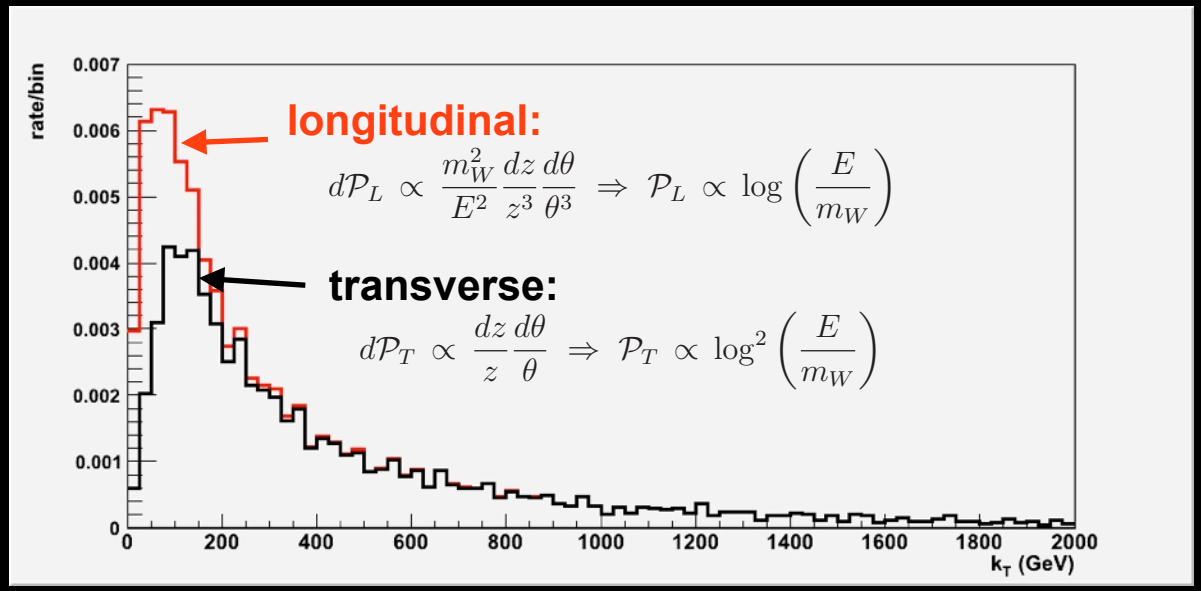
Massive Splitting Functions

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

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)**

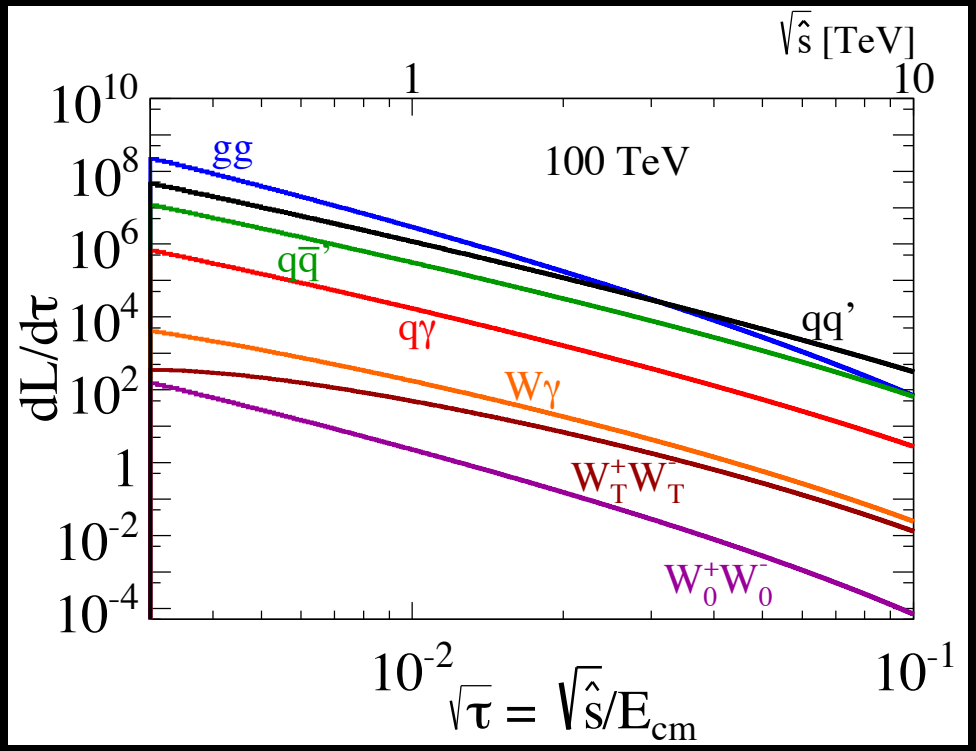
Light Quark Total Splitting Rates

Averaged over flavors & helicities, summed over W & Z

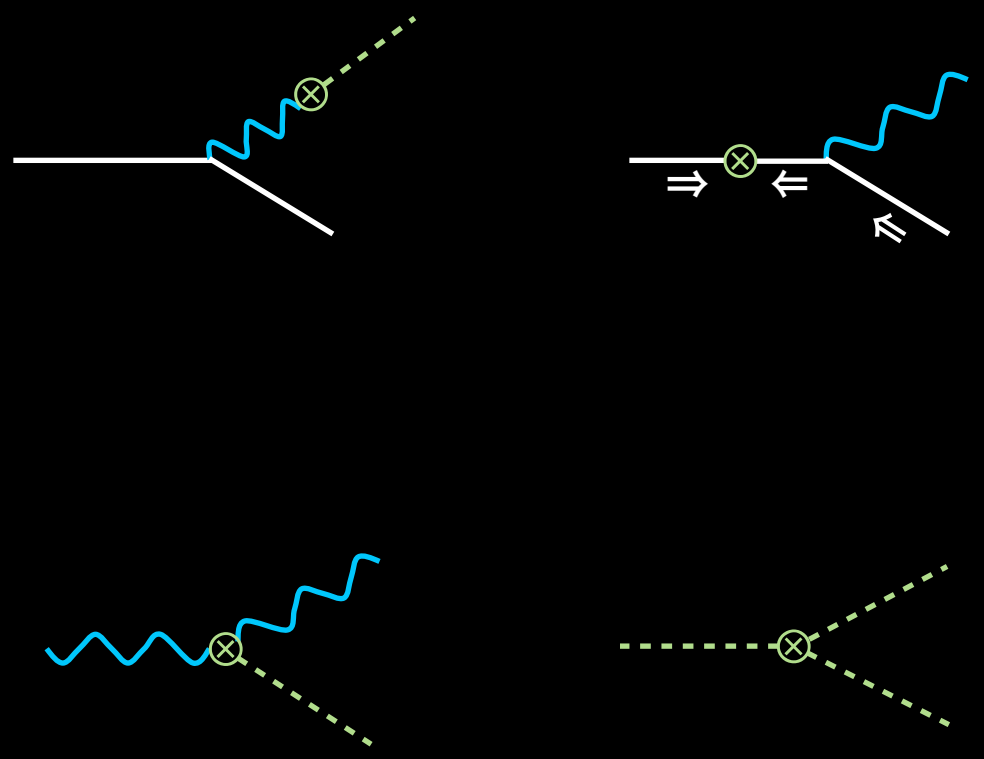
$$\mathcal{P}(q \to V_T q) \simeq (3 \times 10^{-3}) \left[\log \frac{E}{m_{\rm EW}}\right]^2 \quad \Rightarrow \quad \mathcal{P}(1\ \text{TeV}) \simeq 1.7\%, \quad \mathcal{P}(10\ \text{TeV}) \simeq 7\%$$

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

Parton Lumis at 100 TeV Collider

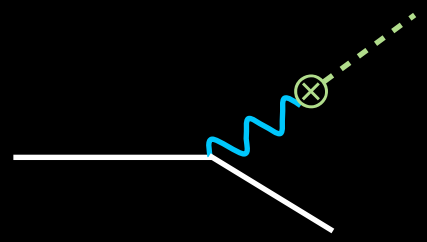


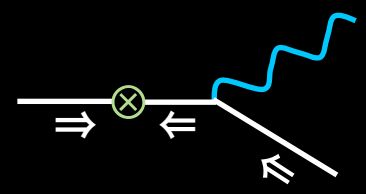
"Broken" Showering at O(v)



"Broken" Showering at O(v)

⇒ **log(E/m)**





⇒ **constant***

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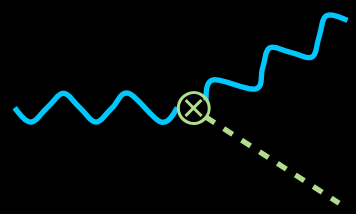
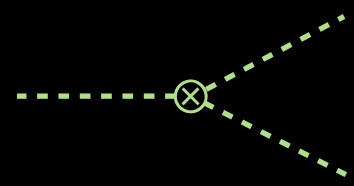




⇒ **constant***

(~0.001)

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

Gauging to Manifest Goldstone Equivalence

(rotating) lightcone gauge condition

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

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

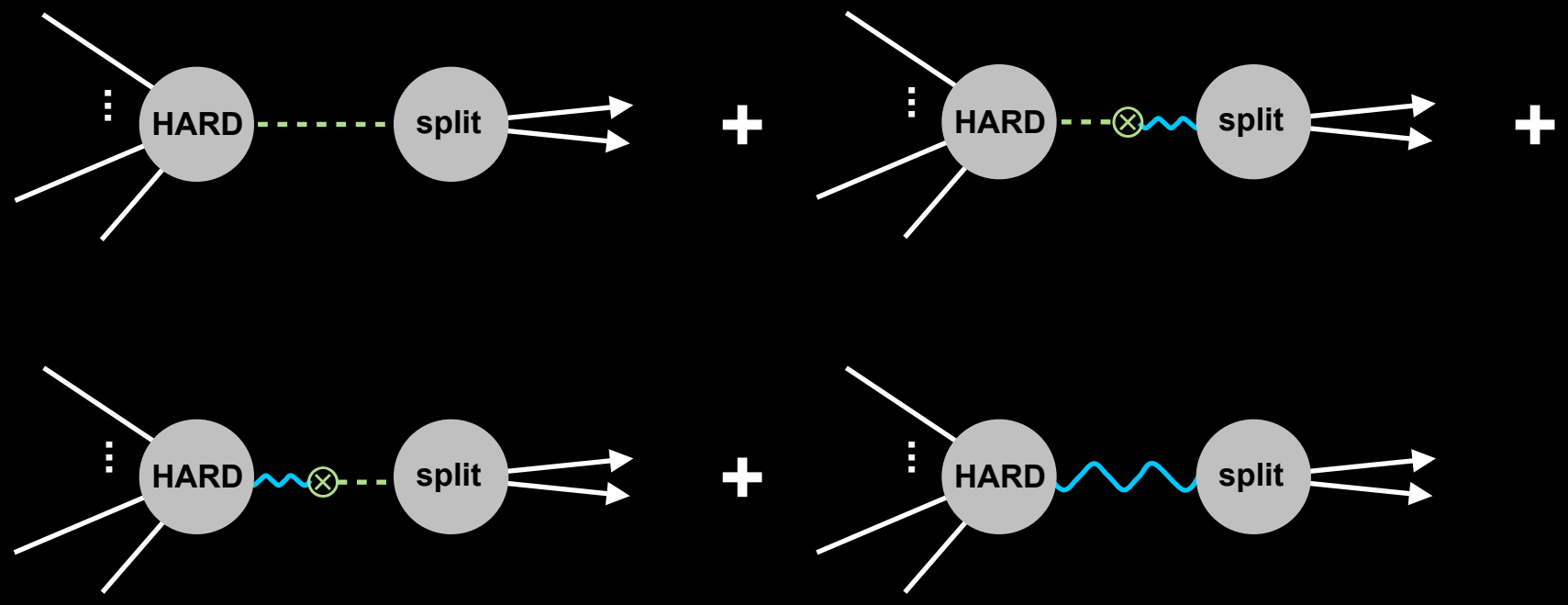
$$\text{long. polarization } \epsilon^\mu_\phi(k) \equiv \frac{\sqrt{|k^2|}}{n(k)\cdot k} n^\mu(k)$$

$$\begin{aligned}
\langle A_T(k)A_T(-k)\rangle &= \frac{i}{k^2-m^2} \\
\langle A_\phi(k)A_\phi(-k)\rangle &= \frac{i}{k^2-m^2}\,\mathrm{sign}(k^2) \\
\langle \phi(k)\phi(-k)\rangle &= \frac{i}{k^2-m^2} \\
\langle A_\phi(k)\phi(-k)\rangle &= \frac{i}{k^2-m^2}\frac{-im}{\sqrt{|k^2|}}\,.
\end{aligned}$$

- Delete (sometimes) problematic k^μ/m part of longitudinal polarization
  - replaced by on- & off-shell in Feynman rules by Goldstone
  - amplitude to create on-shell longitudinal from $A^\mu \sim m/E$
- Keep mixed field basis
- Unlike R_ξ, Goldstone field interpolates physical longitudinal bosons (amplitude ~ i)

* see also **Wulzer (1309.6055), Srivastava & Brodsky (hep-ph/0202141)**, earlier papers

Factorization for Longitudinals



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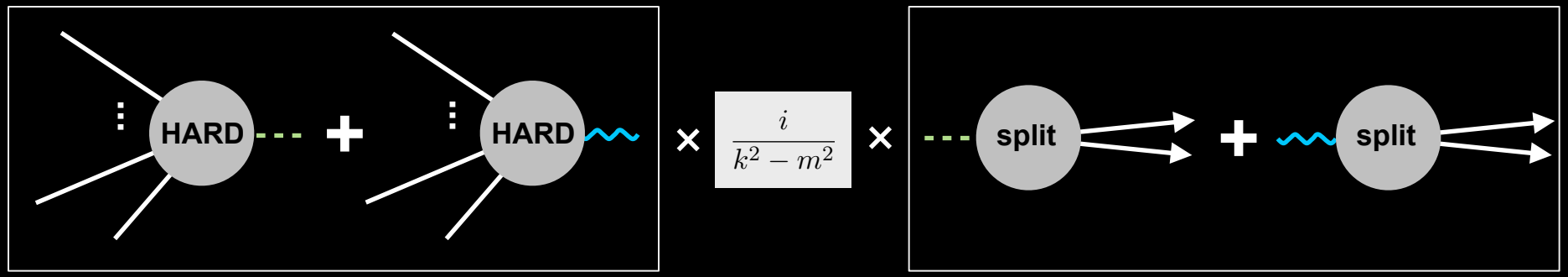


+ regular (~1/E²)

Transverse Vector Total Splitting Rates

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

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

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

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

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

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

Longitudinal Vector Total Splitting Rates

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

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

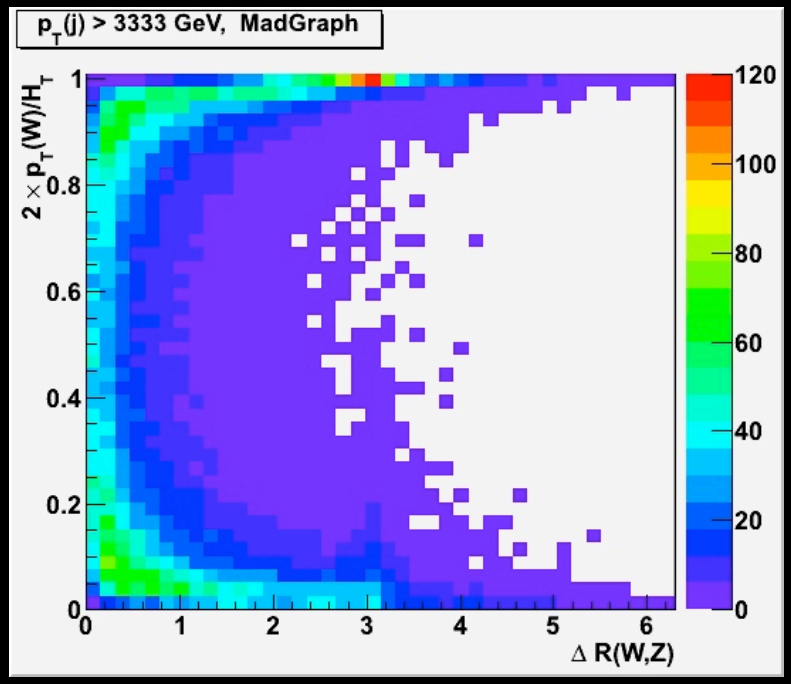
Plus many others.....

Our Shower Program

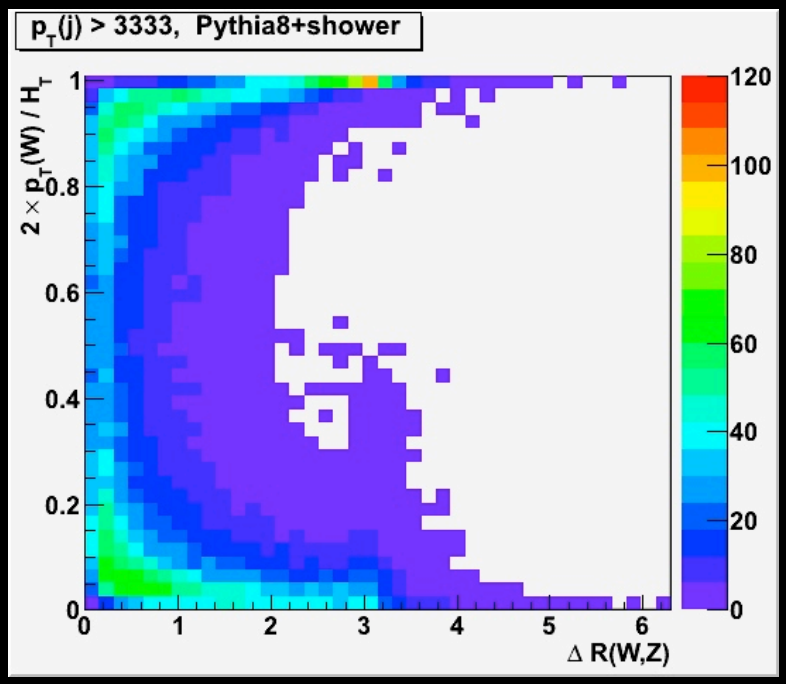
- Currently PYTHIA6-like virtuality-ordered
  - collinear approximation, no coherence between dipoles
- Polarized splittings
- Massive splitting functions
  - amplitudes and phase space
- Reweighting of secondary splittings
- Interleaved with QCD
- Only FSR (so far)
- Built in C++...ideally adapt to run within PYTHIA 8 framework

WZ+Jet Revisited

MadGraph



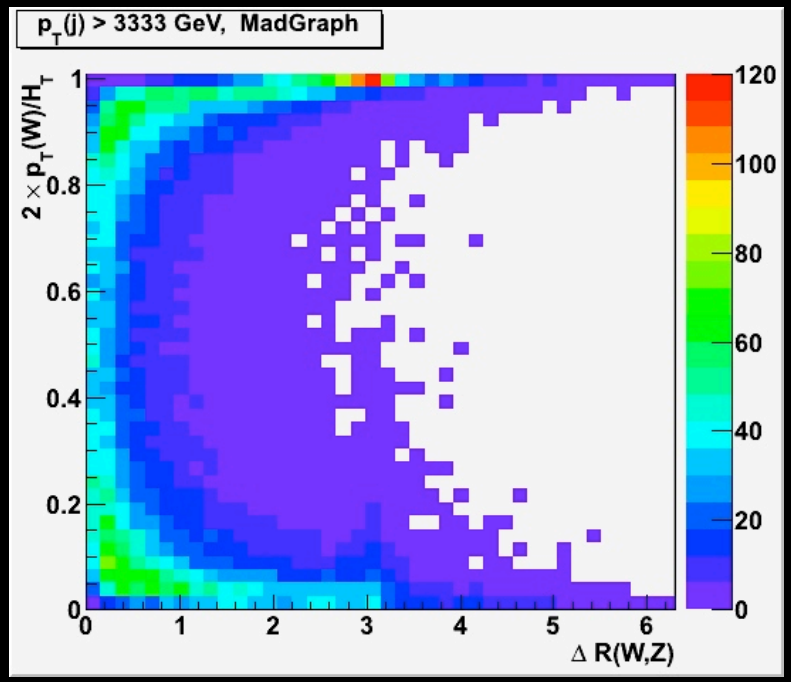
Pythia8 W/Z+jet + EW-Shower



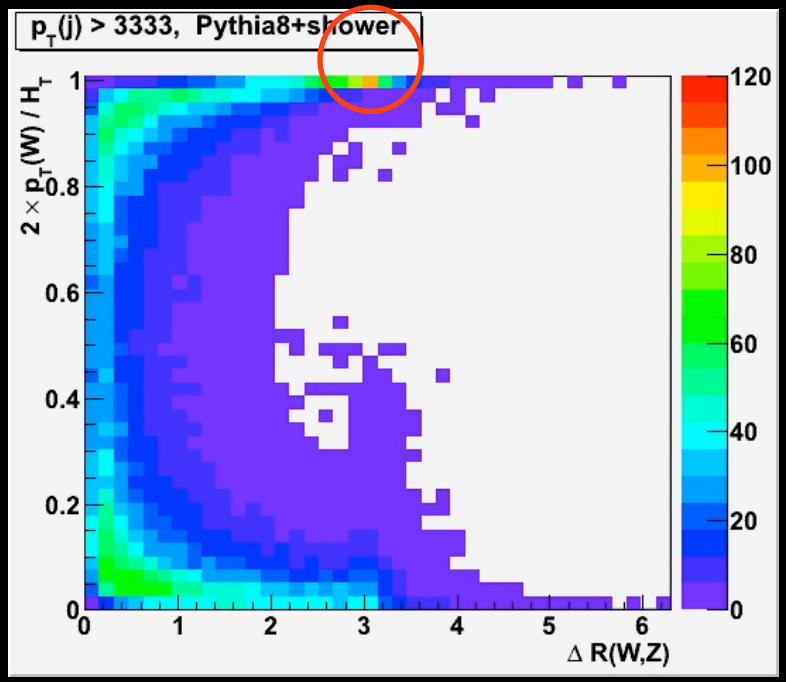
WZ+Jet Revisited

~10% loss from further showering

MadGraph

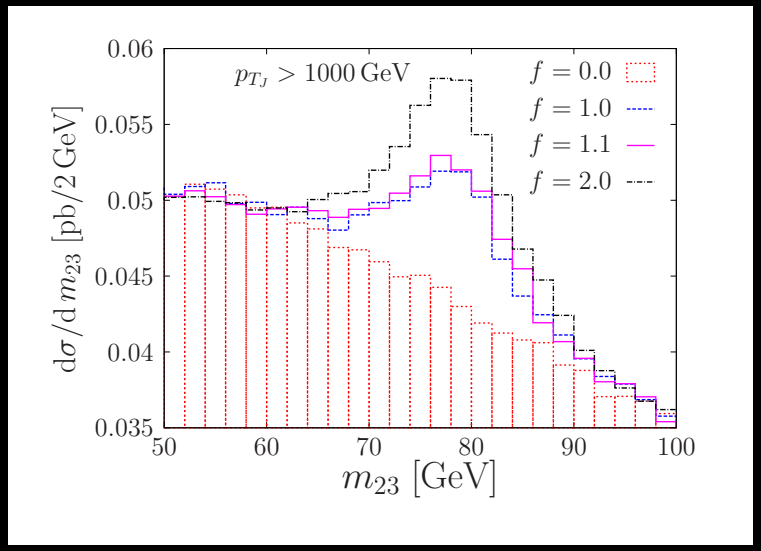


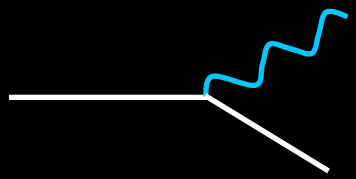
Pythia8 W/Z+jet + EW-Shower



Measurement of Weakstrahlung Rate (LHC)

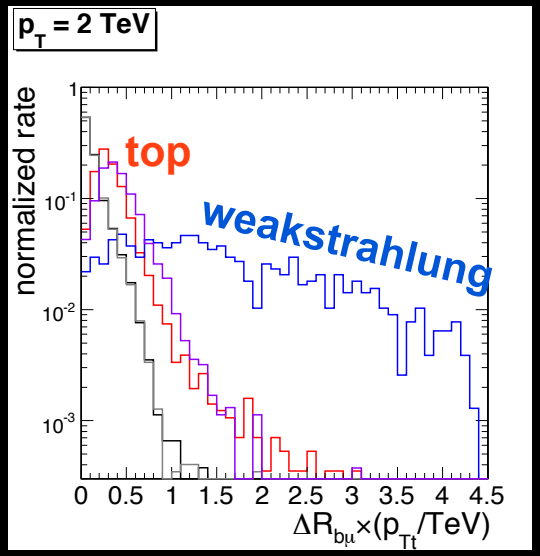
Krauss, Petrov, Schönherr, Spannowsky (1403.4788)





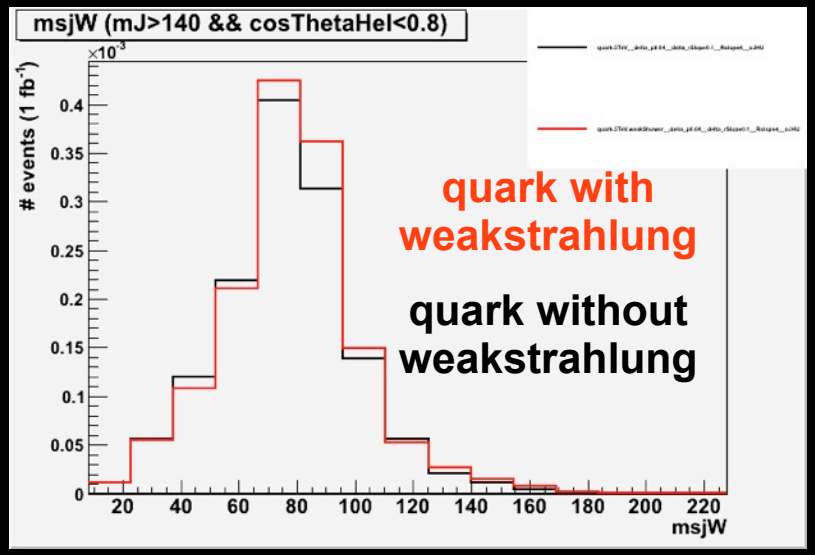
Effect on Top-Tagging (Any p_T > TeV)

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



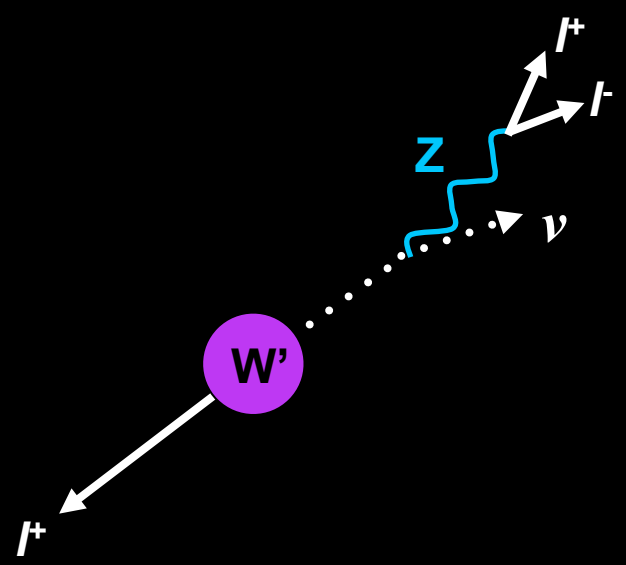
Rehermann & Tweedie (1007.2221)

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

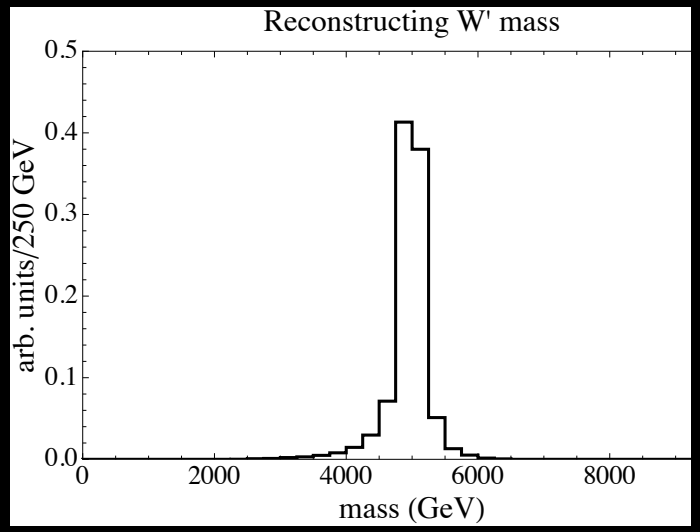


with Z Han & M Son

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: potentially O(1) showering probability
  - KK graviton: 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

"New" Higgs Production Modes

Are they good for something? Reduced systematics? Complementary information?

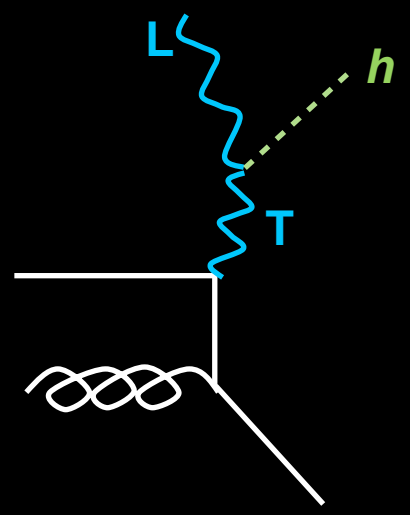
	Process	$\sigma_{\rm NLO}$(8 TeV) [fb]	$\sigma_{\rm NLO}$(100 TeV) [fb]	ρ
$pp \to$	$H\ (m_t, m_b)$	$1.44 \cdot 10^4\ ^{+20\%}_{-16\%}\ ^{+1\%}_{-2\%}$	$5.46 \cdot 10^5\ ^{+28\%}_{-27\%}\ ^{+2\%}_{-2\%}$	38
$pp \to$	Hjj (VBF)	$1.61 \cdot 10^3\ ^{+1\%}_{-0\%}\ ^{+2\%}_{-2\%}$	$7.40 \cdot 10^4\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-1\%}$	46
$pp \to$	$Ht\bar{t}$	$1.21 \cdot 10^2\ ^{+5\%}_{-9\%}\ ^{+3\%}_{-3\%}$	$3.25 \cdot 10^4\ ^{+7\%}_{-8\%}\ ^{+1\%}_{-1\%}$	269
$pp \to$	$Hb\bar{b}$ (4FS)	$2.37 \cdot 10^2\ ^{+9\%}_{-9\%}\ ^{+2\%}_{-2\%}$	$1.21 \cdot 10^4\ ^{+2\%}_{-10\%}\ ^{+2\%}_{-2\%}$	51
$pp \to$	Htj	$2.07 \cdot 10^1\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$5.21 \cdot 10^3\ ^{+3\%}_{-5\%}\ ^{+1\%}_{-1\%}$	252
$pp \to$	$HW^\pm$	$7.31 \cdot 10^2\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$1.54 \cdot 10^4\ ^{+5\%}_{-8\%}\ ^{+2\%}_{-2\%}$	21
$pp \to$	HZ	$3.87 \cdot 10^2\ ^{+2\%}_{-1\%}\ ^{+2\%}_{-2\%}$	$8.82 \cdot 10^3\ ^{+4\%}_{-8\%}\ ^{+2\%}_{-2\%}$	23
$pp \to$	HW^+W^- (4FS)	$4.62 \cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$1.68 \cdot 10^2\ ^{+5\%}_{-6\%}\ ^{+2\%}_{-1\%}$	36
$pp \to$	$HZW^\pm$	$2.17 \cdot 10^0\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-2\%}$	$9.94 \cdot 10^1\ ^{+6\%}_{-7\%}\ ^{+2\%}_{-1\%}$	46
$pp \to$	$HW^\pm\gamma$	$2.36 \cdot 10^0\ ^{+3\%}_{-3\%}\ ^{+2\%}_{-2\%}$	$7.75 \cdot 10^1\ ^{+7\%}_{-8\%}\ ^{+2\%}_{-1\%}$	33
$pp \to$	$HZ\gamma$	$1.54 \cdot 10^0\ ^{+3\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.29 \cdot 10^1\ ^{+5\%}_{-7\%}\ ^{+2\%}_{-2\%}$	28
$pp \to$	HZZ	$1.10 \cdot 10^0\ ^{+2\%}_{-2\%}\ ^{+2\%}_{-2\%}$	$4.20 \cdot 10^1\ ^{+4\%}_{-6\%}\ ^{+2\%}_{-1\%}$	38
$pp \to$	$HW^\pm j$	$3.18 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-1\%}$	$1.07 \cdot 10^4\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	34
$pp \to$	$HW^\pm jj$	$6.06 \cdot 10^1\ ^{+6\%}_{-8\%}\ ^{+1\%}_{-1\%}$	$4.90 \cdot 10^3\ ^{+2\%}_{-6\%}\ ^{+1\%}_{-1\%}$	81
$pp \to$	HZj	$1.71 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+1\%}_{-1\%}$	$6.31 \cdot 10^3\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	37
$pp \to$	$HZjj$	$3.50 \cdot 10^1\ ^{+7\%}_{-10\%}\ ^{+1\%}_{-1\%}$	$2.81 \cdot 10^3\ ^{+2\%}_{-5\%}\ ^{+1\%}_{-1\%}$	80

Table 1: Production of a single Higgs boson at the LHC and at a 100 TeV FCC-hh. The rightmost column reports the ratio ρ of the FCC-hh to the LHC cross sections. Theoretical uncertainties are due to scale and PDF variations, respectively. Monte-Carlo-integration error is always smaller than theoretical uncertainties, and is not shown. For $pp \to HVjj$, on top of the transverse-momentum cut of section 2, I require $m(j_1, j_2) > 100$ GeV, j_1 and j_2 being the hardest and next-to-hardest jets, respectively. Processes $pp \to Htj$ and $pp \to Hjj$ (VBF) do not feature jet cuts.

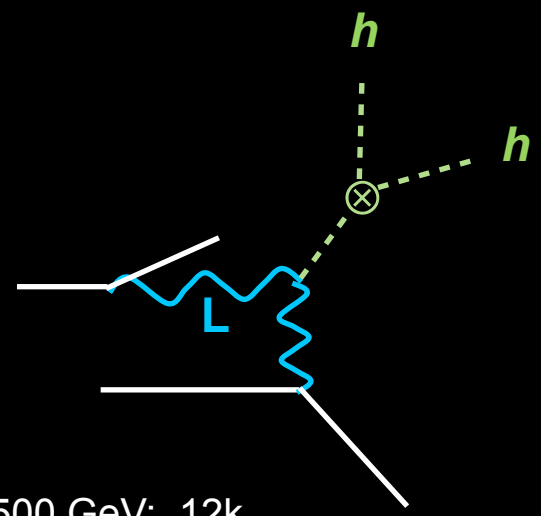
*slide from Mangano (HXSWG meeting, July)

P.Torrielli, arXiv:1407.1623

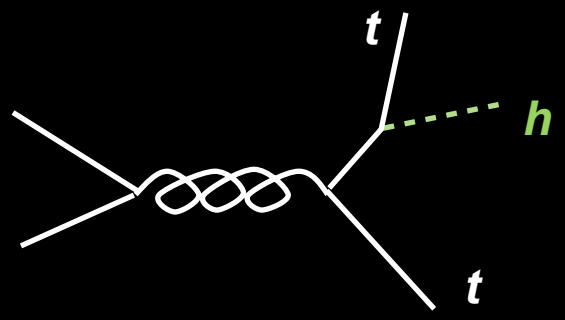
Example Topologies



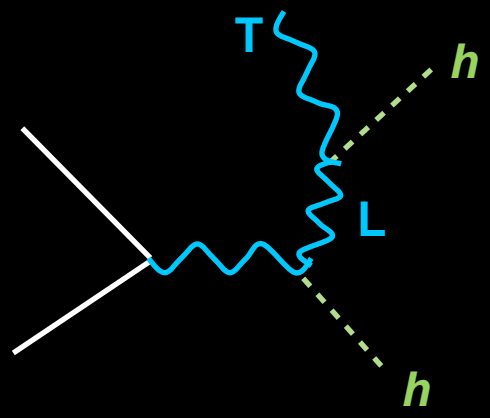
500 GeV: 2.5M (30 ab)$^{-1}$
1 TeV: 250k



500 GeV: 12k
1 TeV: 1.4k



500 GeV: 75M
1 TeV: 6M

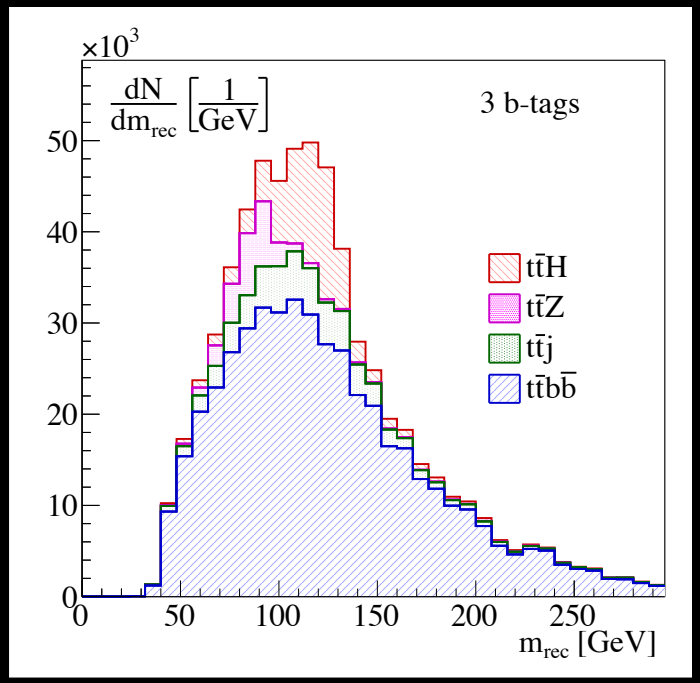


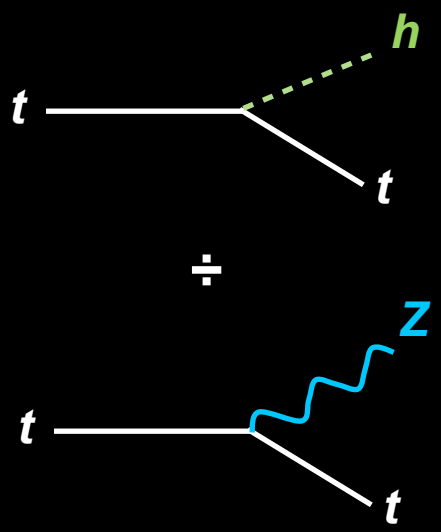
500 GeV: 14k
1 TeV: 2.5k

Balance of "clean" high-p_T topologies vs small high-p_T rates not a priori obvious

Semi-Boosted Measurement of Top Yukawa

Mangano, et al (1507.08169)





Δy ~ % with 20 ab^{-1}

PDF uncertainties cancel

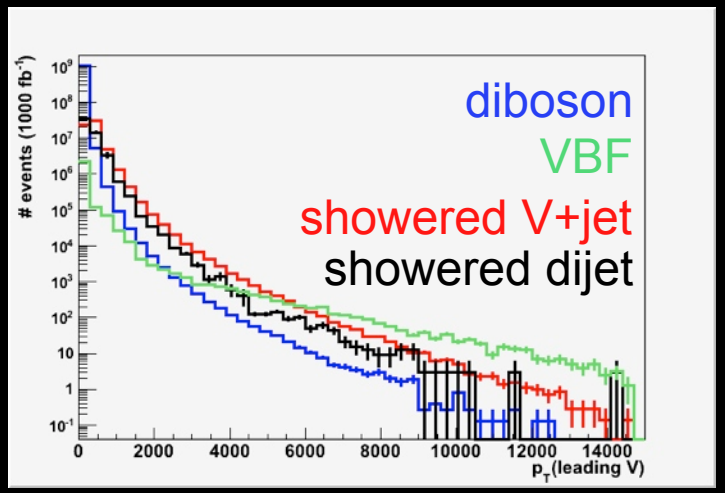
Summary

- 100 TeV collider opens up new kinematic regimes for interactions of EW-scale particles
  - hopefully this at least served as a reminder
- EW splitting processes quickly grow/asymptote in rate
  - range from totally negligible to O(1), depending on what you're looking at
- We're working on a multipurpose EW shower program
  - "quick and dirty" way to capture universal collinear physics
  - main addition is W→WW, lots of other Higgs and Goldstone-equivalent processes
- Opportunities for precision/supplementary coupling measurements in/near these kinematic regions
- Sensitivity to new "light" states?

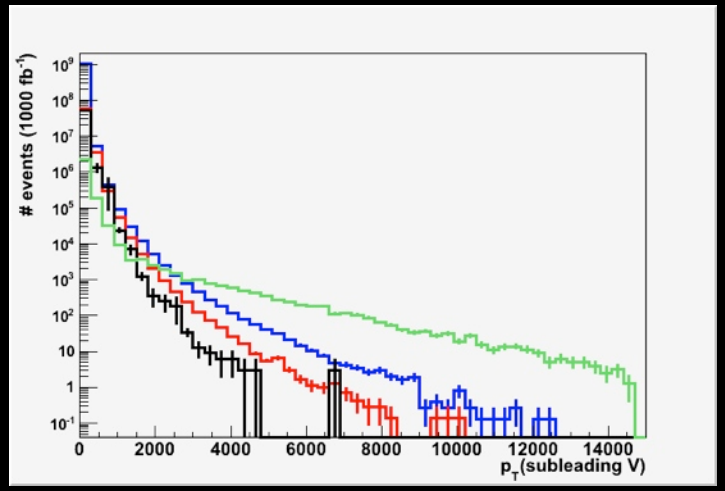
More...

"Shower" Vs "Prompt" Diboson

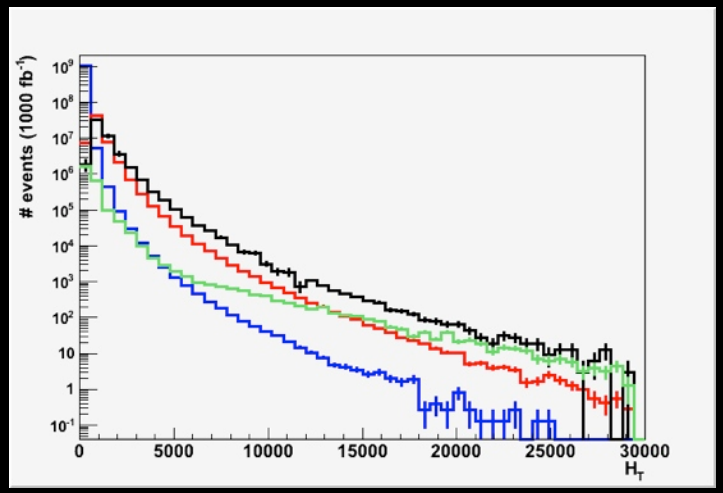
p_T(leading V)



p_T(subleading V)

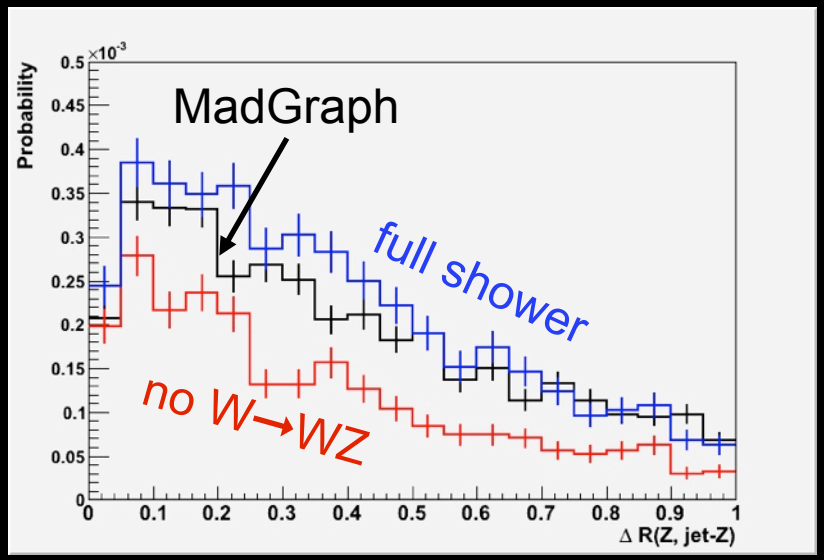


H_T(jets + V's)

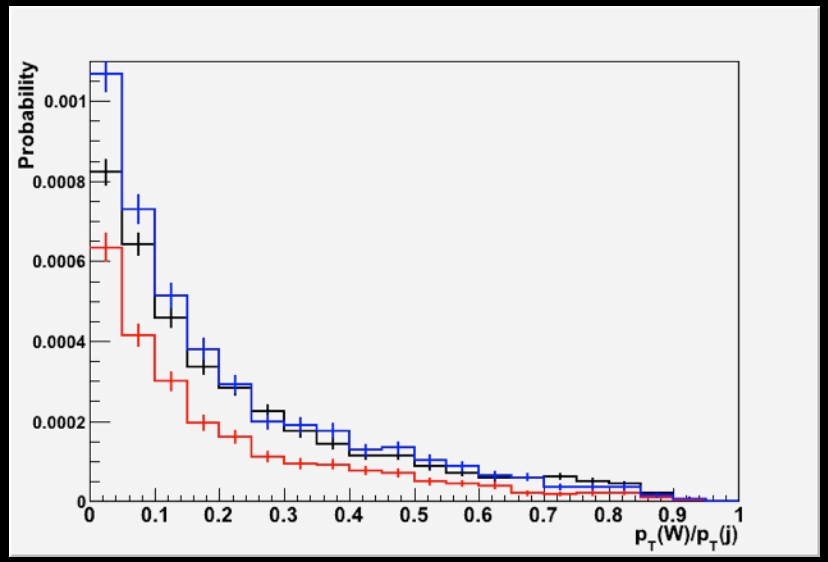


Multiple Weak Emissions Inside One Jet

$u_L(10\ \text{TeV}) \rightarrow d_L W^+ Z$



ΔR(Z, rest of jet)



$p_T(W) / p_T(j)$

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

Isospin Self-Averaged PDFs