Electroweak Splitting Functions and High Energy Showering

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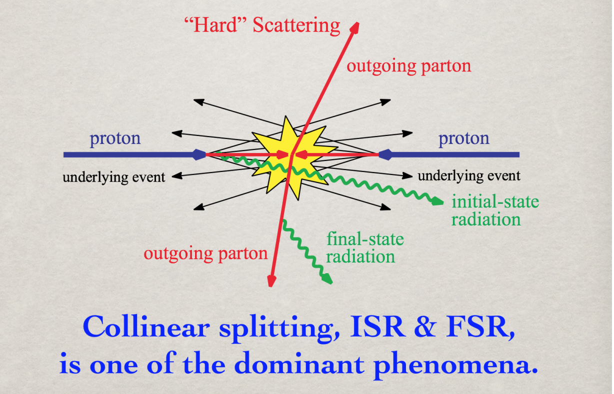
Collisions in Colliders

Proton-proton scattering: sum of free quarks and gluons scatterings.



QCD Parton Shower and Electroweak Shower

- For Strong Interactions, when hard scattering scales $\sim$ 50 GeV

$$\frac{50\,GeV}{\Lambda_{QCD} \sim 500\,MeV} >> 1$$

  Parton shower emerges

- In a 100 TeV Collider, hard scattering could scale $\sim$ 10 TeV

$$\frac{10\,TeV}{m_W \sim 100\,GeV} \sim \frac{50\,GeV}{\Lambda_{QCD} \sim 500\,MeV} >> 1$$

- We are facing a new phenomenon: electroweak parton shower.

Novelties of Electroweak Showering

Novelties of electroweak showering:

- Spontaneous symmetry breaking:
  1. massive particle: perturbative shut-off
  2. additional degrees of freedom: longitudinal and higgs
- Chirality: Left-handed fermions and right-handed fermions couple differently.
- Neutral bosons interference: γ/Z_T; h/Z_L
- Weak isospin self-averaging.

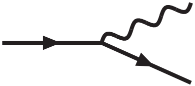
Focus today:

- Neutral interference.
- VEV corrections, i.e. the effects of EW symmetry breaking.

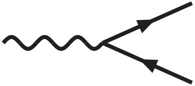
Splitting Functions in Unbroken Limit (showering at high energy scale $>> v$).

$$d\sigma_{X,B+C} \simeq d\sigma_{X,A} \times d\mathcal{P}_{A\to B+C}$$

Splittings analogue to QCD



$$P_{f_L \to f_L + W_T/Z_T} \sim \alpha_W \frac{1+(1+z)^2}{z} \cdot \frac{1}{p_T^2} \qquad P_{W_T \to W_T Z_T/\gamma} \sim \alpha_W \frac{(1-z\bar{z})^2}{z(1-z)} \cdot \frac{1}{p_T^2}$$

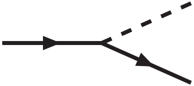


$$P_{W_T/Z_T \to f_L \bar{f}_R} \sim \alpha_W \frac{1}{p_T^2}$$

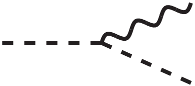
Captures leading log in EW Shower

Splitting Functions in Unbroken Limit (Showering at high energy scale $>> v$).

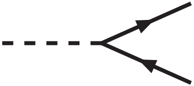
Splittings with higgs and longitudinal, with $W_L^{\pm} \sim \phi_L^{\pm}$ and $Z_L \sim \phi_0$



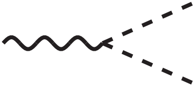
$P_{f_L \to f_R^{(\prime)} + h/W_L^{\pm}} \sim y_{f^{(\prime)}}^2 \frac{1}{p_T^2}$
(helicity flipped)



$P_{W_L^{\pm} \to W_T^{\pm} h/Z_L} \sim \alpha_W \frac{1}{z} \frac{1}{p_T^2}$



$P_{h/W_L^{\pm} \to f_L \bar{f}_L^{(\prime)}} \sim y_{f^{(\prime)}}^2 \frac{1}{p_T^2}$

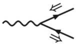


$P_{V_T \to V_L(/h) V_L/h} \sim \alpha_W \frac{1}{p_T^2}$

Captures leading log in EW shower

Neutral Interference

- Splitting formalism assumes interference to be suppressed.
- Interference can be significant for γ/Z intermediated splittings.
- Solution: matrix. $\frac{d\hat{P}_{ij}}{dk_T^2 dz}$.
  1. When $i = j$, "single state splitting functions".
  2. When $i \neq j$, interference terms.

	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{(1-z\bar{z})^2}{z\bar{z}}\right)$	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{z^2+\bar{z}^2}{2}\right)$
	$\to W_T W_T$	$f_s \bar{f}^{(\prime)}_{-s}$
V_T	$2g_2^2 \ (V{=}W^{0,\pm})$	$N_f g_V^2 (Q^V_{f_s})^2$
$[BW]^0_T$	0	$N_f g_1 g_2 Y_{f_s} T^3_{f_s}$

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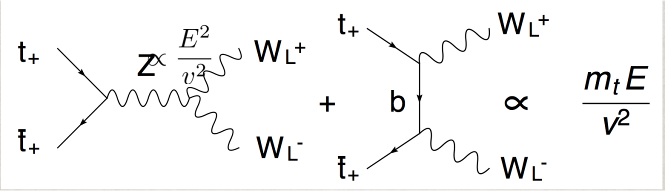
Longitudinal in Broken(Real) Theory: Huge Intereference

Longitudinal vector boson $\epsilon_L \sim \frac{k^\mu}{m_W}$, bad energy behavior and huge interference!



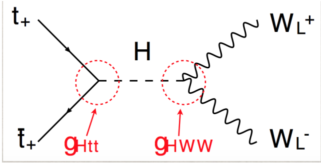
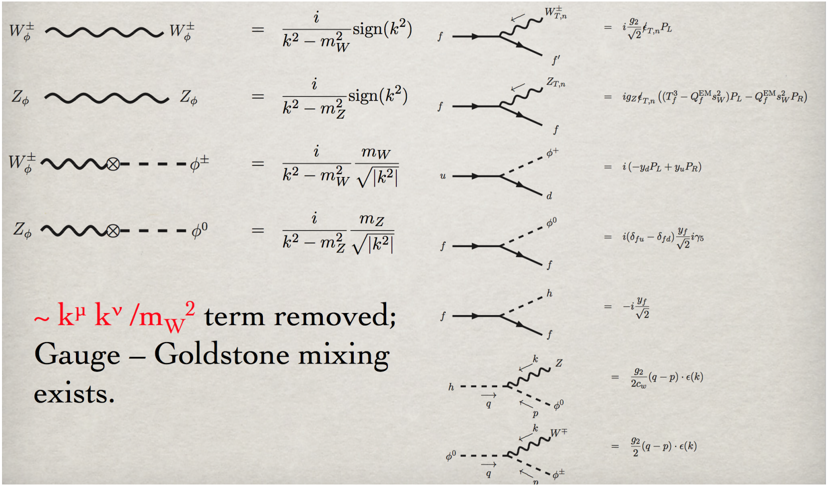


Figure: higgs contribution $\propto \frac{m_t m_h}{v^2}$ fixes the problem.

Goldstone Equivalence Gauge

- Hint to the solution: $\epsilon_L \sim \frac{k^\mu}{m_W} \to \phi_W$ in high energy — goldstone equivalence theorem.
- Write $\epsilon_L^\mu(k) = \frac{k^\mu}{m_W} - \frac{m_W}{n \cdot k} n^\mu$, with $n^\mu = (-1, \hat{k})$. So impose gauge-fixing $\frac{1}{2\xi}(n^\mu W_\mu)^2$.
- Consequences:
    1. $n \cdot k \neq 0$: k^μ terms are eliminated – power counting is good
    2. $n \cdot n = 0$, $\epsilon_n \simeq \frac{m_W}{2E}$, VEV corrections to unbroken limit.
    3. $|W_L >= |W_n > +i|\phi >$ —- manifest goldstone equivalence theorem
    4. Broken theory continuously goes to unbroken theory when $v \to 0$



$\epsilon^\mu_{s=\pm,n}$ are "stripped " out of propagators, and inserted into vertices.

Systematic VEV(mass) corrections

"Scalarizing" k^μ/m_W enables systematic incorporation of all splittings (up to log) proportional to VEV(masses)

- Massless $f \to f + V_L$ corresponds to $f \to f\phi$ according to goldstone equivalence

$$y_f = 0 \to \quad \text{gives } 0$$

- Contribution comes from VEV correction $V_n \sim \frac{m_V}{E}$: "Effective W approximation".

$$\frac{d\mathcal{P}_{f\to f+V_L}}{dz dk_T^2} \sim \frac{\alpha_2}{2\pi}\frac{1-z}{z}\frac{m_V^2}{k_T^4} \tag{1}$$

- Has been known for years: vector boson fusion observed in LHC

  S. Dawson (1985); G. Kane et al. (1984); Chanowitz & Gailard (1984)

Ultra-collinear splitting

There are characteristically new channels in the broken phase:

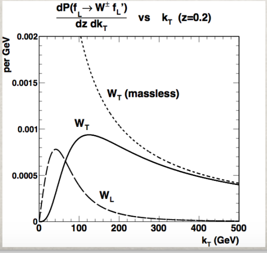
"Ultra collinear": $\frac{v^2}{k_T^2}\,\frac{dk_T^2}{k_T^2} \sim (1 - \frac{v^2}{Q^2})$

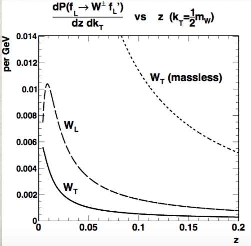
$k_T^2 > m_W^2$, it shuts off;

$k_T^2 < m_W^2$, flattens out!

The DPFs for W_L thus don't run at leading log:

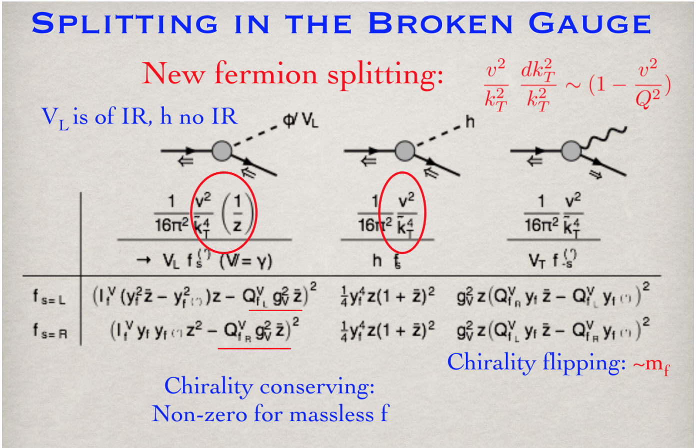
"Bjorken scaling" restored (higher-twist effects)!





New Broken Splittings: ultra-collinear behavior (11 new types)

A whole new set of broken splittings



New Broken Splittings: ultra-collinear behavior (11 new types)

A whole new set of broken splittings

Splitting in the Broken Gauge

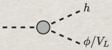
New gauge boson splitting in 3-W_L

Vector boson V_L is of IR.

$$\frac{v^2}{k_T^2}\,\frac{dk_T^2}{k_T^2} \sim (1 - \frac{v^2}{Q^2}$$

$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}\left(\frac{1}{z\bar{z}}\right)$	$\to W_L^+ W_L^-$	$Z_L W_L^\pm / Z_L$
$W_L^\pm$	0	$\frac{1}{16}g_2^4\left((\bar{z}-z)(2+z\bar{z})-t_W^2\bar{z}(1+\bar{z})\right)^2$
h	$\frac{1}{4}\left(g_2^2(1-z\bar{z})-\lambda_h z\bar{z}\right)^2$	$\frac{1}{8}\left(g_Z^2(1-z\bar{z})-\lambda_h z\bar{z}\right)^2$
Z_L	$\frac{1}{16}g_2^4\left((\bar{z}-z)(2+z\bar{z}-t_W^2 z\bar{z})\right)^2$	0
$[hZ_L]$	$\frac{i}{8}g_2^2\left(g_2^2(1-z\bar{z})-\lambda_h z\bar{z}\right)(\bar{z}-z)\left(2+z\bar{z}-t_W^2 z\bar{z}\right)$	0

h has no IR.



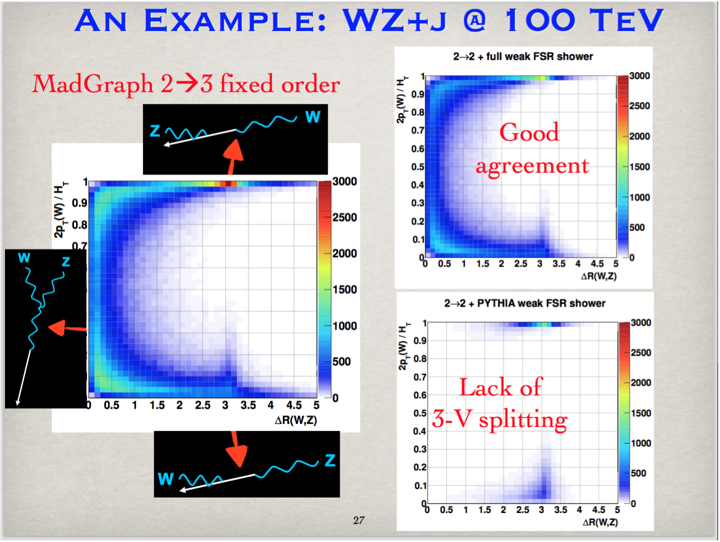
	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}\left(\frac{1}{\bar{z}}\right)$ $\to h\, W_L^\pm / Z_L$	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$ $h\, h$
$W_L^\pm$	$\frac{1}{4}z\left(g_2^2(1-z\bar{z})+\lambda_h\bar{z}\right)^2$	0

Estimations of Splitting Rates at 1 TeV and 10 TeV

Process	$\approx \mathcal{P}(E)$ (leading-log term)	$\mathcal{P}(1\ \mathrm{TeV})$	$\mathcal{P}(10\ \mathrm{TeV})$
$q \to V_T q^{(\prime)}$ (CL+IR)	$(3\times 10^{-3})\left[\log\frac{E}{m_W}\right]^2$	1.6%	7%
$q \to V_L q^{(\prime)}$ (UC+IR)	$(2\times 10^{-3})\log\frac{E}{m_W}$	0.4%	1.1%
$t_R \to W_L^+ b_L$ (CL)	$(8\times 10^{-3})\log\frac{E}{m_W}$	2.5%	4%
$t_R \to W_T^+ b_L$ (UC)	(6×10^{-3})	0.6%	0.6%
$V_T \to V_T V_T$ (CL+IR)	$(0.015)\left[\log\frac{E}{m_W}\right]^2$	7%	34%
$V_T \to V_L V_T$ (UC+IR)	$(0.014)\log\frac{E}{m_W}$	2.7%	7%
$V_T \to f\bar{f}$ (CL)	$(0.02)\log\frac{E}{m_W}$	5%	10%
$V_L \to V_T h$ (CL+IR)	$(2\times 10^{-3})\left[\log\frac{E}{m_W}\right]^2$	0.8%	4%
$V_L \to V_L h$ (UC+IR)	$(2\times 10^{-3})\log\frac{E}{m_W}$	0.5%	1%

- Double log $>$ single log.
- "Color" factor $C_A(adjoint) > C_F(fundamental)$: biggest from gauge-triple splitting

"Weak jets": EW Showering with Multiple Gauge Bosons



Top decay & shower

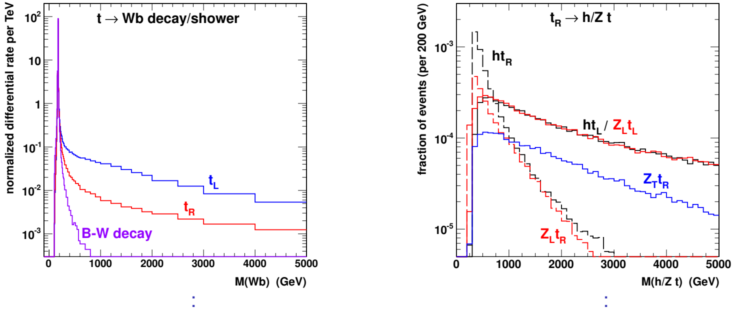
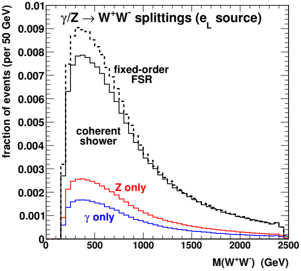


Figure: a) Splitting corrections to "tail" of top decay; b) interplay of multiple elements of top showering: yukawa (ϕ) & gauge coupling (W_n); helicity conserving & flipping.

Neutral boson interference: γ/Z_T initiated splittings



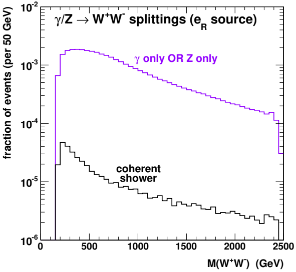


Figure: Left: LH electron source, constructive interference;
Right: RH electron source, mainly B_0 intermediated, destructive. More transparent in B_0/W_0 basis.

Collimated higgses

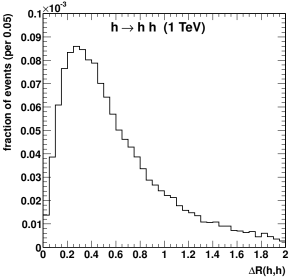


Figure: $h \to hh$, rare but interesting.

Summary

- With the increase of energy scale in colliders, we are facing a new phenomenon of EW shower.
- EW sector presents rich physics
- With the help of a new gauge (GEG), we are able to calculate all the EW (collinear log) splitting functions.
    1. Unbroken limit: analogue to QCD
    2. Broken: systematic VEV corrections – ultra-collinear splittings
- We incorporate EW showering into a Monte Carlo program
    1. More complete
    2. More accurate in implementation
- Looking forward to seeing them in real world! (and in your programs).

Thank you!

New Broken Splittings: ultra-collinear behavior

A whole new set of broken splittings

SPLITTING IN THE BROKEN GAUGE

New gauge boson splitting to $W_L W_T$

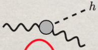
Vector boson V_L is of IR.

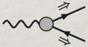
$$\frac{v^2}{k_T^2}\,\frac{dk_T^2}{k_T^2} \sim \left(1-\frac{v^2}{Q^2}\right)$$

$$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}\left(\frac{1}{z}\right)$$

	$\to W_L^\pm\,\gamma_T$	$W_L^\pm\,Z_T$	$Z_L\,W_T^\pm$	$W_L^+\,W_T^-$ or $W_L^-\,W_T^+$
$W_T^\pm$	$e^2 g_2^2 \bar{z}^3$	$\frac{1}{4}c_W^2 g_2^4 \bar{z}\left((1+\bar{z})+t_W^2 z\right)^2$	$\frac{1}{4}g_2^4\bar{z}(1+\bar{z})^2$	0
γ_T	0	0	0	$e^2 g_2^2 \bar{z}$
Z_T	0	0	0	$\frac{1}{4}c_W^2 g_2^4 \bar{z}\left((1+\bar{z})-t_W^2 z\right)^2$
$[\gamma Z]_T$	0	0	0	$\frac{1}{2}c_W e g_2^3 \bar{z}\left((1+\bar{z})-t_W^2 z\right)$

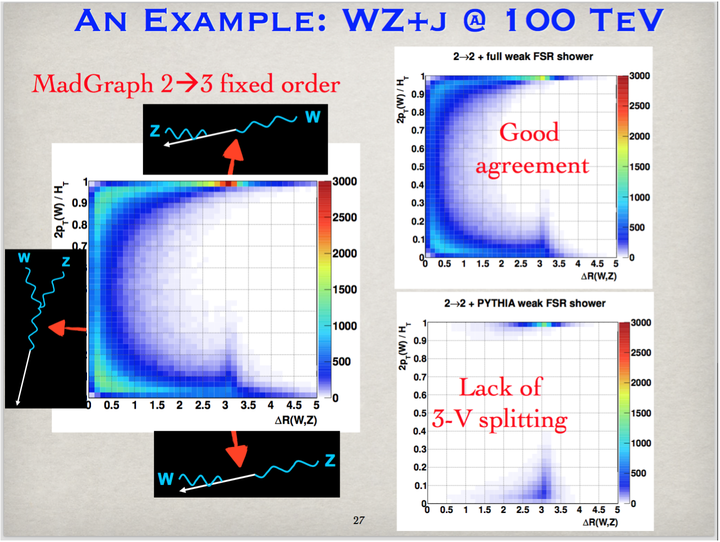
h & f have no IR.



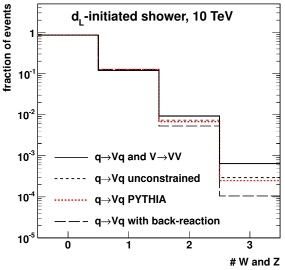


	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$
	$\to h\,V_T\ (V \neq \gamma)$	$f_s\,\bar{f}_s^{(\prime)}$
V_T	$\frac{1}{4}z\bar{z}g_V^4$	$\frac{1}{2}g_V^2\left(Q_{f_s}^V y_{f^{(\prime)}} z + Q_{f_{-s}}^V y_f \bar{z}\right)^2$
$[\gamma Z]_T$	0	$\frac{1}{2}e g_Z y_f^2 Q_f^\gamma \left(Q_{f_s}^Z z + Q_{f_{-s}}^Z \bar{z}\right)$

"Weak jets": EW Showering with Multiple Gauge Bosons



EW Showering with Multiple Gauge Bosons



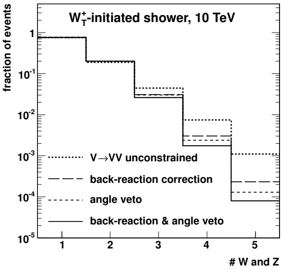


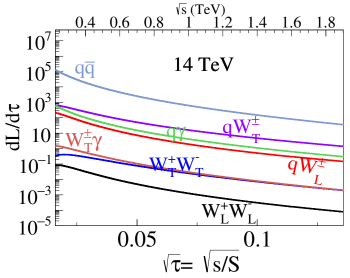
Figure: $O(10\%)$ suppression for every additional boson radiation;
Back reaction & angular veto: more precisely (comparing with Pythia 8) taking care of phase space.

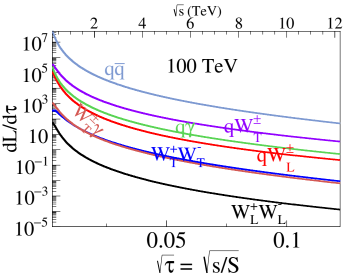
Implementation and New Phenomenon: EW PDF

- At high energy, EW particles "show up" in the initial beams, i.e. EW PDFs.
- A useful intermediate concept is luminosities, with which the total cross section could be written as,

$$\sigma_{PP}(V_1 V_2 \to X) = \int_{\tau_{\rm low}}^{\tau_{\rm high}} d\tau \, \frac{d\mathcal{L}_{V_1 V_2}}{d\tau} \, \hat{\sigma}(V_1 V_2 \to \hat{X}_\tau) \,, \qquad (2)$$

-
$$\frac{d\mathcal{L}_{V_1 V_2}}{d\tau} \simeq \frac{2}{(\delta_{V_1 V_2}+1)} \int_\tau^1 \frac{d\xi}{\xi} \int_{\tau/\xi}^1 \frac{dz_1}{z_1} \int_{\tau/\xi/z_1}^1 \frac{dz_2}{z_2} \times \sum_{q_1,q_2} f_{V_1\in q_1}(z_1) f_{V_2\in q_2}(z_2) \; f_{q_1\in P}(\xi) f_{q_2\in P}\left(\frac{\tau}{\xi z_1 z_2}\right) \quad (3)$$


√s (TeV)
14 TeV
dL/dτ
qq̄
qγ
qW±T
W±Tγ
W+TW-T
qW±L
W+LW-L
√τ= √s/S


√s (TeV)
100 TeV
dL/dτ
qq̄
W±Tγ
qγ
qW±T
W+TW-T
qW±L
W+LW-L
√τ = √s/S

:

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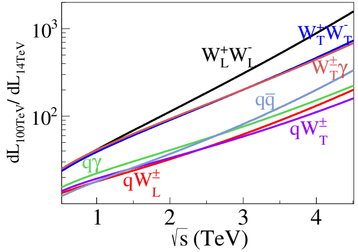
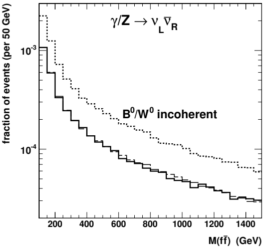
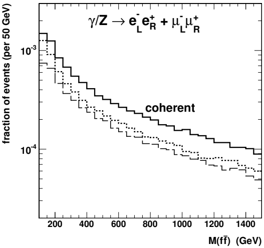

dL100TeV/ dL14TeV
W+TW-T
W+LW-L
W±Tγ
qq̄
qW±T
qγ
qW±L
√s (TeV)

More on neutral boson interference





Implementation and New Phenomenon: h/Z_L and higgs

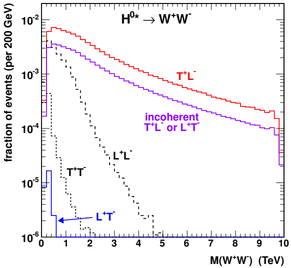


Figure: (a) h/Z_L interference, usually maximal. More transparent in H_0/H_0^* basis (b) $h \to hh$, rare but interesting.

EW Showering Effects on New Physics

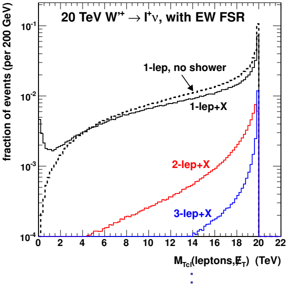
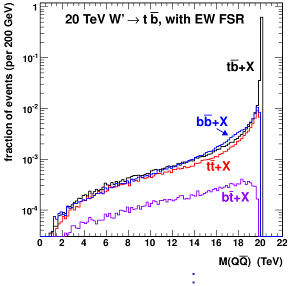


Figure: Showered events from 20 TeV W'^{+} decays. Invariant mass more sharply peaked for multiple splittings.

Isospin self-averaging & Combining QCD effects



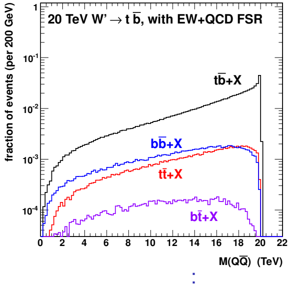


Figure: Showered events from 20 TeV W'^{+} decays. (a) $W'^{+} \rightarrow t_L \bar{b}_R$, full EW shower, and (b) combining EW and QCD showering.