Splitting & Showering in the EW Sector

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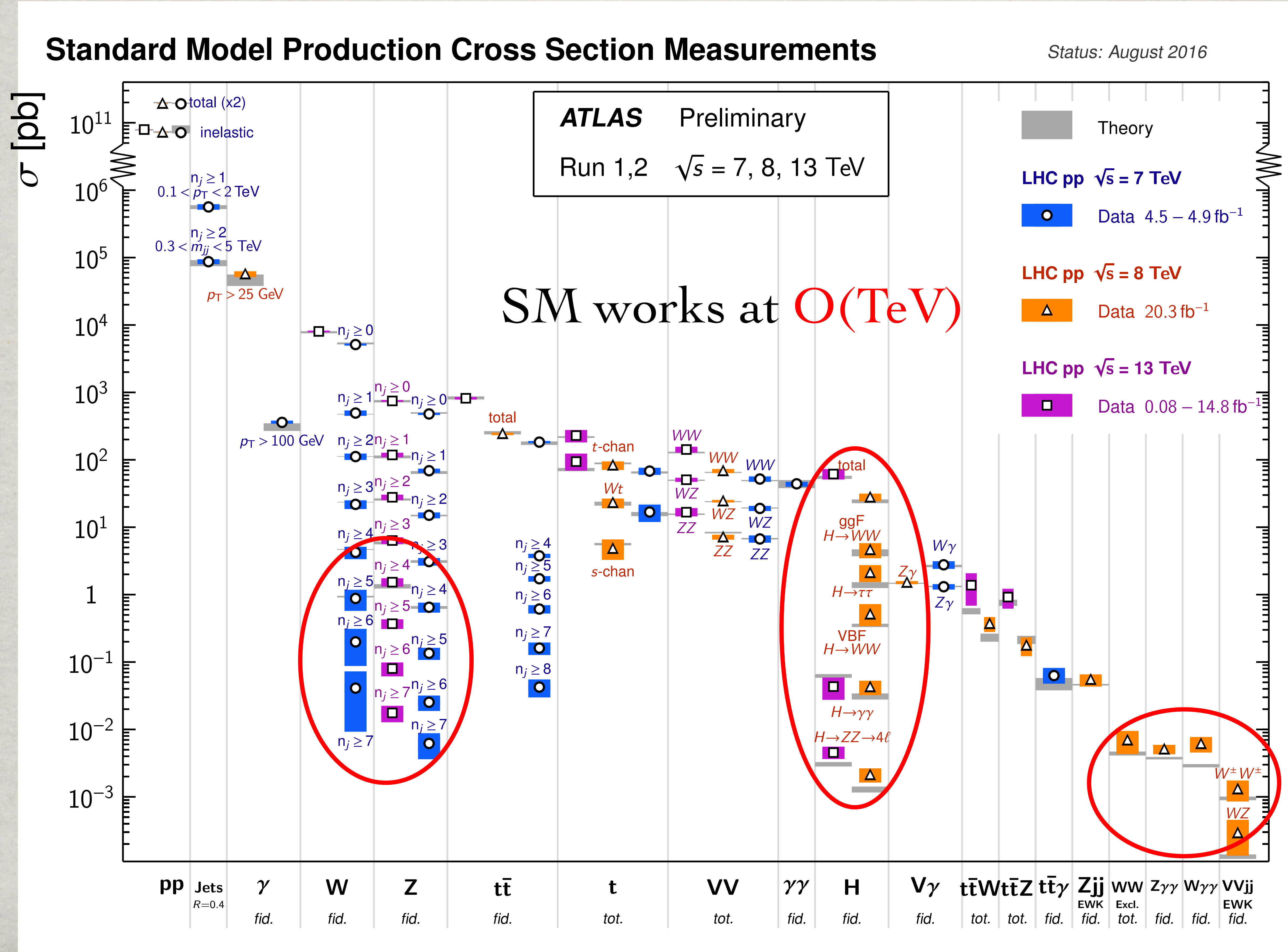
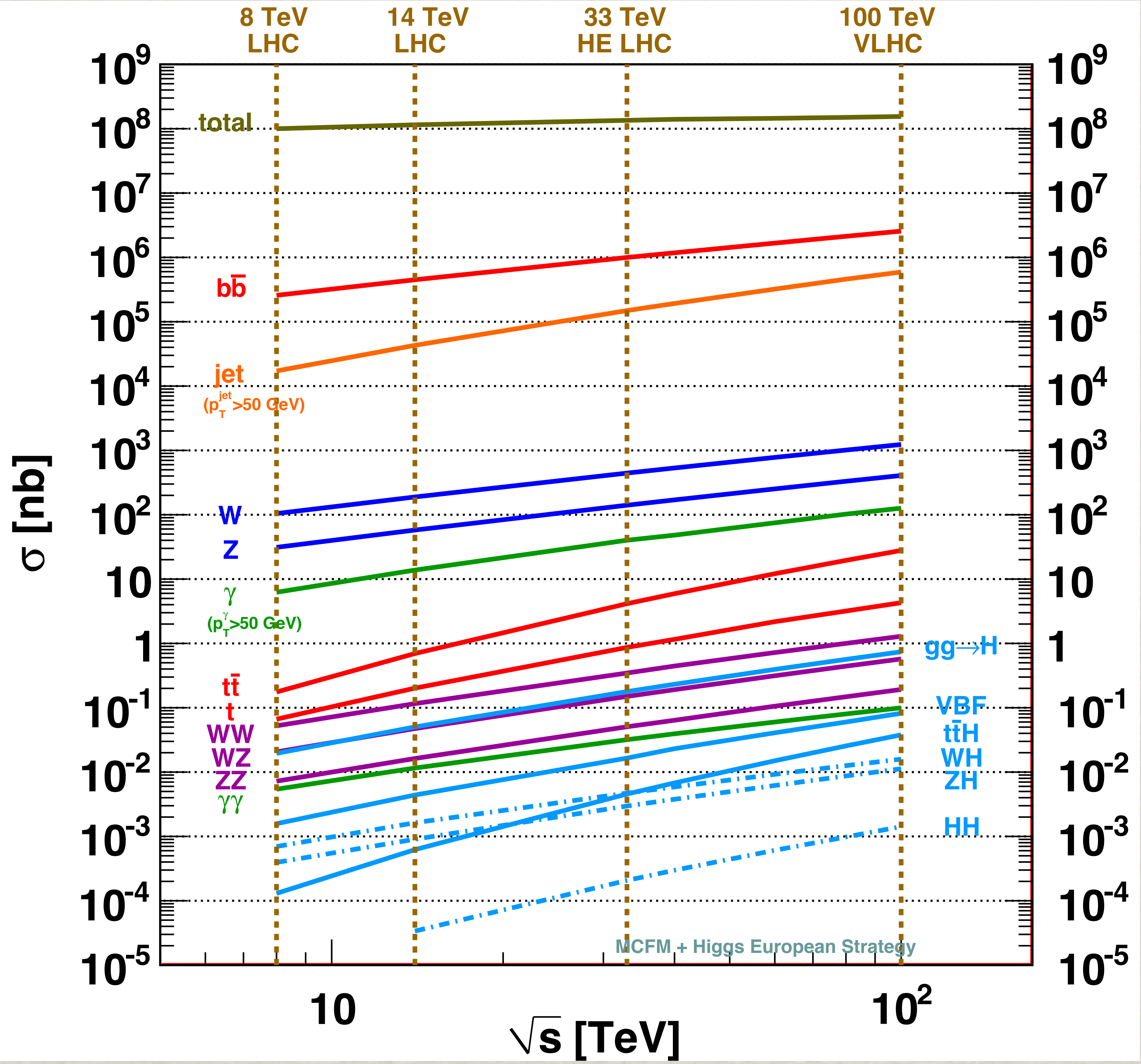
In collaboration with J.M. Chen & B. Tweedie, arXiv:1611.00788

LHC Rocks!



Standard Model Production Cross Section Measurements
Status: August 2016
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
SM works at O(TeV)
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 14.8 fb⁻¹
σ [pb]
total (x2)
inelastic
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
Vγ
tt̄W
tt̄Z
tt̄γ
Zjj
WW
Zγγ
Wγγ
VVjj
fid.
tot.

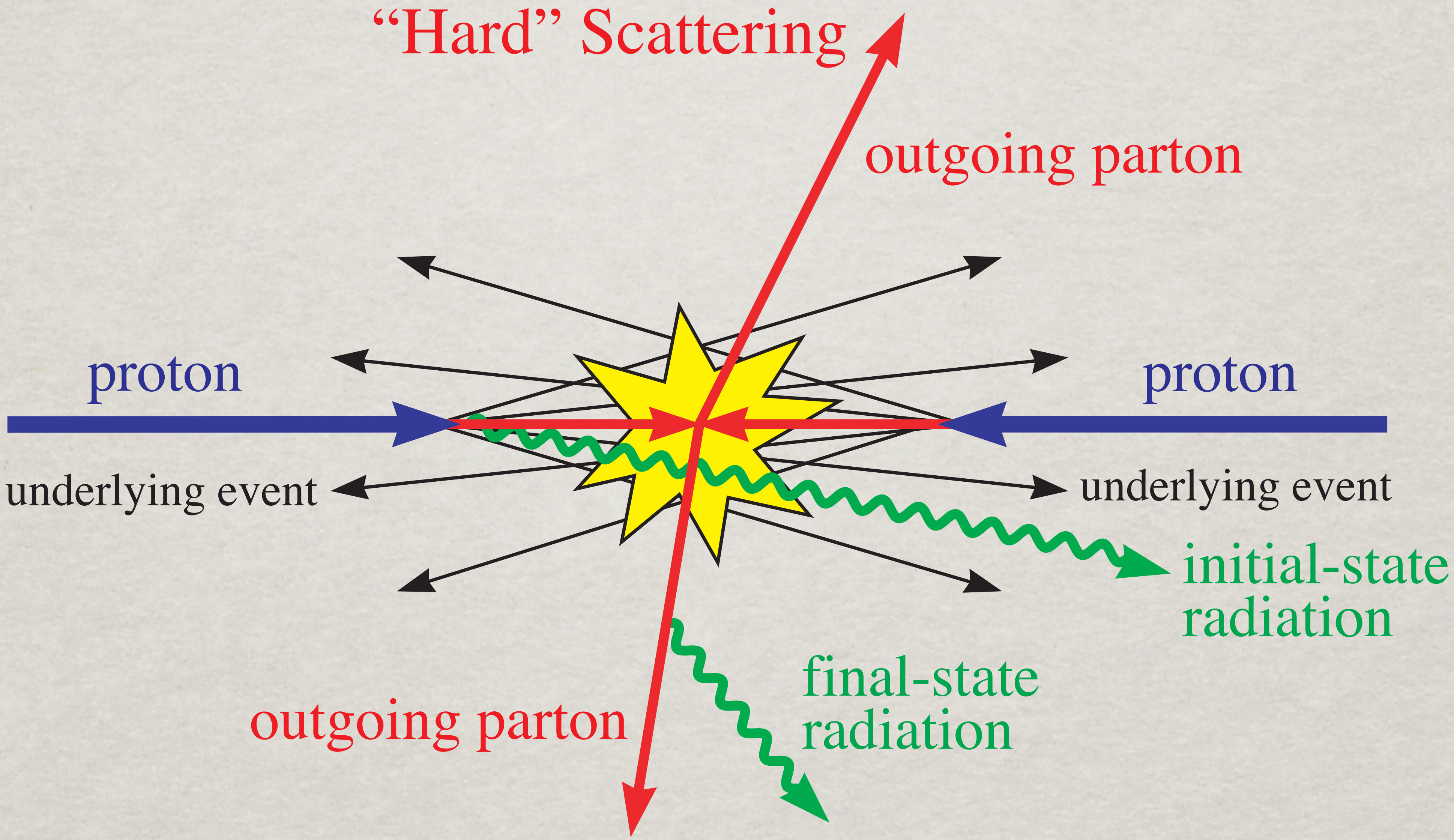
W/Z, Higgs & top @ FCC_{hh}/SPPC



Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

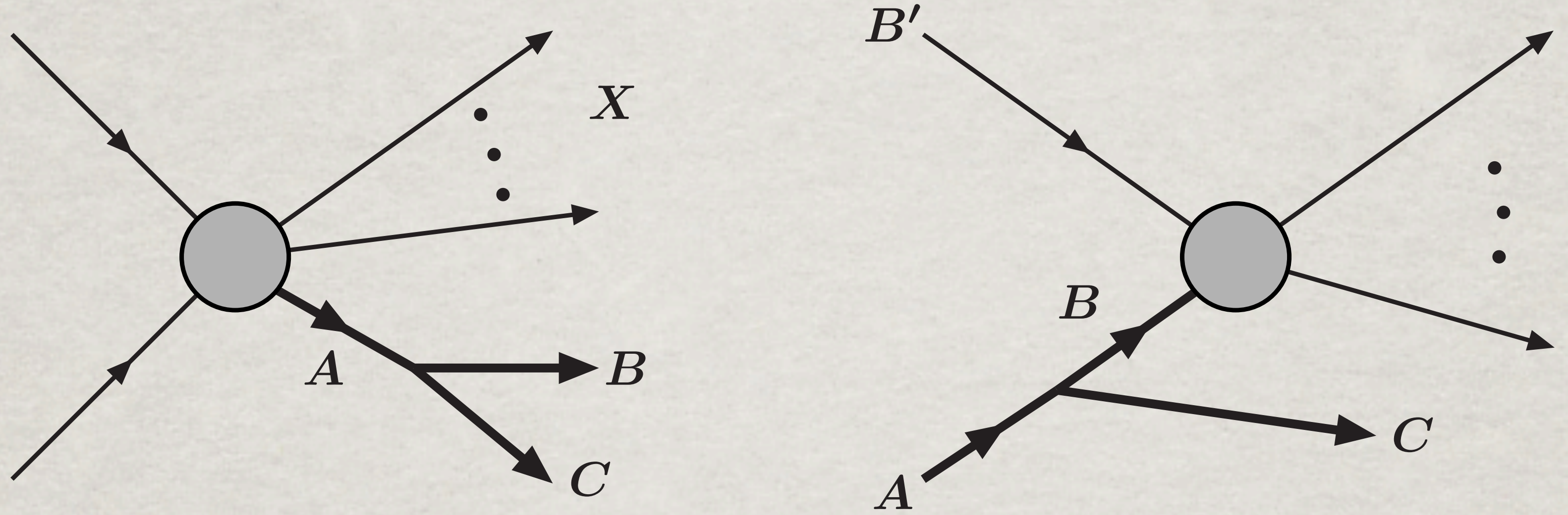
Snowmass QCD Working Group: 1310.5189

Reality in Hadronic Collisions



Collinear splitting is one of the dominant phenomena.

Formalism:



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

$$E_B \approx zE_A, \quad E_C \approx \bar{z}E_A, \quad k_T \approx z\bar{z}E_A\theta_{BC}$$

$$\frac{d\mathcal{P}_{A\to B+C}}{dz\, dk_T^2} \simeq \frac{1}{16\pi^2} \frac{z\bar{z}\, |\mathcal{M}^{(\mathrm{split})}|^2}{(k_T^2 + \bar{z}m_B^2 + zm_C^2 - z\bar{z}m_A^2)^2}$$

On the dimensional ground:

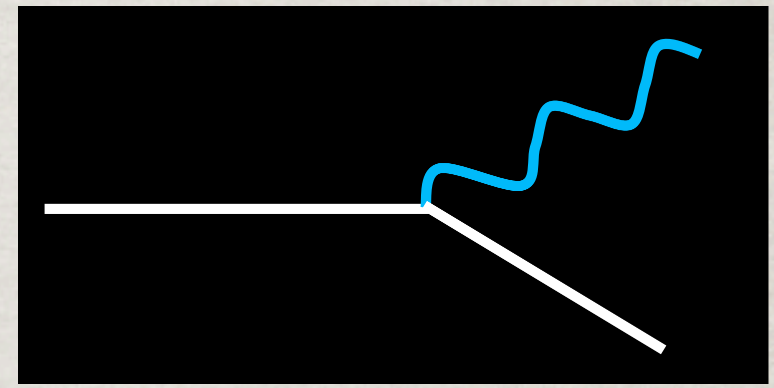
$$|\mathcal{M}_{split}|^2 \sim k_T^2 \text{ or } m^2$$

Splitting Functions: QED

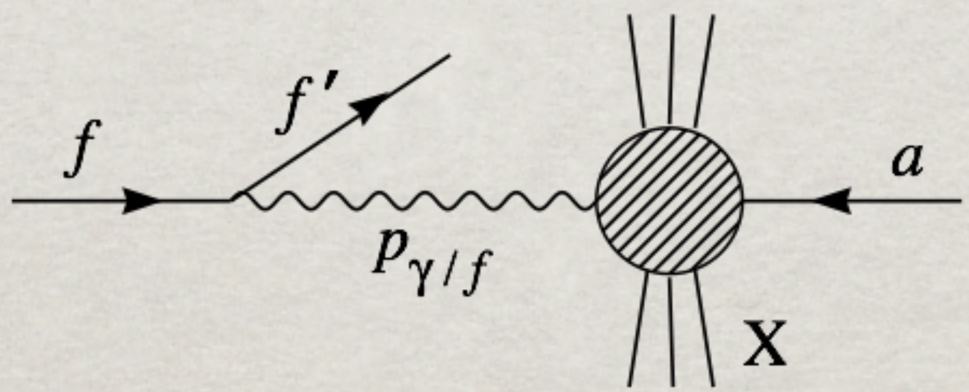
Most familiar example in QED: f → f γ

$$p_{\gamma/f}(z) = \frac{1+\bar{z}}{z}, \quad \bar{z} = 1 - z.$$

$$P_{\gamma/f}(z) = \frac{\alpha}{2\pi}\frac{1+\bar{z}}{z}\ln\frac{Q^2}{m_f^2}\ .$$



The familiar Weizsäcker-Williams approximation



$$\sigma(fa \to f'X) \approx \int dx\ dp_T^2\ P_{\gamma/f}(x,p_T^2)\ \sigma(\gamma a \to X),$$

$$P_{\gamma/e}(x,p_T^2) = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\left(\frac{1}{p_T^2}\right)\Big|_{m_e}^{E}.$$

Note the infrared & collinear behavior.

Splitting Functions: QCD

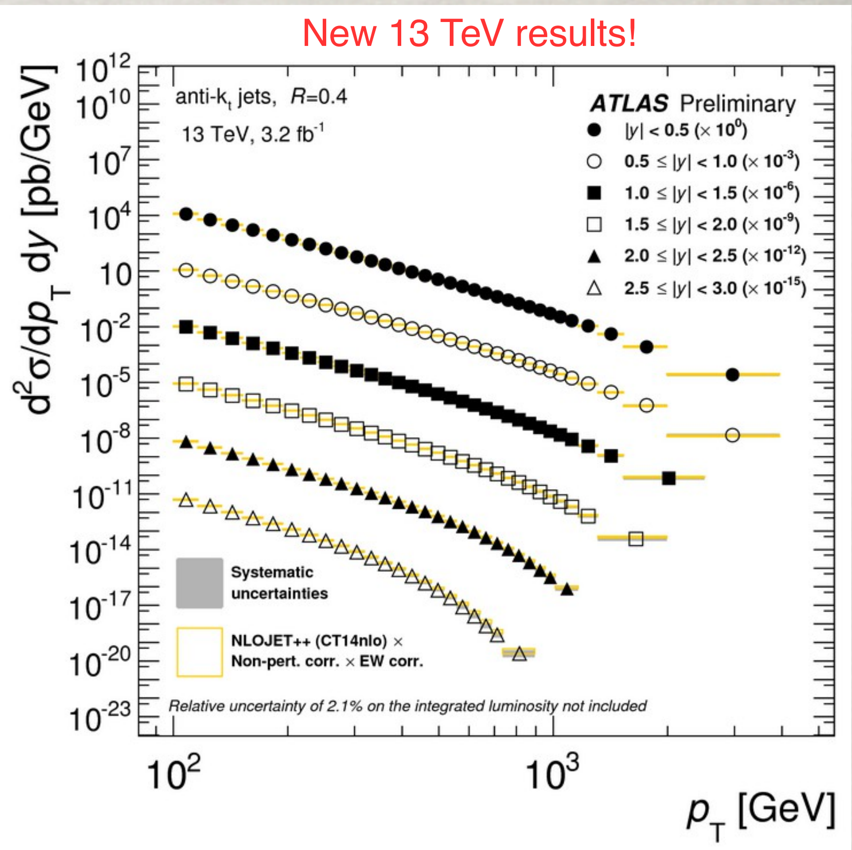
Most common in hadronic collisions: *q, g*

$$P_{gq}(z) = \frac{1+\bar{z}^2}{z}, \quad P_{gg}(z) = \frac{(1-z\bar{z})^2}{z\bar{z}}, \quad P_{qg}(z) = \frac{z^2+\bar{z}^2}{2}.$$

ISR, parton distribution & (DGLAP) evolution:

$$f_B(z,\mu^2) = \sum_A \int_z^1 \frac{d\xi}{\xi} f_A(\xi) \int_{m^2}^{\mu^2} d\mathcal{P}_{A\to B+C}(z/\xi, k_T^2).$$

$$\frac{\partial f_B(z,\mu^2)}{\partial \mu^2} = \sum_A \int_z^1 \frac{d\xi}{\xi} \frac{d\mathcal{P}_{A\to B+C}(z/\xi,\mu^2)}{dz\, dk_T^2} f_A(\xi,\mu^2)\,.$$



FSR, parton showers:

$$\Delta_A(t) = \exp[-\sum_B \int_{t_0}^t \int dz P_{A\to BC}(z)],$$

$$f_A(x,t) = \Delta_A(t) f_A(x,t_0) + \int_{t_0}^t \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} P_{A\to BC}(z)\ f_A(x/z,t')$$

Very important formulation for LHC physics!

EW Splitting Functions

Motivations:

- We have marched into the territory where $E >> M_W$ where EW symmetry can be restored.
- Conceptually different from QCD: Λ_{QCD} vs vev: EW sector remains perturbative.
- New degrees of freedom: *the Higgs sector / Longitudinal vector bosons*
- Clear understanding of the "Equivalence theorem".
- Most sensitive to new physics above the EW scale.

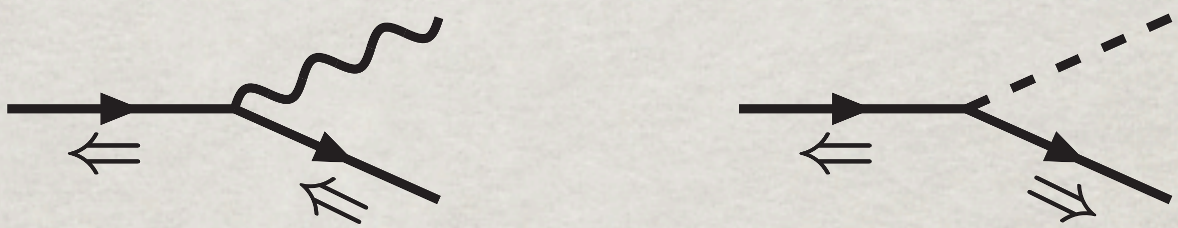
Splitting Functions: EW

Start from the unbroken phase – all massless.

$$\mathcal{L}_{SU(2)\times U(1)} = \mathcal{L}_{gauge} + \mathcal{L}_{\phi} + \mathcal{L}_{f} + \mathcal{L}_{Yuk}$$

Chiral fermions: f_s, gauge bosons: $B, W^0, W^{\pm}$; & $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(h - i\phi^0) \end{pmatrix}$

Fermion splitting:



	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{1+\bar{z}^2}{z}\right)$		$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{z}{2}\right)$
	$\to V_T\, f_s^{(\prime)}$	$[BW]_T^0\, f_s$	$H^{0(*)}\, f_{\text{-}s}$ or $\phi^{\pm}\, f'_{\text{-}s}$
$f_{s=L,R}$	$g_V^2 (Q_{f_s}^V)^2$	$g_1 g_2 Y_{f_s} T_{f_s}^3$	$y^2_{f_R^{(\prime)}}$

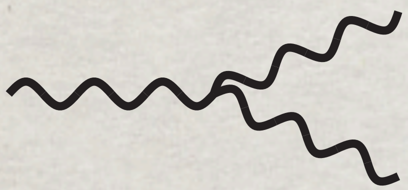
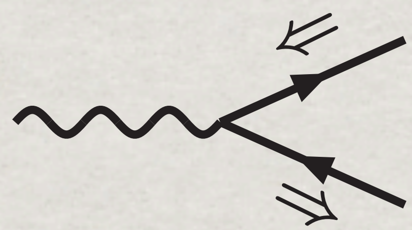
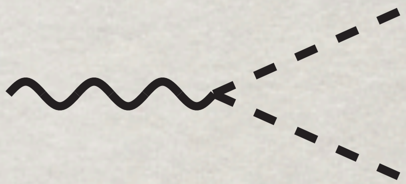
Infrared & collinear singularities (P_{gq})

Collinear singularity, helicity flip, Yukawa coupling (new)

Splitting Functions: EW

SM in the unbroken phase

Gauge boson splitting:

	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{(1-z\bar{z})^2}{z\bar{z}}\right)$	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{z^2+\bar{z}^2}{2}\right)$	$\frac{1}{8\pi^2}\frac{1}{k_T^2}(z\bar{z})$	
	$\to\ W_T\, W_T$	$f_s\ \bar{f}^{(\prime)}_{\text{-}s}$	$\phi^+\ \phi^-$ or $H^0\ H^{0*}$	$\phi^+\ H^{0*}$ or $\phi^-\ H^0$
V_T	$2g_2^2\ (V{=}W^{0,\pm})$	$N_f g_V^2 (Q_{f_s}^V)^2$	$\frac{1}{4}g_V^2$	$\frac{1}{2}g_2^2$
$[BW]_T^0$	0	$N_f g_1 g_2 Y_{f_s} T_{f_s}^3$	$\frac{1}{2}g_1 g_2 T^3_{\phi^+,H^0}$	0

Infrared & collinear (P_{gg})

Collinear (P_{qg})

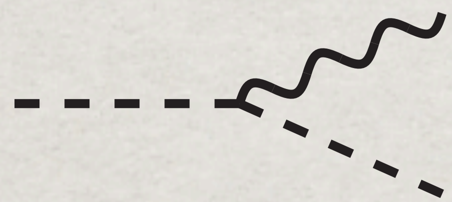
Interference (BW^0) must be included!

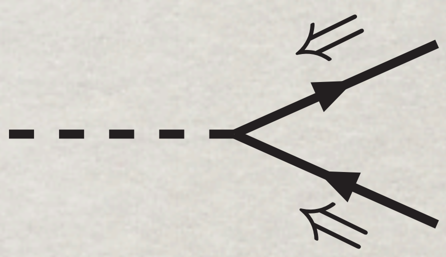
Collinear (new)

Splitting Functions: EW

SM in the unbroken phase

Scalar splitting (new):





	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{2\bar{z}}{z}\right)$			$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{1}{2}\right)$	
	$\rightarrow\ V_T^0\, H$	$[BW]_T^0\, H$	$W_T^{\pm}\, H'$	$u_R\, \bar{u}_R^{(\prime)}$	$\bar{d}_L\, d_L^{(\prime)}$ or $\bar{e}_L\, e_L^{(\prime)}$
$H = \phi^+, H^0$	$\frac{1}{4}g_V^2$	$\frac{1}{2}g_1 g_2 T^3_{\phi^+,H^0}$	$\frac{1}{2}g_2^2$	$3y_u^2$	$N_{d,e}y_{d,e}^2$

Infrared & collinear singularities
(a charge source, similar to P_{gq})

Collinear,
similar to (P_{qg})

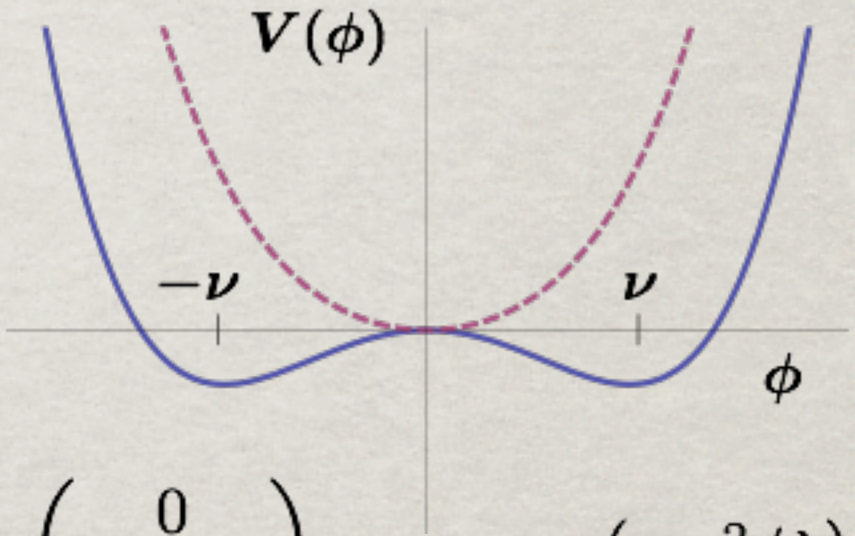
EW Symmetry breaking:

The scalar part of the Lagrangian is

The Higgs: $\mathcal{L}_\phi = (D^\mu\phi)^\dagger D_\mu\phi - V(\phi) \quad D_\mu\phi = \left(\partial_\mu + ig\frac{\tau^i}{2}W_\mu^i + \frac{ig'}{2}B_\mu\right)\phi,$

$$V(\phi) = +\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2.$$

$$\phi = \frac{1}{\sqrt{2}}e^{i\sum\xi^i L^i}\begin{pmatrix} 0 \\ \nu + H \end{pmatrix}$$



Unitary gauge: $\phi \to \phi' = e^{-i\sum\xi^i L^i}\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \nu + H \end{pmatrix} \quad \nu = (-\mu^2/\lambda)^{1/2}$

$$\begin{aligned}\mathcal{L}_\phi &= (D^\mu\phi)^\dagger D_\mu\phi - V(\phi) \\ &= M_W^2 W^{\mu+}W_\mu^-\left(1+\frac{H}{\nu}\right)^2 + \frac{1}{2}M_Z^2 Z^\mu Z_\mu\left(1+\frac{H}{\nu}\right)^2 \\ &+ \frac{1}{2}(\partial_\mu H)^2 - V(\phi).\end{aligned}$$

Goldstone-boson Equivalence Theorem:

Lee, Quigg, Thacker (1977); Chanowitz & Gailard (1984)

At high energies $E >> M_W$, the longitudinally polarized gauge bosons behave like the corresponding Goldstone bosons. (They remember their origin!)

"Scalarization" to implement the Goldstone-boson Equivalence Theorem (GET):

$$\epsilon(k)_L^\mu = \frac{E}{m_W}(\beta_W, \hat{k}) \approx \frac{k^\mu}{m_W}$$

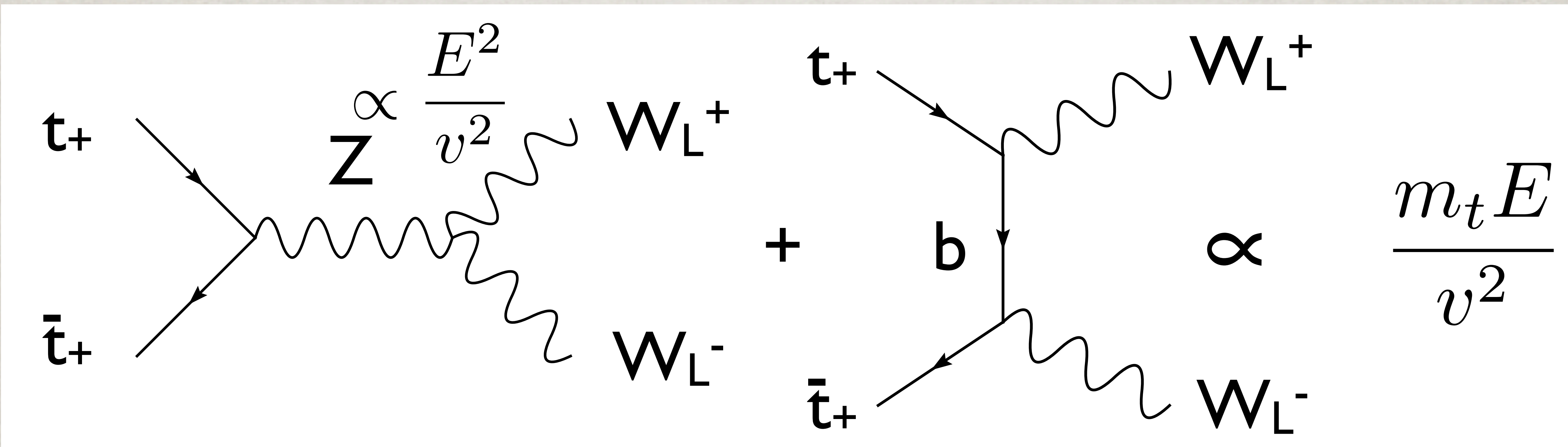
[Excersise: Try the decay $H \to W^+_L W^-_L$ via a coupling $-g^{\mu\nu}$ and derive the equivalent $H\phi^+\phi^-$ vertex.]

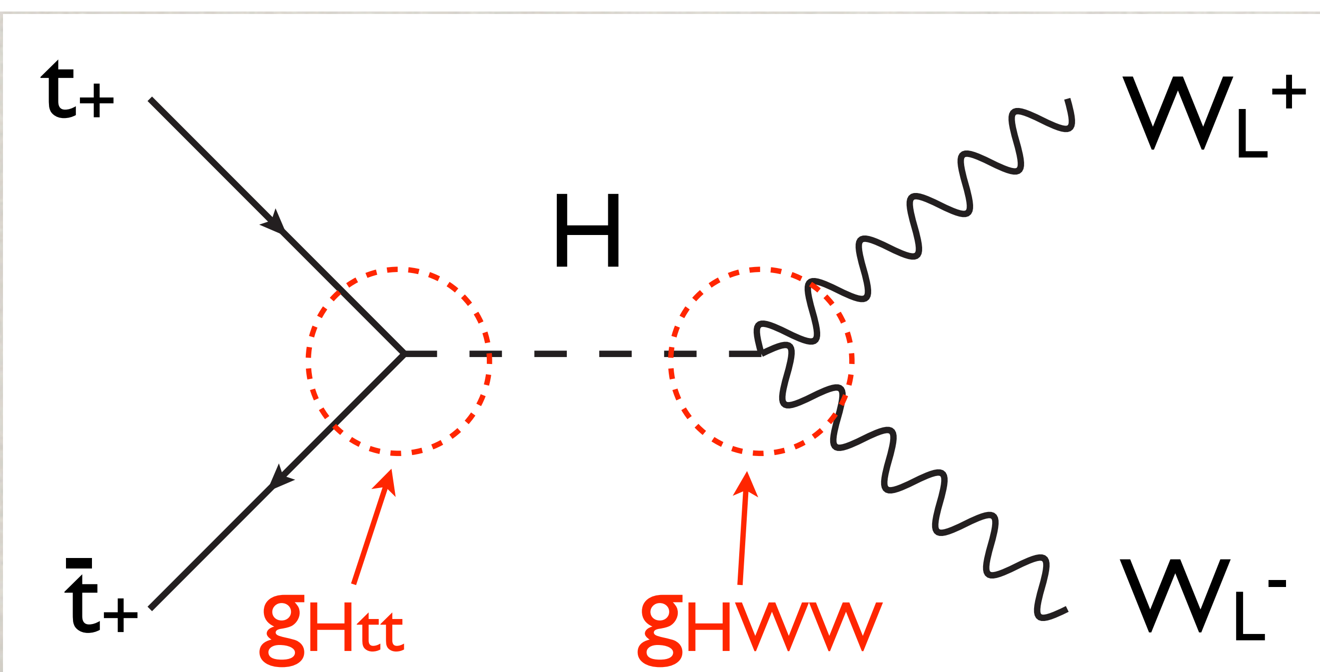
(a). Unitarity at higher energies:

$$\epsilon(k)^{\mu}_{L} = \frac{E}{m_W}(\beta_W, \hat{k}) \approx \frac{k^{\mu}}{m_W}$$

bad high-energy behavior!

Appelquist & Chanowitz (1987).





A "light Higgs" fixes it:

$$\propto \frac{m_t m_H}{v^2}$$

D. Dicus & V. Mathur (1973);
Lee, Quigg, Thacker (1977).

(b). Puzzle of massless fermion radiation

V_L contributions dominant at high energies:

$$\epsilon(k)_L^\mu = \frac{E}{m_W}(\beta_W, \hat{k}) \approx \frac{k^\mu}{m_W}$$

Then, massless fermion splitting

$$f \to f\, V_L$$

would be zero, in accordance with GET for

$$f \to f\, \phi \quad (y_f = 0).$$

GET ignored the EWSB effects at the order M_W/E

Corrections to GET
1st example: "Effective W-Approximation"

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

At colliding energies $E \gg M_W$,

$$P_{q\to qV_T} = (g_V^2 + g_A^2)\ \frac{\alpha_2}{2\pi}\ \frac{1+(1-x)^2}{x}\ \ln\frac{Q^2}{\Lambda^2}$$

$$P_{q\to qV_L} = (g_V^2 + g_A^2)\ \frac{\alpha_2}{\pi}\ \frac{1-x}{x}$$

- $f \to f\, W_L,\ f\, Z_L$ do not vanish & non-log!
- Vector boson fusion observed at the LHC

WW, ZZ→h & W^+W^+ scattering

There are characteristically new channels in the broken phase:

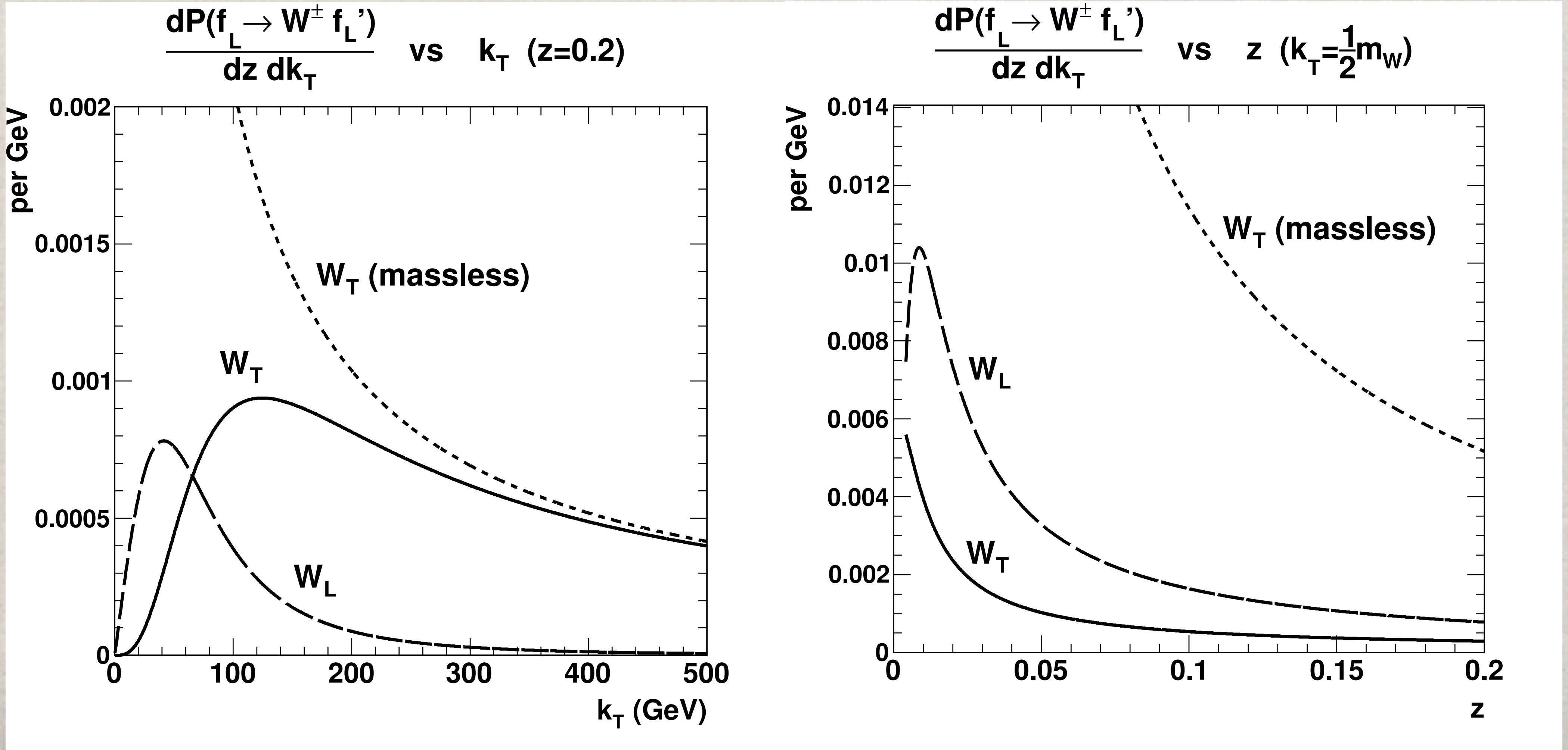
$$\frac{v^2}{k_T^2}\ \frac{dk_T^2}{k_T^2} \sim (1 - \frac{v^2}{Q^2})$$

"Ultra collinear":

$k_T^2 > m_W^2$, 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)!



"Goldstone Equivalence Gauge" (GEG)

$$\epsilon(k)^\mu_L = \frac{E}{m_W}(\beta_W, \hat{k}) = \frac{k^\mu}{m_W} - \frac{m_W}{E + |\vec{k}|} n^\mu, \quad n^\mu = (1, -\hat{k}).$$

1^{st} term leads to GET → ϕ, well behaved;
2^{nd} term captures EWSB ~ A_n^μ, well behaved

Separate them out by a special gauge choice:

$$\mathcal{L}_{\text{fix}} = -\frac{1}{2\xi}\big[n(k)\cdot W(k)\big]\big[n(k)\cdot W(-k)\big] \qquad (\xi \to 0)$$

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

$$\epsilon^\mu_{\text{long}}(k) \to \frac{\sqrt{|k^2|}}{n(k)\cdot k}\, n^\mu(k) \overset{\text{on-shell}}{\to} \frac{m_W}{E + |\vec{k}|}\left(-1, \hat{k}\right).$$

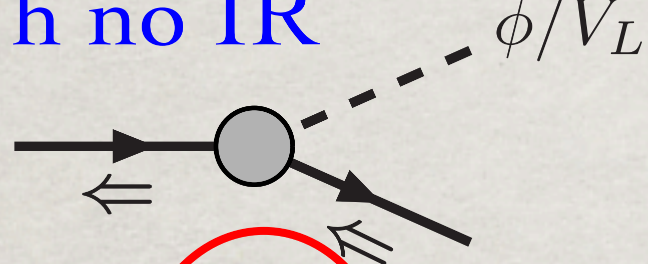
GEG:

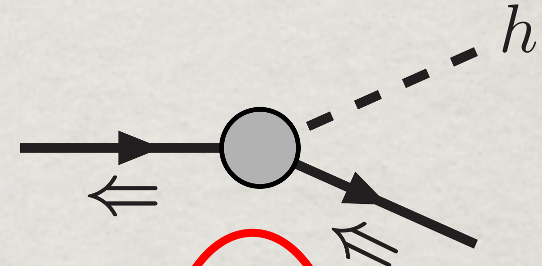
- Non-covariant but physical gauge:
  Hybrid of Coulomb & light-cone gauge
  → rotational and collinear boost invariance.
- ε_L: Time-like component is removed:
  - $\xi \to 0$ eliminates the V_L collinear propagation
  - Goldstones remain as dynamical degrees of freedom.
- $\varepsilon_L \sim M_W/E$ as the remainder vector field:
- Gauge – Goldstone boson mixing exists.
- Measures the departure from GET, keeps track of EWSB effect: As the "Higher-twist" power-counting by v^2/s ! → direct analogues to QCD Λ^2/Q^2 !

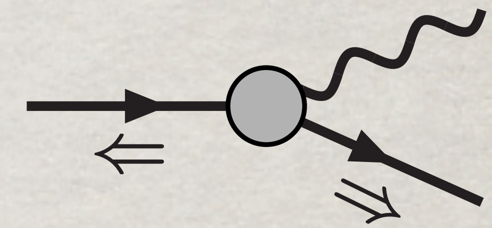
Splitting in the Broken Gauge

New fermion splitting: $\frac{v^2}{k_T^2}\ \frac{dk_T^2}{k_T^2} \sim (1 - \frac{v^2}{Q^2})$

V_L is of IR, h no IR







	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}\left(\frac{1}{z}\right)$ $\rightarrow\ V_L\ f_s^{(\prime)}\ (V \neq \gamma)$	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$ $h\ f_s$	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$ $V_T\ f_{\text{-}s}^{(\prime)}$
$f_{s=L}$	$\left(I_f^V\,(y_f^2\bar{z} - y_{f^{(\prime)}}^2)z - Q_{f_L}^V g_V^2\,\bar{z}\right)^2$	$\frac{1}{4}y_f^4 z(1+\bar{z})^2$	$g_V^2\, z\left(Q_{f_R}^V y_f\,\bar{z} - Q_{f_L}^V y_{f^{(\prime)}}\right)^2$
$f_{s=R}$	$\left(I_f^V\, y_f y_{f^{(\prime)}}\, z^2 - Q_{f_R}^V g_V^2\,\bar{z}\right)^2$	$\frac{1}{4}y_f^4 z(1+\bar{z})^2$	$g_V^2\, z\left(Q_{f_L}^V y_f\,\bar{z} - Q_{f_R}^V y_{f^{(\prime)}}\right)^2$

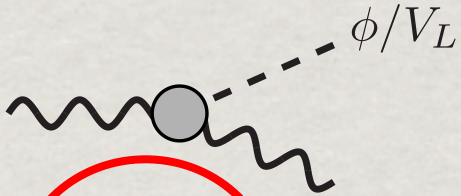
Helicity conserving:
Non-zero for massless f

Helicity flipping: $\sim m_f$

Splitting in the Broken Gauge

New gauge boson splitting to $W_L W_T$

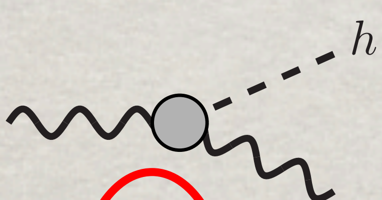
Vector boson V_L is of IR.

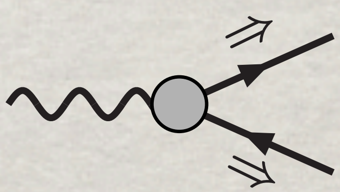


$$\frac{v^2}{k_T^2}\ \frac{dk_T^2}{k_T^2} \sim \left(1-\frac{v^2}{Q^2}\right)$$

	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}\left(\frac{1}{z}\right)$			
	$\to W_L^{\pm}\,\gamma_T$	$W_L^{\pm}\,Z_T$	$Z_L\,W_T^{\pm}$	$W_L^{+}\,W_T^{-}$ 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.



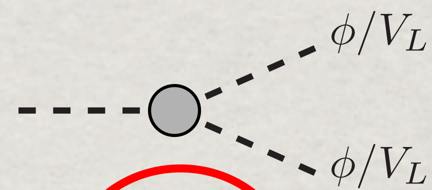


	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$
	$\to h\,V_T\ (V\neq\gamma)$	$f_s\,\bar{f}_s^{(\prime)}$
V_T	$\frac{1}{4}z\bar{z}g_V^4$	$\frac{1}{2}g_V^2\left(Q^V_{f_s}y_{f^{(\prime)}}z + Q^V_{f_{\text{-}s}}y_f\bar{z}\right)^2$
$[\gamma Z]_T$	0	$\frac{1}{2}e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

Splitting in the Broken Gauge

New gauge boson splitting in 3-W_L

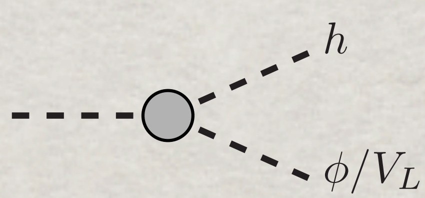
Vector boson V_L is of IR.

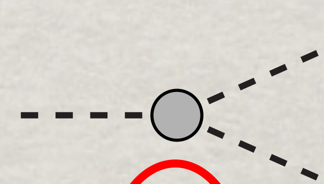


$$\frac{v^2}{k_T^2}\ \frac{dk_T^2}{k_T^2} \sim (1 - \frac{v^2}{Q^2})$$

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





	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}\left(\frac{1}{\bar{z}}\right)$	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$
	$\to h\,W_L^\pm/Z_L$	$h\,h$
$W_L^\pm$	$\frac{1}{4}z\left(g_2^2(1-z\bar{z})+\lambda_h\bar{z}\right)^2$	0
h	0	$\frac{9}{8}\lambda_h^2 z\bar{z}$
Z_L	$\frac{1}{4}z\left(g_Z^2(1-z\bar{z})+\lambda_h\bar{z}\right)^2$	0
$[hZ_L]$	0	0

Splitting Probabilities:

gauge couplings

Process	$\approx \mathcal{P}(E)$ (leading-log term)	$\mathcal{P}$(1 TeV)	$\mathcal{P}$(10 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%

- Non-Abelian gauge splitting larger than fermion splitting!
- Collinear splittings larger than perturbative radiation!
- Ultra-collinear splittings small

EW Shower Implementation: Sudakov Formalism

- On-shell massive particle: Breit-Wigner resonance
- Sequential showering with "back-reactions":

$$A^* \to B^*C \to (DE)C$$

$$\frac{d\mathcal{P}(B^* \to DE)}{dz_{DE}\, dk^2_{T,DE}} \times \left(\frac{d\mathcal{P}(A^* \to B^*C)/dz^* dk_T^{2*}}{d\mathcal{P}(A^* \to BC)/dz\, dk_T^2} \cdot \left|\det\left[\frac{dz^* dk_T^{2*}}{dz\, dk_T^2}\right]\right| \right)$$

- Mixed state evolution:

In QED/QCD, it is sub-leading, after color/spin averaging.
But in chiral EW theory, need "density matrix" treatment:

$$\rho_{ij} \propto \mathcal{M}_i^{(\mathrm{prod})*} \mathcal{M}_j^{(\mathrm{prod})}$$

$$d\mathcal{P} = \frac{\rho_{ij}\, d\mathcal{P}_{ji}}{\mathrm{tr}[\rho]} \qquad \left[\frac{d\mathcal{P}_{A\to B+C}}{dz\, dk_T^2}\right]_{ij} \simeq \frac{1}{16\pi^2}\frac{1}{z\bar{z}}\, \mathcal{M}_k^{(\mathrm{split})*} \mathcal{D}_{ki}^* \mathcal{D}_{jl} \mathcal{M}_l^{(\mathrm{split})}$$

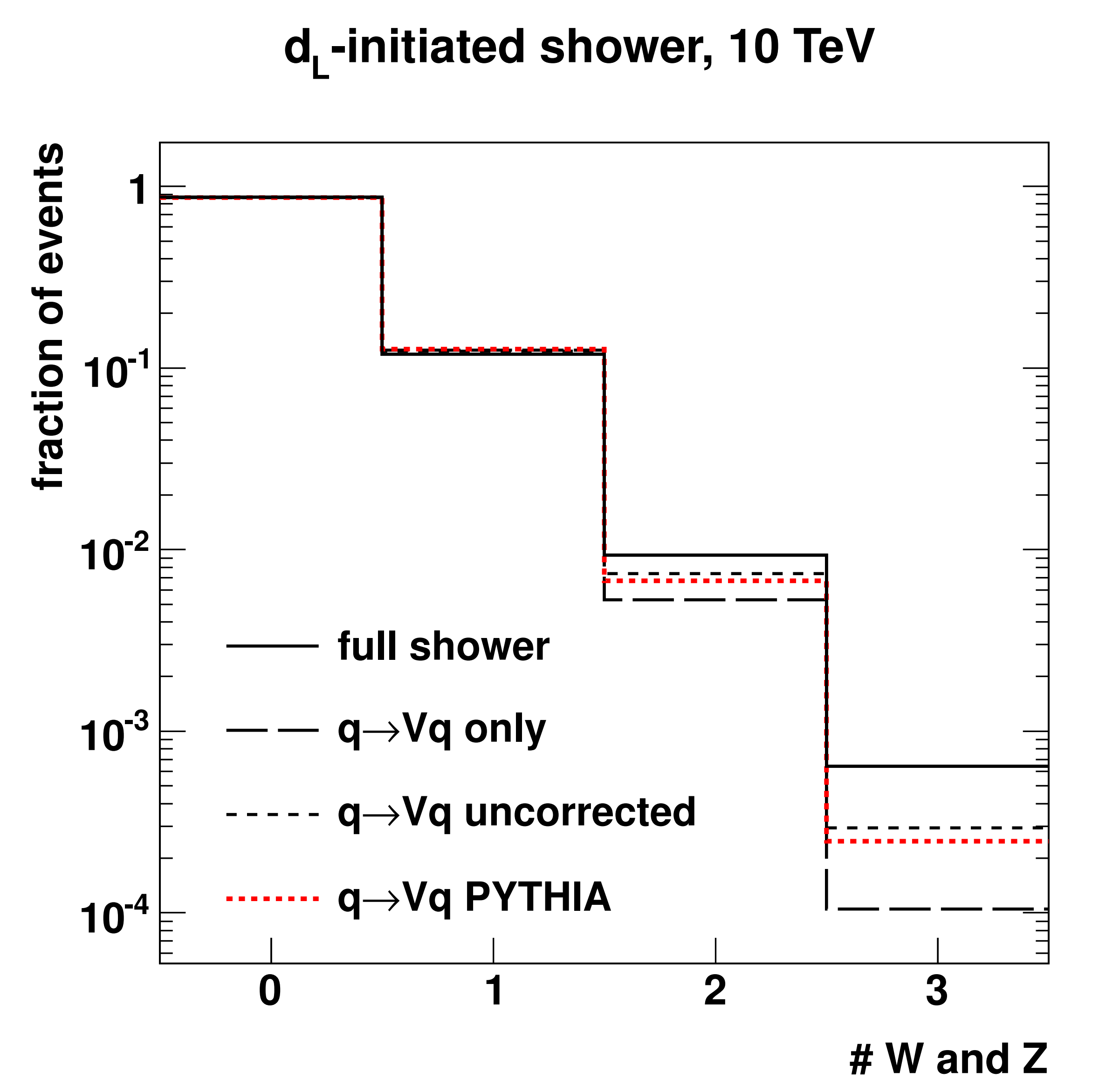
Multi Gauge-boson Production

At 100 TeV: M. Mangano's talk

Diagramatic calculations

W W	σ=770 pb
W W W	σ=2 pb
W W Z	σ=1.6 pb
W W W W	σ=15 fb
W W W Z	σ=20 fb

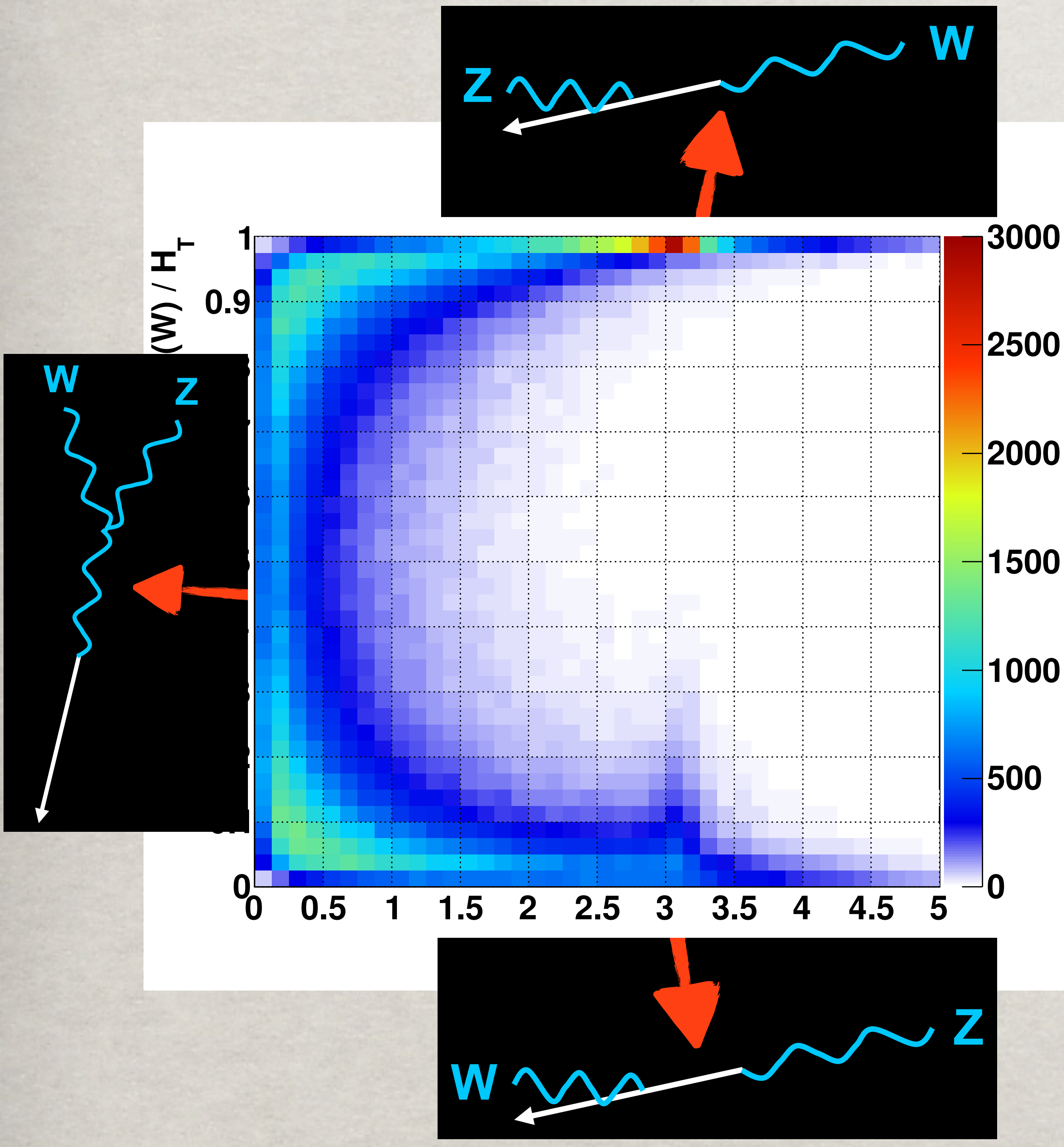
....

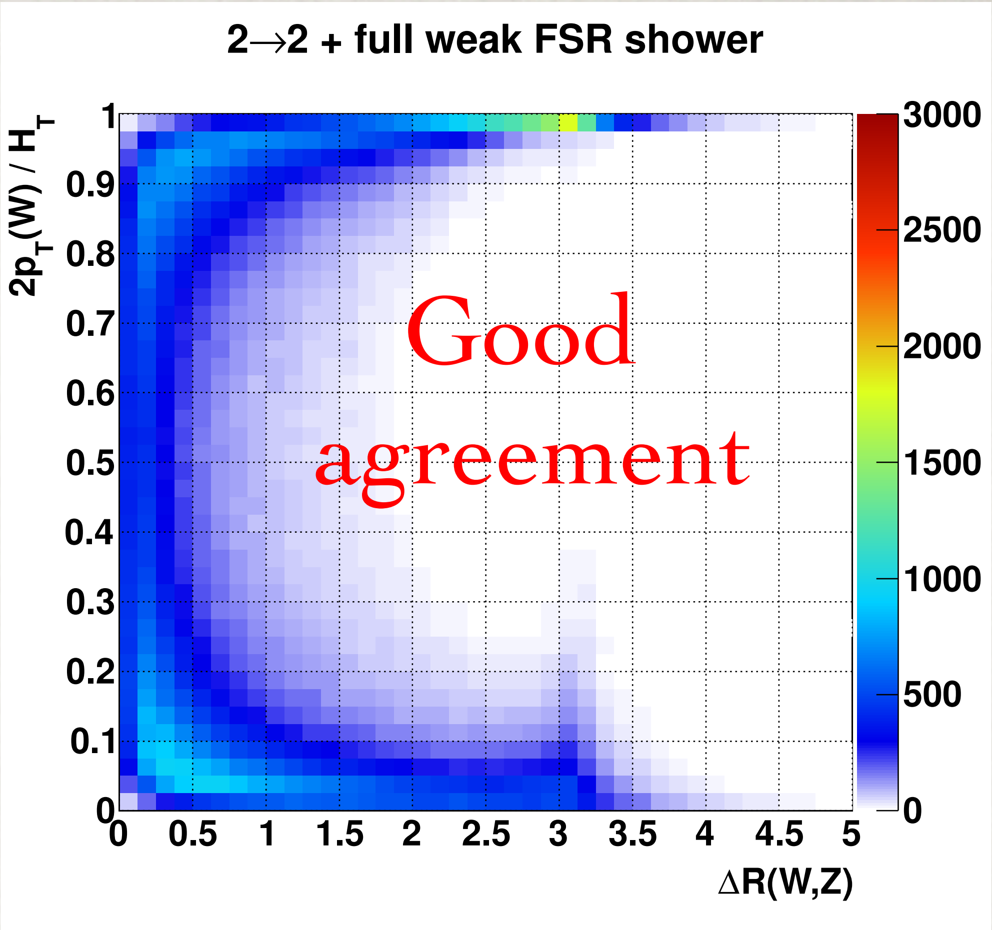


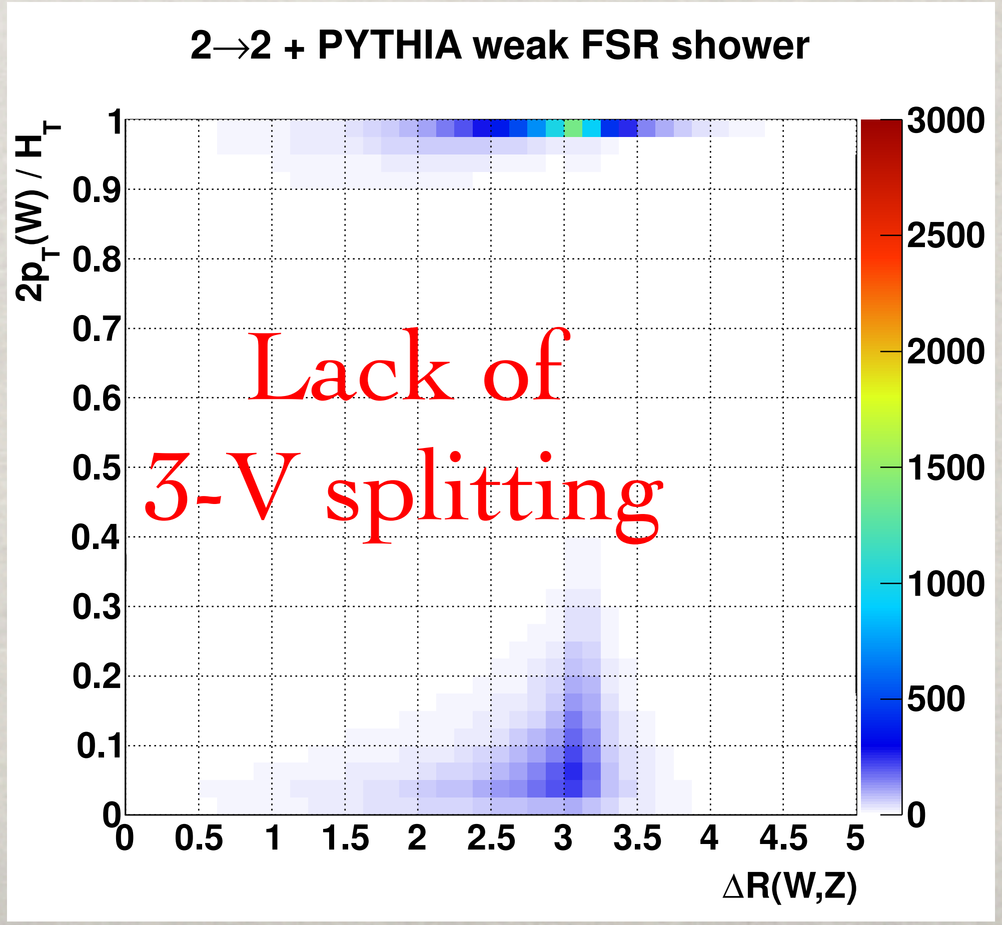
Each *W* costs you a factor of ~ 1/100 (EW coupling)

Logarithmic enhanced production: each W costs ~ 1/10

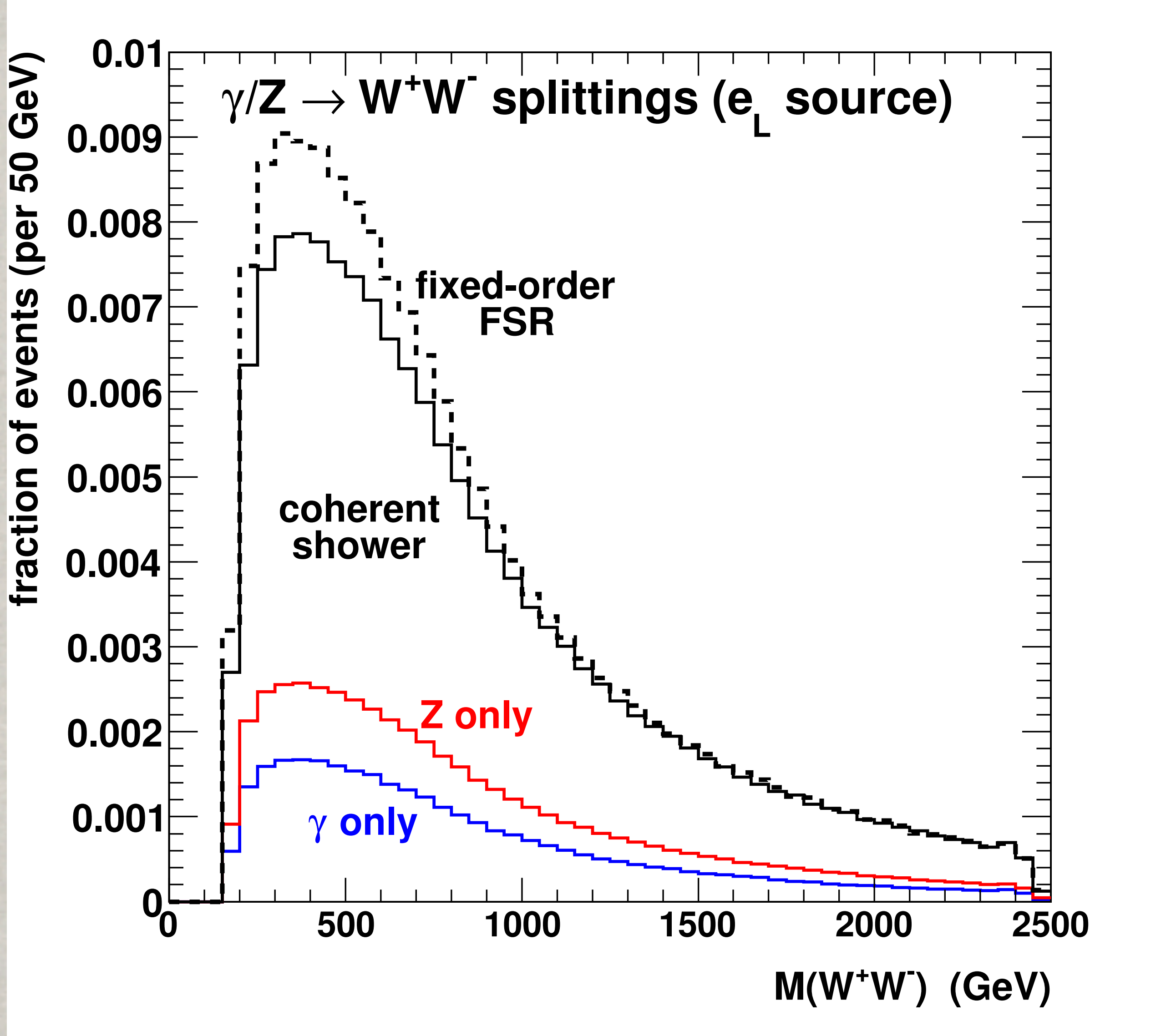
An Example: WZ+J @ 100 TeV

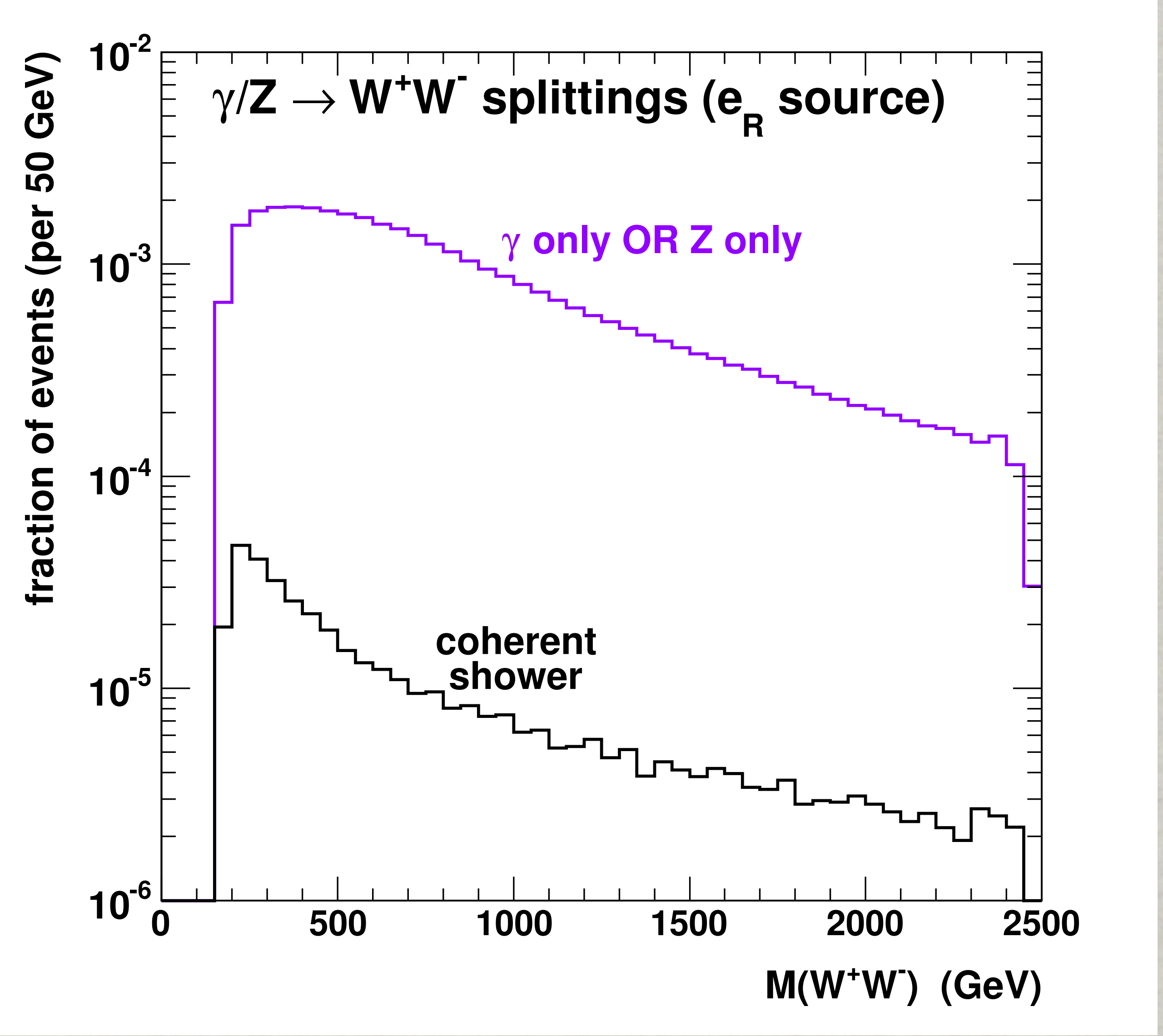






Coherence in Showering

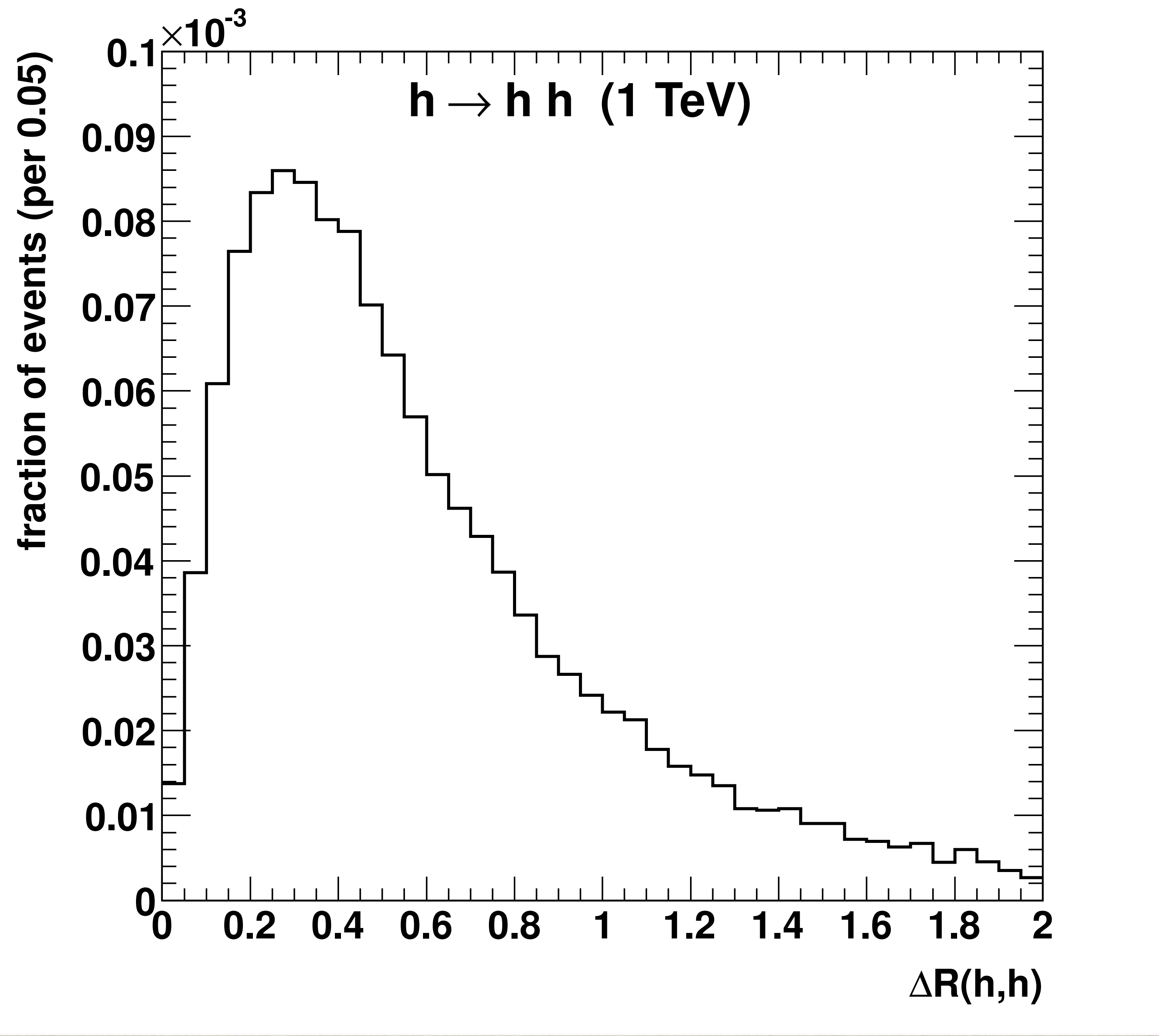




Coherent treatment important
(almost) a pure W_3^0 exchange

(almost)
a pure B^0 exchange

Higgs in Showering



Ultra-collinear behavior

New Physics with energetic Multi tops/Gauge-bosons

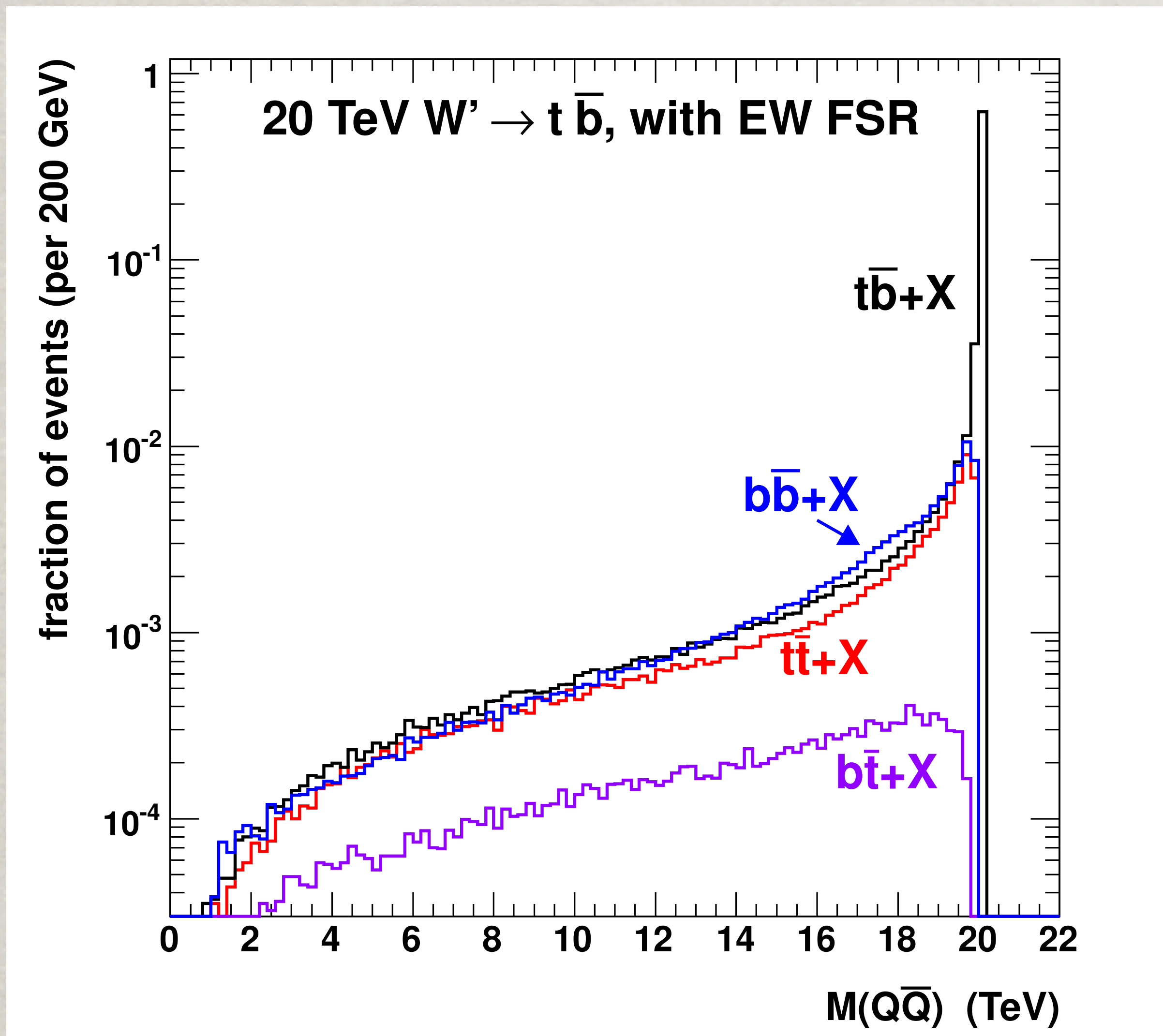
SUSY examples: $\tilde{b}\tilde{b}^* \to t\chi^- \ \bar{t}\chi^+, \ \tilde{t}W^- \ \tilde{t}^*W^+ \to 4W^\pm \ b\bar{b}.$

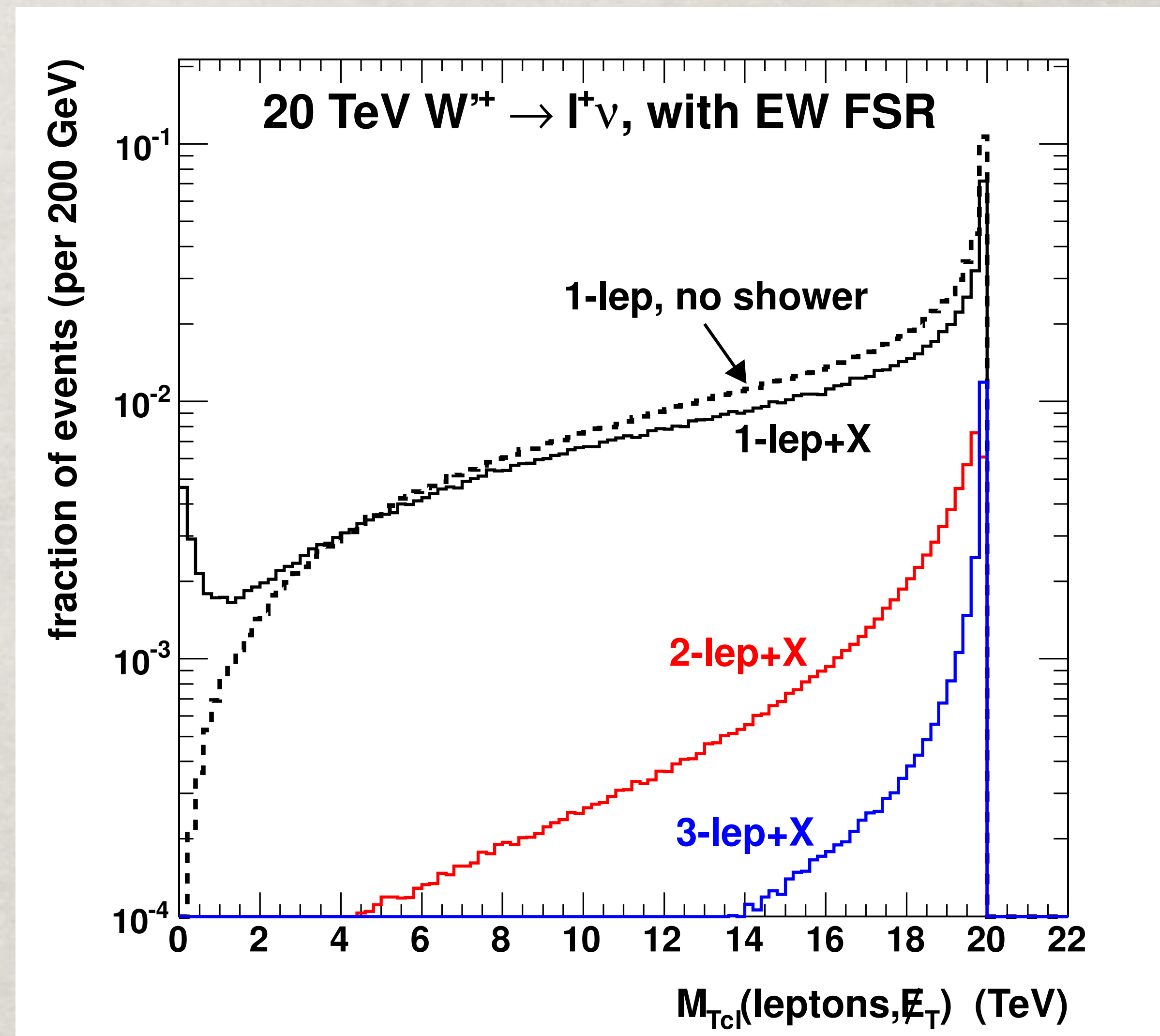
Heavy quark examples: *TT', BB', ...*

Energetic *W±, Z, H, t* as new radiation sources from heavy W', *Z'* decays, subsequent showering.

An Example: $W^{+\prime}$ Shower

$$W_L^{+\prime} \to t\bar{b},\ t\bar{t}(W^-),\ b\bar{b}(W^+),\ b\bar{t}(W^+W^+).$$



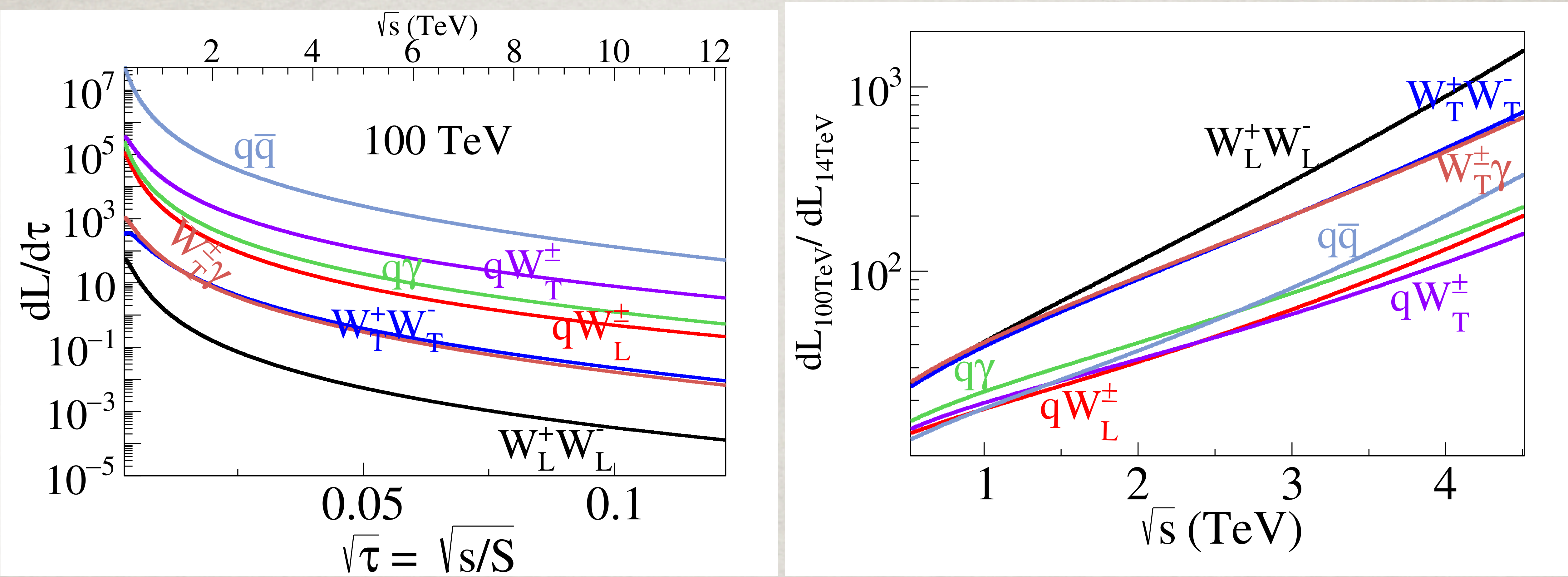


With W/Z showers, all t/b iso-spin components exist.

WW Partonic luminosities

TH, R. Ruiz, B. Tweedie, in prep

$$\Phi_{VV'}(\tau) = \frac{1}{(\delta_{VV'}+1)} \int_\tau^1 \frac{d\xi}{\xi} \int_{\tau/\xi}^1 \frac{dz_1}{z_1} \int_{\tau/\xi/z_1}^1 \frac{dz_2}{z_2} \sum_{q,q'} \quad (7)$$
$$\times \left[f_{V/q}(z_2) f_{V'/q'}(z_1)\, f_{q/p}(\xi) f_{q'/p}\left(\frac{\tau}{\xi z_1 z_2}\right) + f_{V/q}(z_2) f_{V'/q'}(z_1)\, f_{q/p}\left(\frac{\tau}{\xi z_1 z_2}\right) f_{q'/p}(\xi) \right]$$



Lumi($W^+_T W^-_T$) similar size to lumi(tt) @ 10 TeV;

Lumi($W^+_T W^-_T$) ~ Lumi($W^\pm \gamma$), Electro=weak

Lumi($W^+_L W^-_L$) 100 times smaller: "untra-collinear"

Lumi(100/14) increased by 30 – 3000 for 500 GeV - 4 TeV!

Conclusions

- With the discovery of the Higgs boson, we have a consistent QM, relativistic theory up to high scales, where is $\Lambda \sim 4\pi v$?

- EW sector presents rich physics:
  - Perturbative cutoff via SSB
  - Longitudinals/scalars
  - Chirality
  - Yukawa showers
  - Neutral boson interference
  - Weak isospin self-averaging

- EW splitting/showering will become an increasingly important part at higher energies.
- It may serve as a tool for future discovery.