Welcome to the 24th International Summer Institute on Phenomenology of Elementary Particle Physics and Cosmology (SI 2018)!

- SI 1995 – 2005: Fuji-Yoshida, Japan
- SI 2006: Pohang, Korea
- SI 2008: Chi-Tou, Taiwan
- SI 2015: Huarou, Beijing, China

- 2018, the 24th SI: PanShan, Tianjin, China
  by **Nankai University**

Thanks to the local organizing committee:
Profs. Xueqian Li, Lei Chang, Yuming Wang + …
Thanks to the International Advisory Committee!

Thank you all for coming!
Enjoy the conference and the scenery!

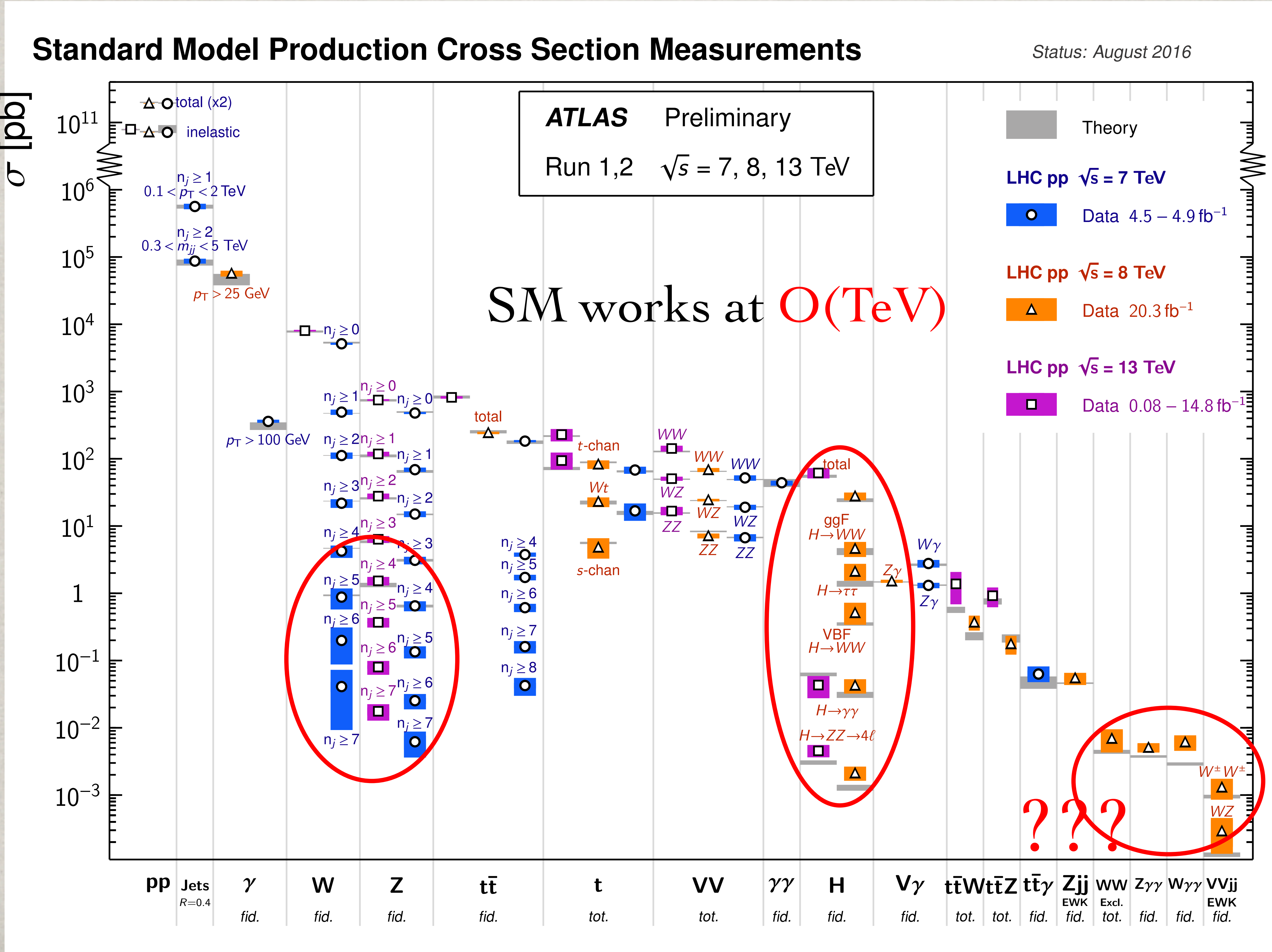
EW Sector @ High Energies

Univ. of Pittsburgh & Tsinghua University
Tao Han 韩涛

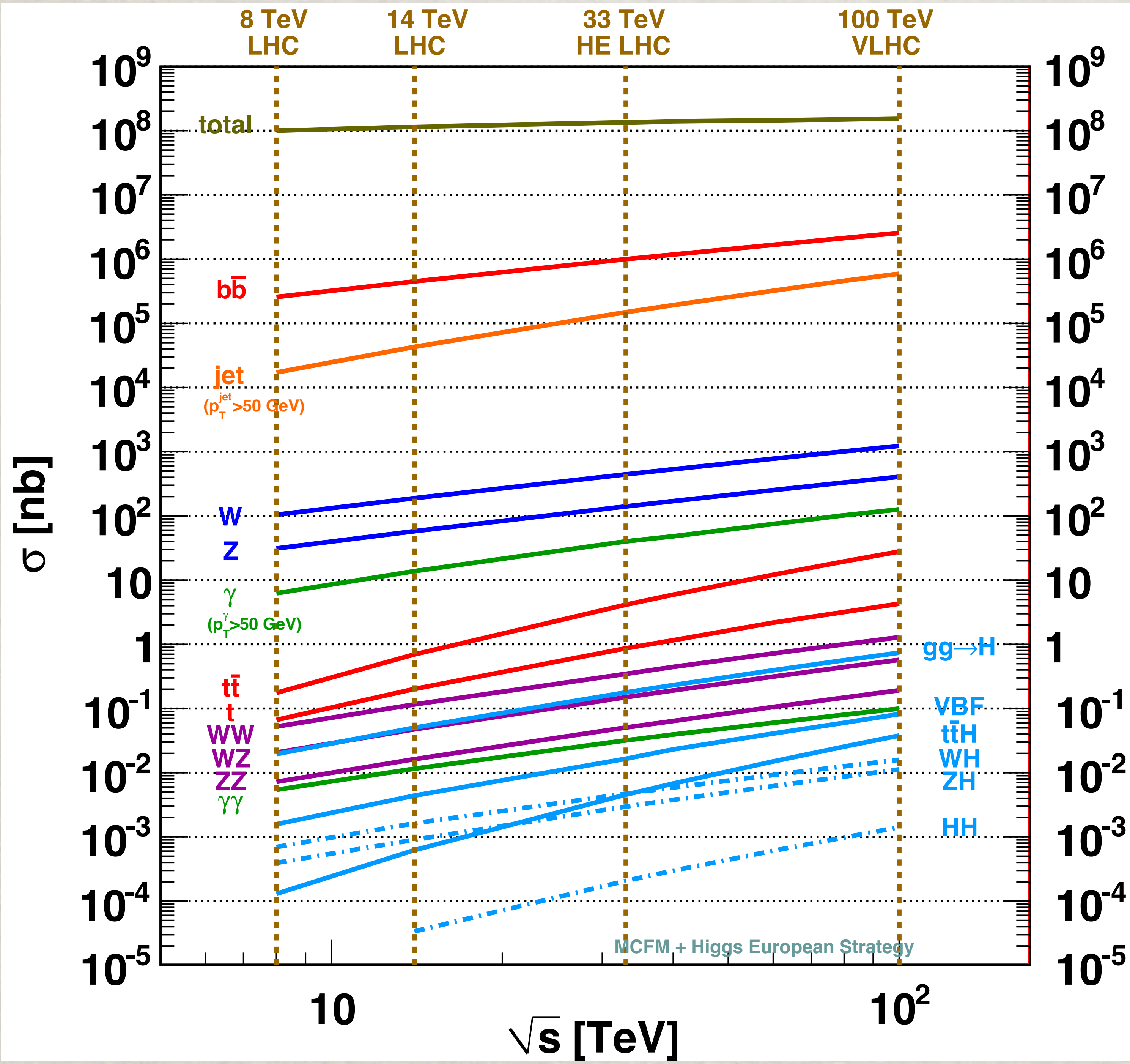
24th International Summer Institute
PanShan, Aug. 13, 2018

With J.M. Chen & B. Tweedie, arXiv:1611.00788; arXiv:18xx

LHC Rocks!


Standard Model Production Cross Section Measurements
Status: August 2016
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 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
SM works at O(TeV)
σ [pb]
total (x2)
inelastic
nj ≥ 1 0.1 < pT < 2 TeV
nj ≥ 2 0.3 < mjj < 5 TeV
pT > 25 GeV
pT > 100 GeV
total
t-chan
Wt
s-chan
WW
WZ
ZZ
ggF H→WW
H→ττ
VBF H→WW
H→γγ
H→ZZ→4ℓ
Zγ
Wγ
W±W±
WZ
? ? ?
pp
Jets R=0.4
γ fid.
W fid.
Z fid.
tt̄ fid.
t tot.
VV tot.
γγ fid.
H fid.
Vγ fid.
tt̄W tot.
tt̄Z tot.
tt̄γ fid.
Zjj EWK fid.
WW Excl. tot.
Zγγ fid.
Wγγ fid.
VVjj EWK fid.

Future High Energy Frontier: 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: arXv:1310.5189;
N. Arkani-Hamed, TH, M. Mangano, L.-T. Wang, 1511.06495;
CERN Yellow books, + many others …

EW at Higher Energies

Some numerology:

$$(1).\ \frac{E}{v}:\quad G_F E_\beta^2 \sim \left(\frac{\text{MeV}}{M_W}\right)^2 \sim 10^{-8},\quad \left(\frac{10\ \text{TeV}}{M_W}\right)^2 \sim 10^4\ !$$

$$\epsilon_L^\mu(p) \sim \frac{p^\mu}{M_W}$$ → need a proper treatment.

$$(2).\ \frac{v}{E}:\ \frac{v}{100\ \text{TeV}} \sim \frac{\Lambda_{QCD}}{100\ \text{GeV}}$$

- v/E power counting → Higher twist effects.

  $v/E,\ m_t/E,\ M_W/E \to 0!$

  massless theory; EW symmetry restored !

Some numerology:

(3). $$\frac{m_t}{100\ \text{TeV}} \sim \frac{m_b}{2\ \text{TeV}}$$

The top quark at the FCC/SppC would be as "massless" as b-quark was at the Tevatron.

→ Top quark PDF? 6-flavors?

Daswon, Ismail, I. Low (2014);
TH, Sayre, Westhoff (2015).

At scale Q: $$\frac{\alpha_s}{\pi} C_F \ln \frac{Q^2}{m_t^2} \sim \delta$$

$$Q \approx m_t \cdot \exp(\frac{\pi\delta}{2\alpha_s C_F})$$

For $\delta = 20\% - 30\%,\ \alpha_s \sim 0.08,$

$Q = (25 - 110) m_t \Rightarrow (4 - 20)\ \text{TeV}.$

Some numerology:

(4). EW logarithms

At scale Q : $\frac{\alpha_2}{\pi} C_w \ln^2 \frac{Q^2}{M_W^2} \sim \delta$

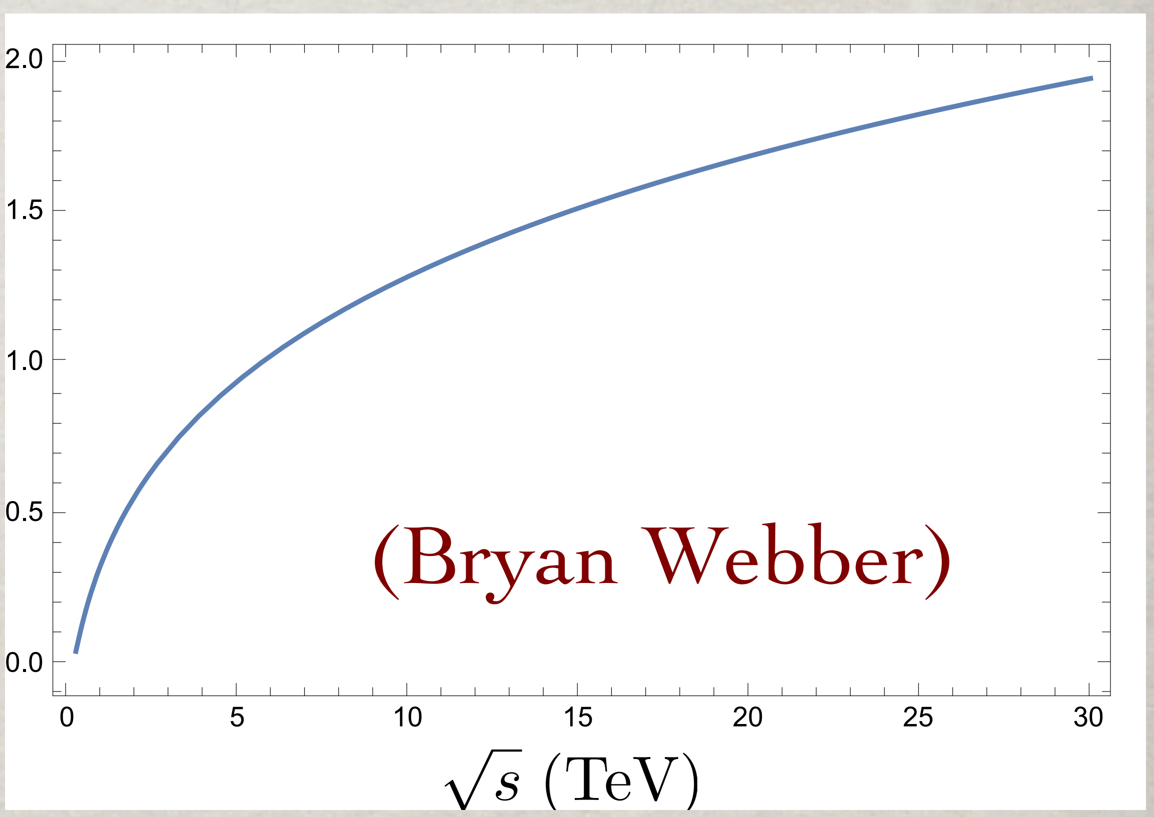
$$Q \approx M_W \cdot \exp\left(\frac{\pi\delta}{4\alpha_2 C_w}\right)^{\frac{1}{2}}$$

J. Chiu, A. Manohar et al., 2005;
Manohar, Bauer et al. (SCET);
M. Chiesa et al., PRL (2013);
T. Becher et al., 1305.4202;
Bauer, Ferland, 1601.07190;

For $\delta = 50\%,\ \alpha_2 \sim 0.035,$

$Q \approx 30 M_W \Rightarrow 2.5$ TeV.

- Virtual Sudakov suppression;
- Real emission enhancement.



SU(2) versus SU(3):
Gauge boson splitting

"Color factors" : $\frac{C_A}{C_F} = \frac{2N^2}{N^2-1} \Rightarrow (\frac{9}{4})_{N=3}$ and $(\frac{8}{3})_{N=2}$.

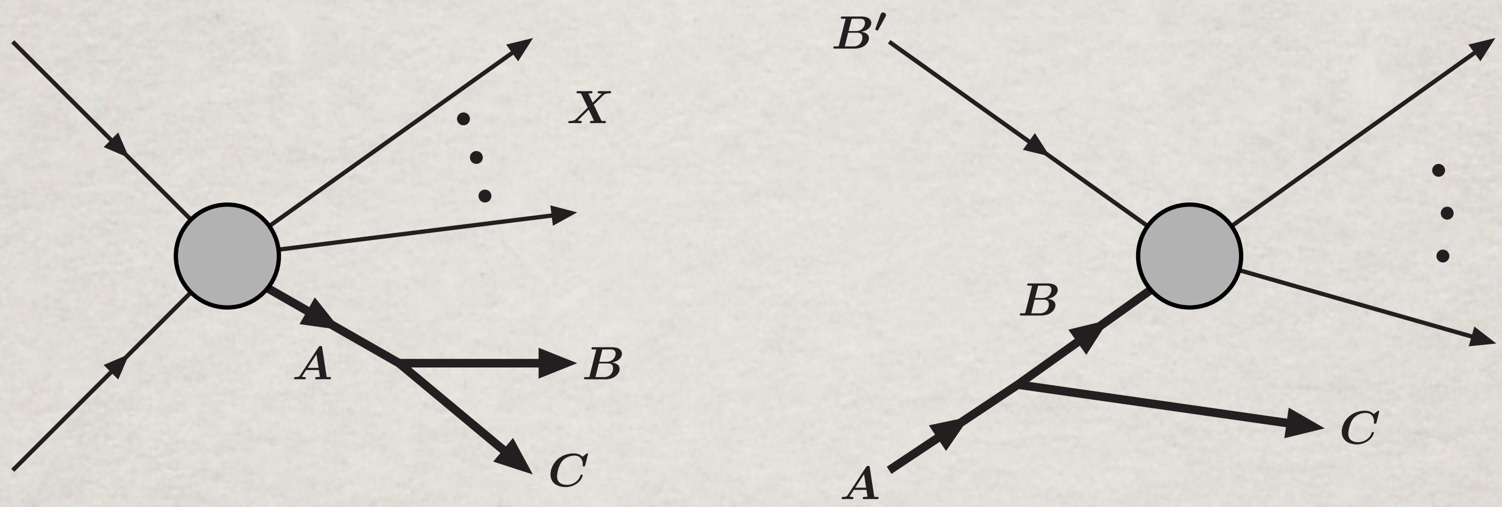
Today:

1. EW Splitting Functions

2. EW Showering

3. EW PDF: Factorization, Resummation (on going efforts)

Formalism:



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

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

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

On the dimensional ground: $|\mathcal{M}_{split}|^2 \sim k_T^2$ or m^2

In general, the splitting formalism must be

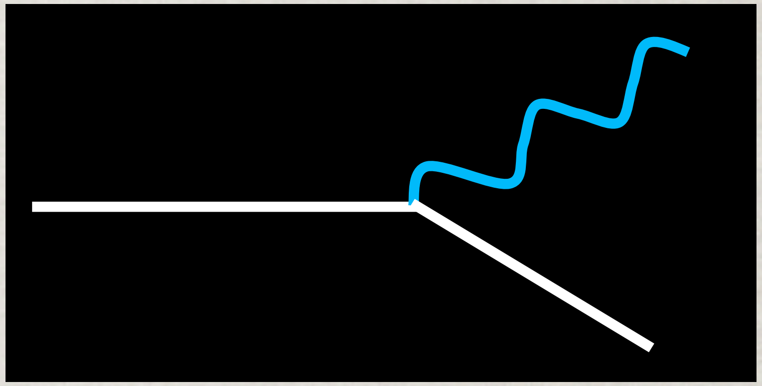
- infra-red safe
- leading behavior

Splitting Functions: QED

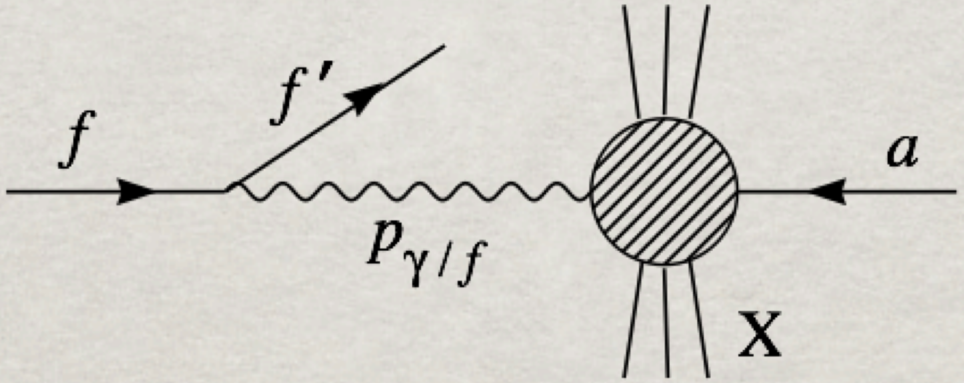
Most familiar example in QED: f → f γ

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

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



The familiar Weizsäcker-Williams approximation



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

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

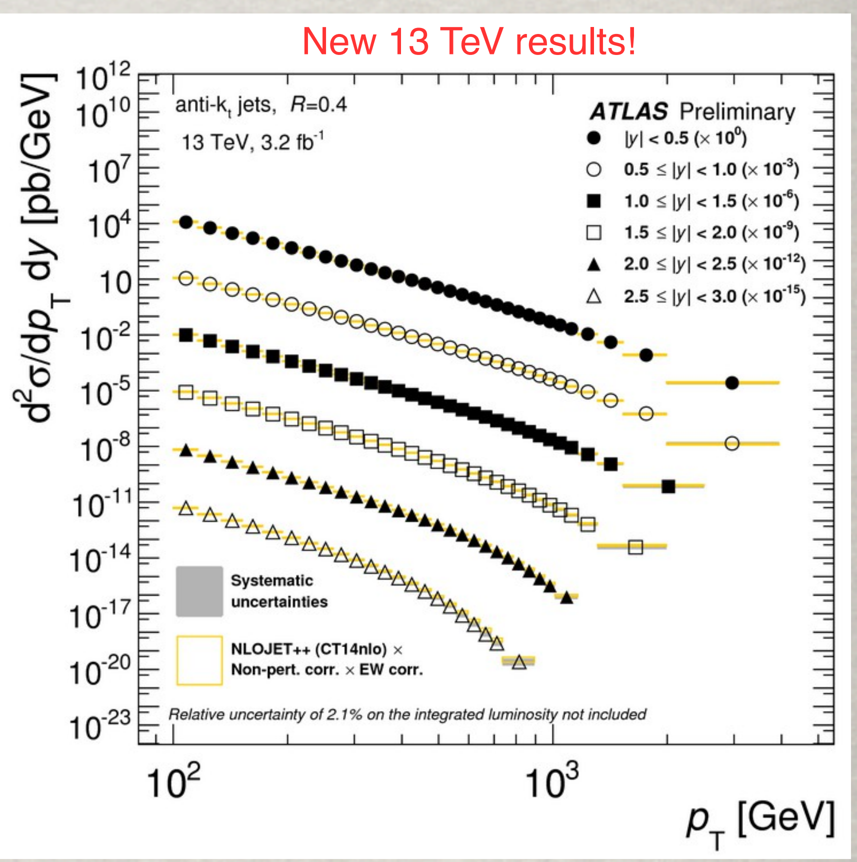
Note the infrared & collinear behavior.

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, PDF (DGLAP):



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

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

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!

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:

	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{1+\bar{z}^2}{z}\right)$		$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{z}{2}\right)$
	$\to V_T\ f_s^{(\prime)}$	$[BW]^0_T\ f_s$	$H^{0(*)}\ f_{\text{-}s}$ or $\phi^\pm\ f'_{\text{-}s}$
$f_{s=L,R}$	$g_V^2 (Q^V_{f_s})^2$	$g_1 g_2 Y_{f_s} T^3_{f_s}$	$y^2_{f_R^{(\prime)}}$

Ciafaloni et al., Hep-ph/0505047.

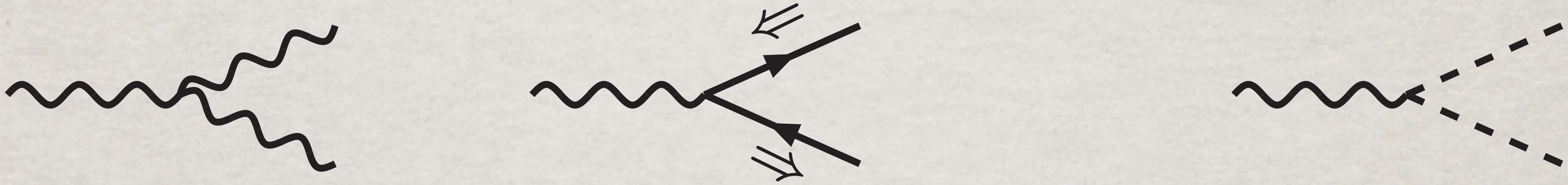
Infrared & collinear singularities (P_{gq})

Collinear singularity, Chirality-flip, Yukawa (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	$2g_2^2\ (V{=}W^{0,\pm})$	$N_f g_V^2 (Q^V_{f_s})^2$	$\frac{1}{4}g_V^2$	$\frac{1}{2}g_2^2$
$[BW]^0_T$	0	$N_f g_1 g_2 Y_{f_s} T^3_{f_s}$	$\frac{1}{2}g_1 g_2 T^3_{\phi^+,H^0}$	0

Infrared & collinear (P_{gg})

Collinear (P_{qg})

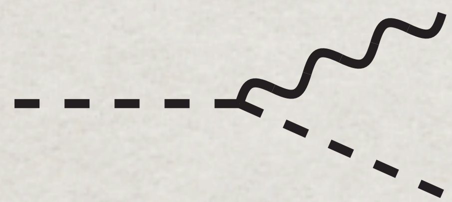
Interference (BW^0) must be included!

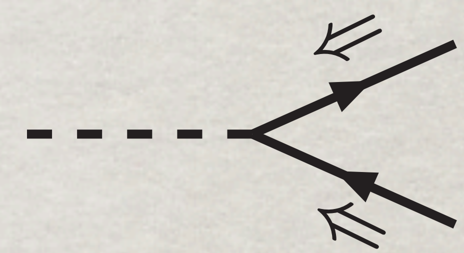
Collinear (new)

Splitting Functions: EW

SM in the unbroken phase

Scalar splitting (new):





	$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{2\bar{z}}{z}\right)$			$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{1}{2}\right)$	
	$\to\ V_T^0\, H$	$[BW]_T^0\, H$	$W_T^{\pm}\, H'$	$u_R\, \bar{u}_R^{(\prime)}$	$\bar{d}_L\, d_L^{(\prime)}$ 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 & Goldstone-boson Equivalence Theorem (GET):

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

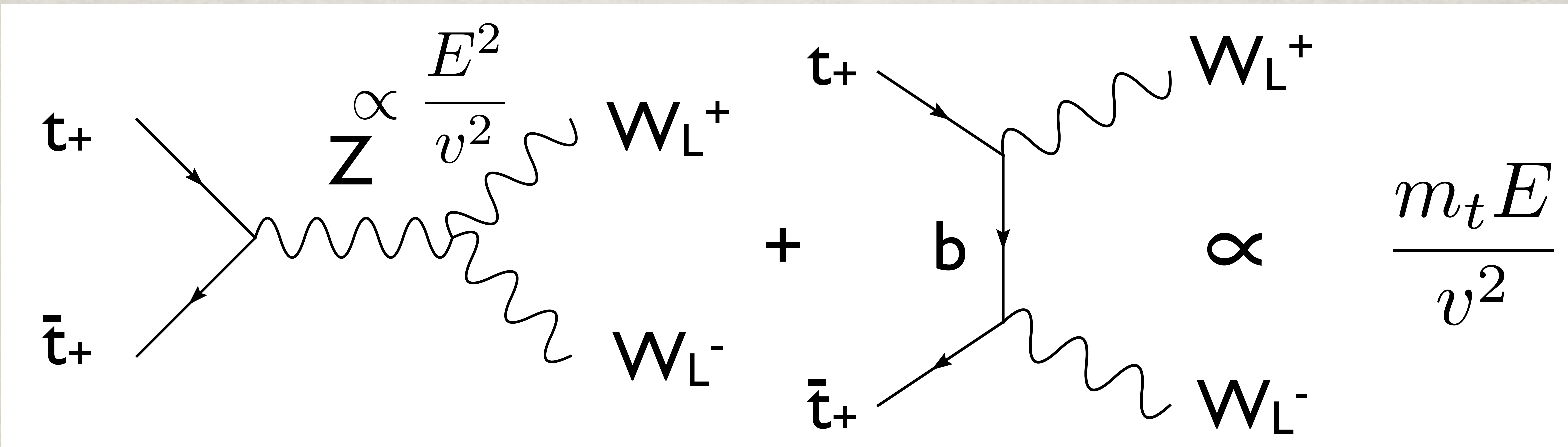
At high energies $E \gg M_W$, the longitudinally polarized gauge bosons behave like the corresponding Goldstone bosons. (They remember their origin!)

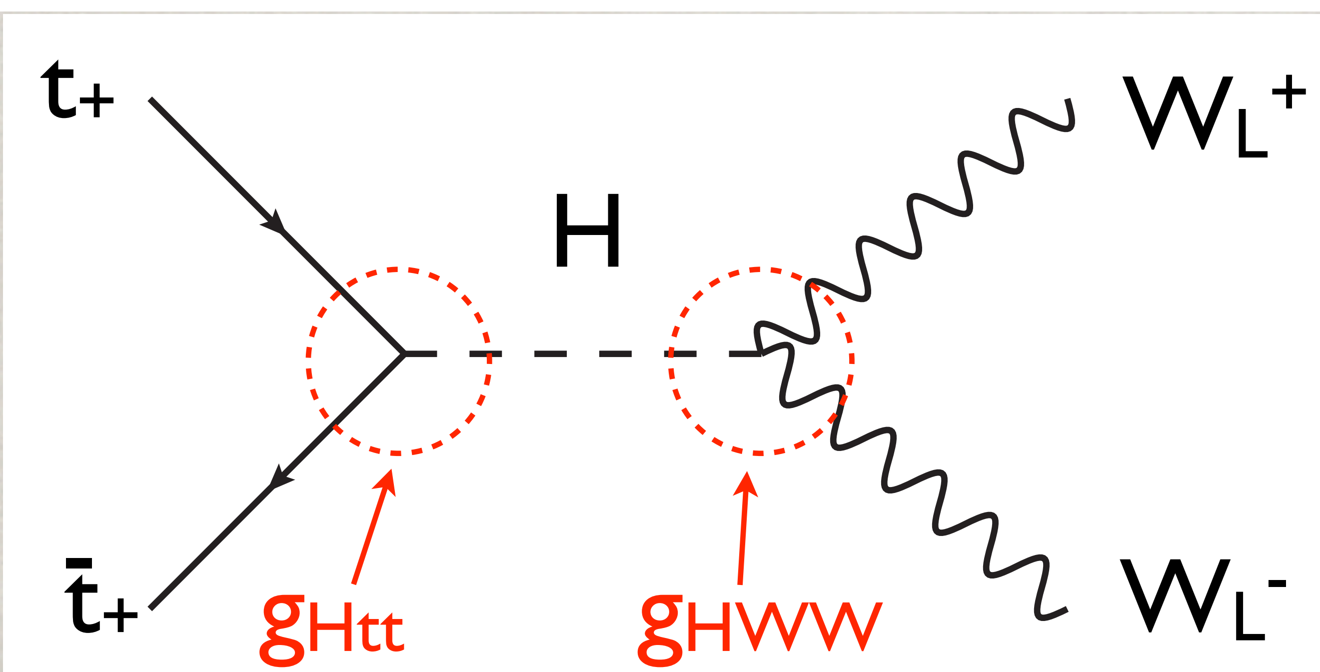
"Scalarization" to implement the Goldstone-boson Equivalence Theorem (GET):

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

(a). Unitarity at higher energies:

$$\epsilon(k)_L^\mu = \frac{E}{m_W}(\beta_W, \hat{k}) \approx \frac{k^\mu}{m_W}$$ bad high-energy behavior!





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:

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

Then, massless fermion splitting

$$f \to f\, V_L$$

would be zero, in accordance with GET for

$$f \to f\, \phi \qquad (y_f \to 0).$$

GET ignored the EWSB effects at the order M_W/E

(higher twist effects)

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

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

At colliding energies E >> M_W,

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

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

- Vector boson fusion observed at the LHC
  WW, ZZ→h & W^+W^+ scattering
- f → f W_L, f Z_L do not vanish; no collinear-log!

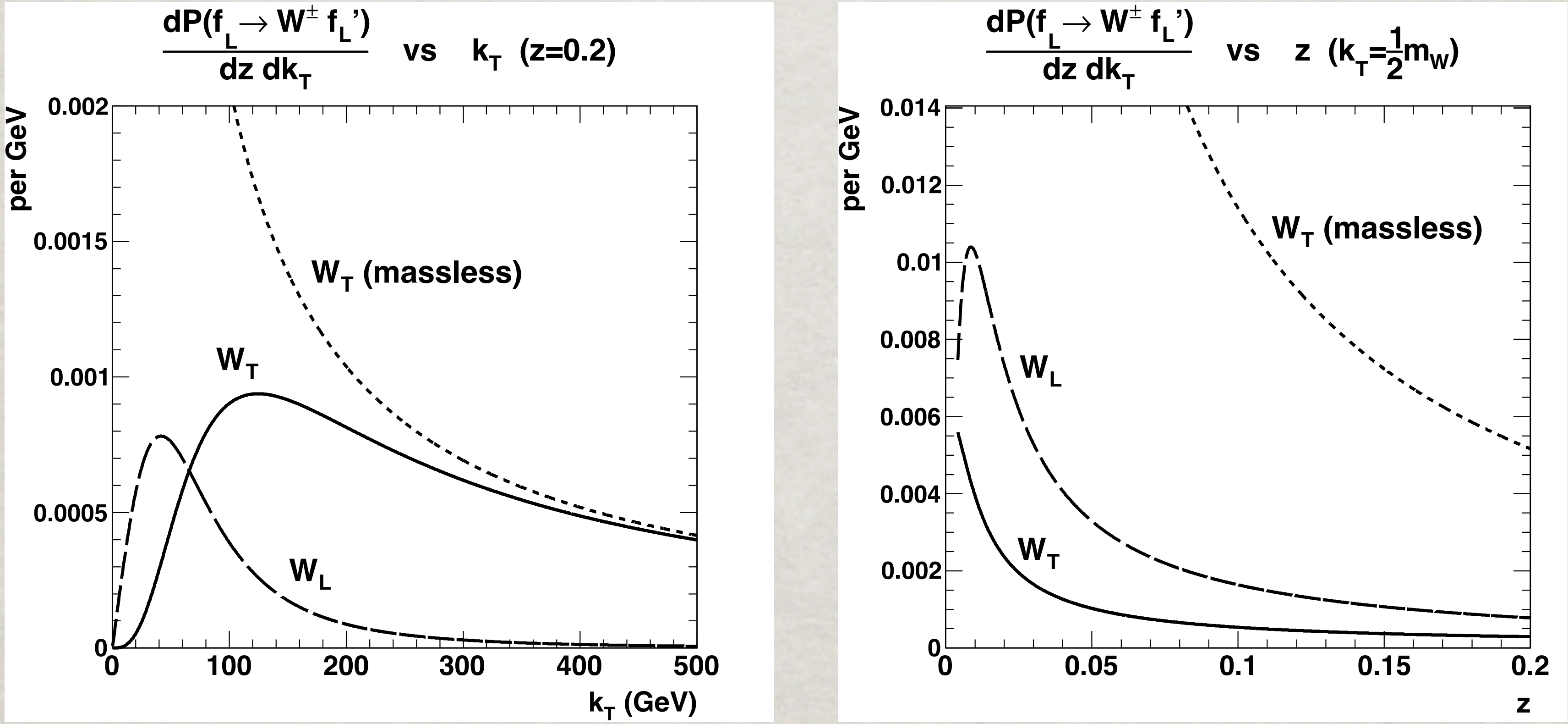
“Ultra collinear behavior”

New characteristics with the mass:

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

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

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



- Kinematic basis for “forward jet-tagging, central jet-vetoing” ! Barger, Cheung, TH, Phillips (1989).
- The DPFs for W_L thus don’t run at leading log: “Bjorken scaling” restored (higher-twist effects)!

"Goldstone Equivalence Gauge" (GEG)

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

1st term leads to GET ~ ϕ, well behaved;

2nd term captures EWSB ~ A_n^μ, well behaved

Separate them out by a special gauge choice:
(hybrid of Coulomb & light-cone gauge)

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

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

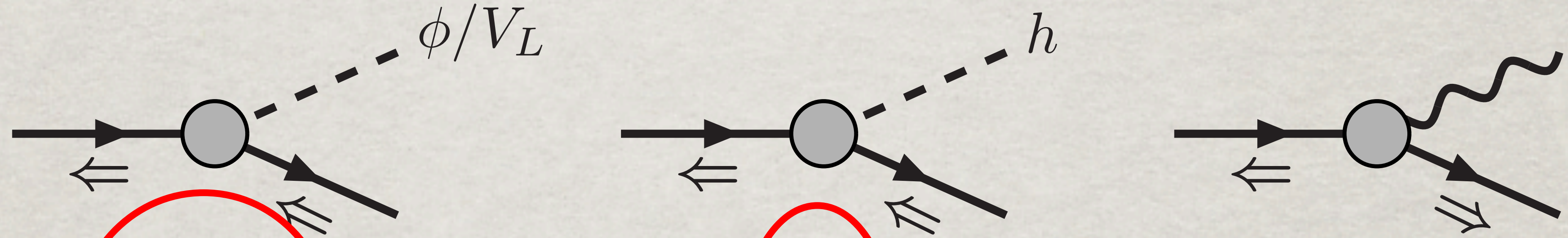
$$\epsilon^\mu_{\text{long}}(k) \to \frac{\sqrt{|k^2|}}{n(k)\cdot k}\, n^\mu(k) \overset{\text{on-shell}}{\to} \frac{m_W}{E+|\vec{k}|}\left(-1, \hat{k}\right).$$

A similar work by A. Wulzer, arXiv:1703.08562.

Splitting in the Broken Gauge Corrections to GET

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



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

Chirality conserving:
Non-zero for massless f

Chirality flipping: $\sim m_f$

Splitting in the Broken Gauge

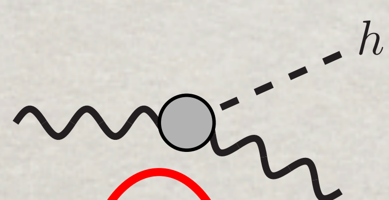
New gauge boson splitting to $W_L W_T$

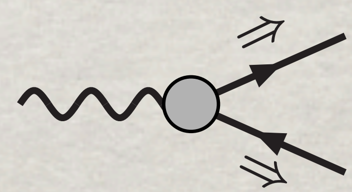
Vector boson V_L is of IR.

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

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



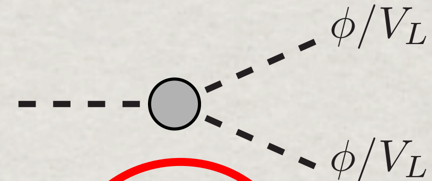


	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$	$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$
	$\to h\ V_T\ (V \neq \gamma)$	$f_s\ \bar{f}_s^{(\prime)}$
V_T	$\frac{1}{4}z\bar{z}g_V^4$	$\frac{1}{2}g_V^2\left(Q_{f_s}^V y_{f^{(\prime)}} z + Q_{f_{-s}}^V y_f \bar{z}\right)^2$
$[\gamma Z]_T$	0	$\frac{1}{2}e g_Z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

Splitting in the Broken Gauge

New gauge boson splitting in 3-W_L

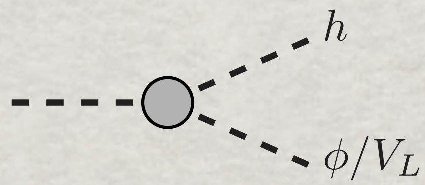
Vector boson V_L is of IR.

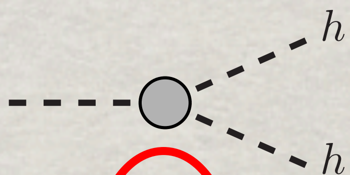


$$\frac{v^2}{k_T^2}\ \frac{dk_T^2}{k_T^2} \sim (1 - \frac{v^2}{Q^2})$$

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

Process gauge couplings	$\approx \mathcal{P}(E)$	$\mathcal{P}$(1 TeV)	$\mathcal{P}$(10 TeV)
$q \to V_T q^{(\prime)}$ (CL+IR)	$(3 \times 10^{-3}) \left[\log \frac{E}{m_W}\right]^2$	3%	7%
$q \to V_L q^{(\prime)}$ (UC+IR)	$(2 \times 10^{-3}) \log \frac{E}{m_W}$	0.8%	1.1%
$t_R \to W_L^+ b_L$ (CL)	$(8 \times 10^{-3}) \log \frac{E}{m_W}$	2%	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)	$(0.015) \left[\log \frac{E}{m_W}\right]^2$	8%	36%
$V_T \to V_L V_T$ (UC+IR)	$(0.014) \log \frac{E}{m_W}$	3%	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)	$(2 \times 10^{-3}) \left[\log \frac{E}{m_W}\right]^2$	1%	4%
$V_L \to V_L h$ (UC+IR)	$(2 \times 10^{-3}) \log \frac{E}{m_W}$	0.4%	1%

- Non-Abelian gauge spliting larger than fermion splitting!
- Collinear splittings larger than perturbative radiation!

Now some results at 100 TeV →

Multi Gauge-boson Production

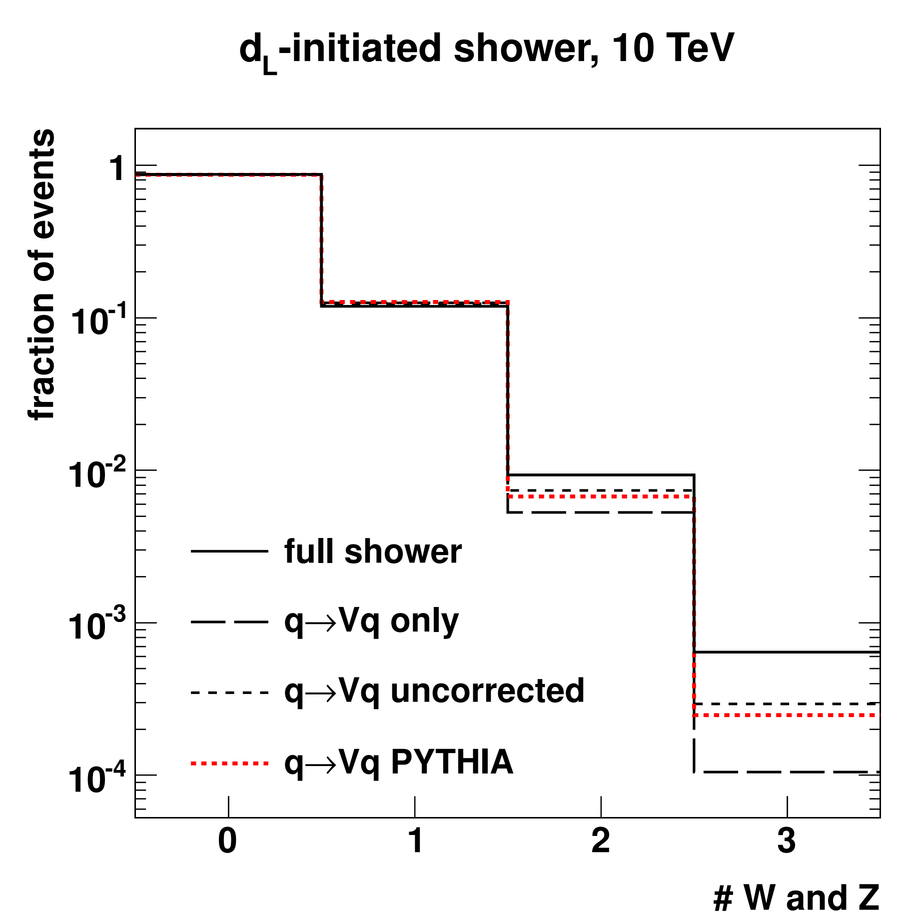
W radiation costs ~ 1/10

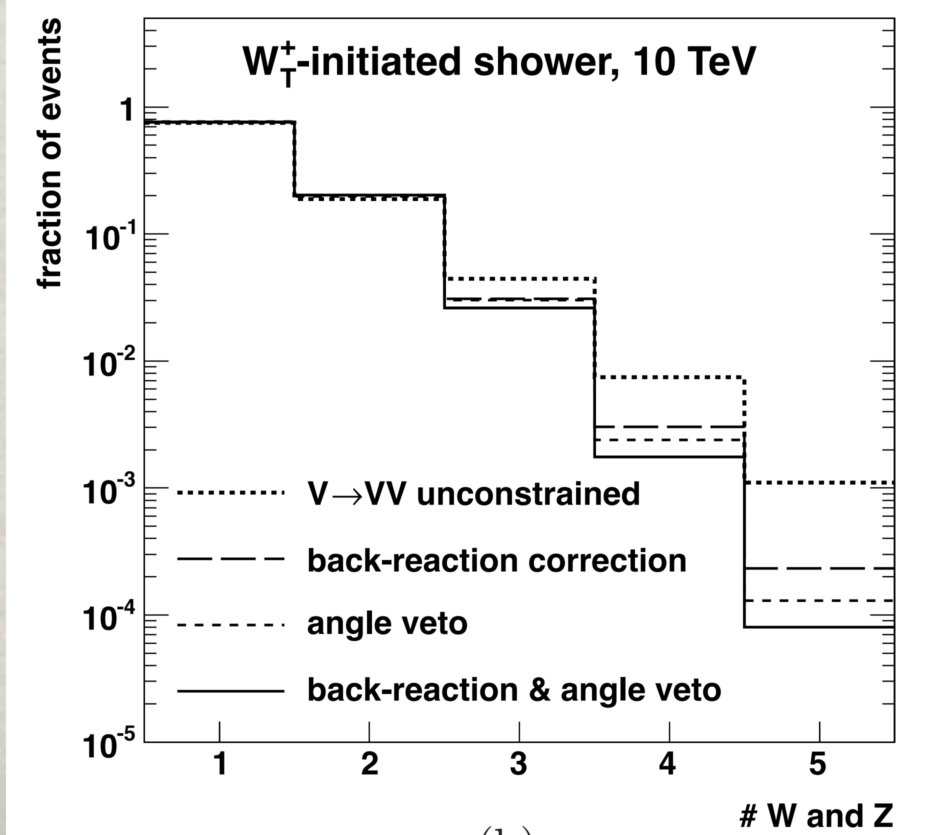
At 100 TeV: M. Mangano's talk

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

....

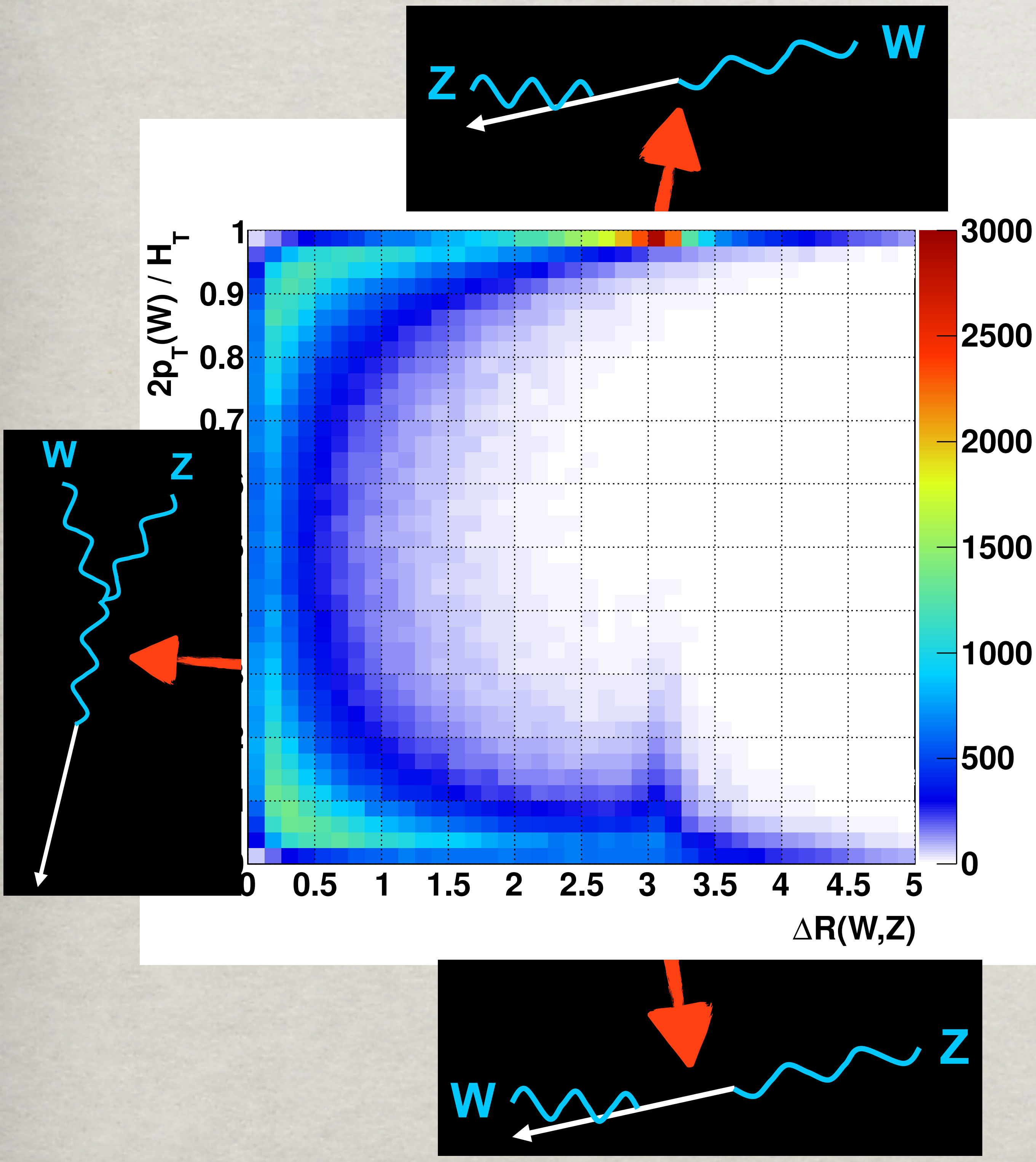


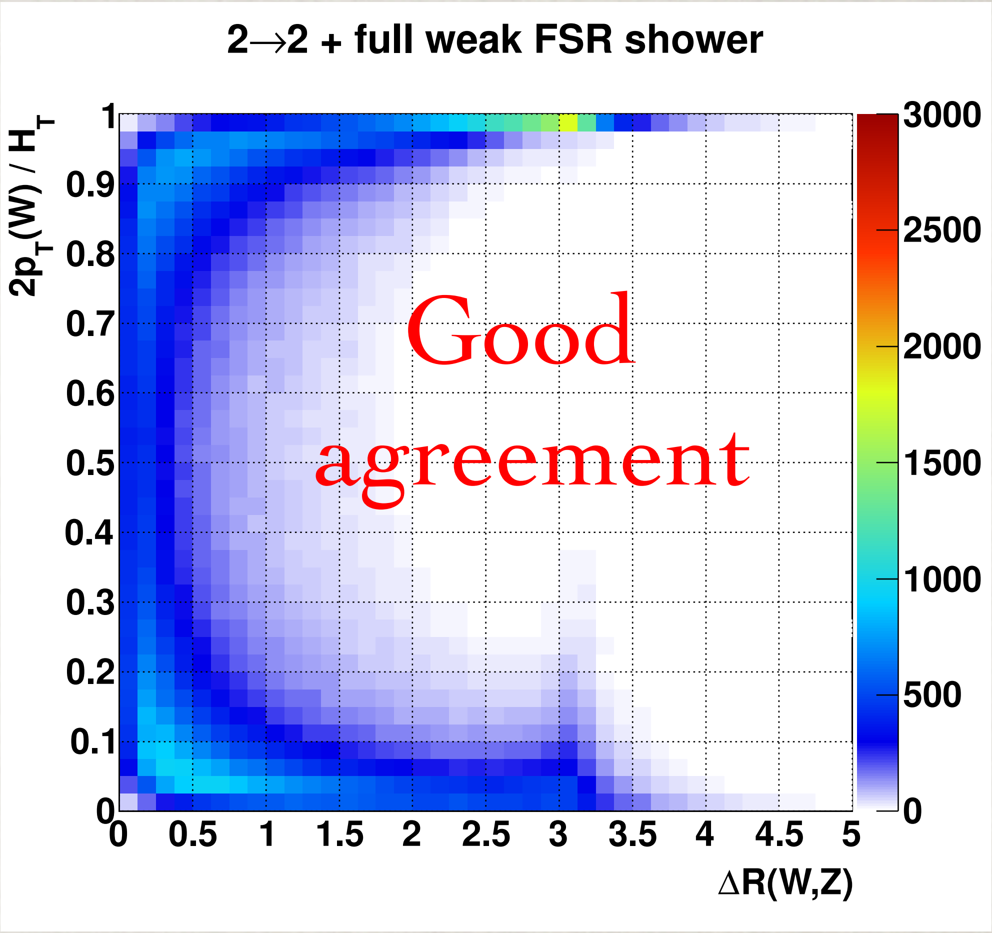


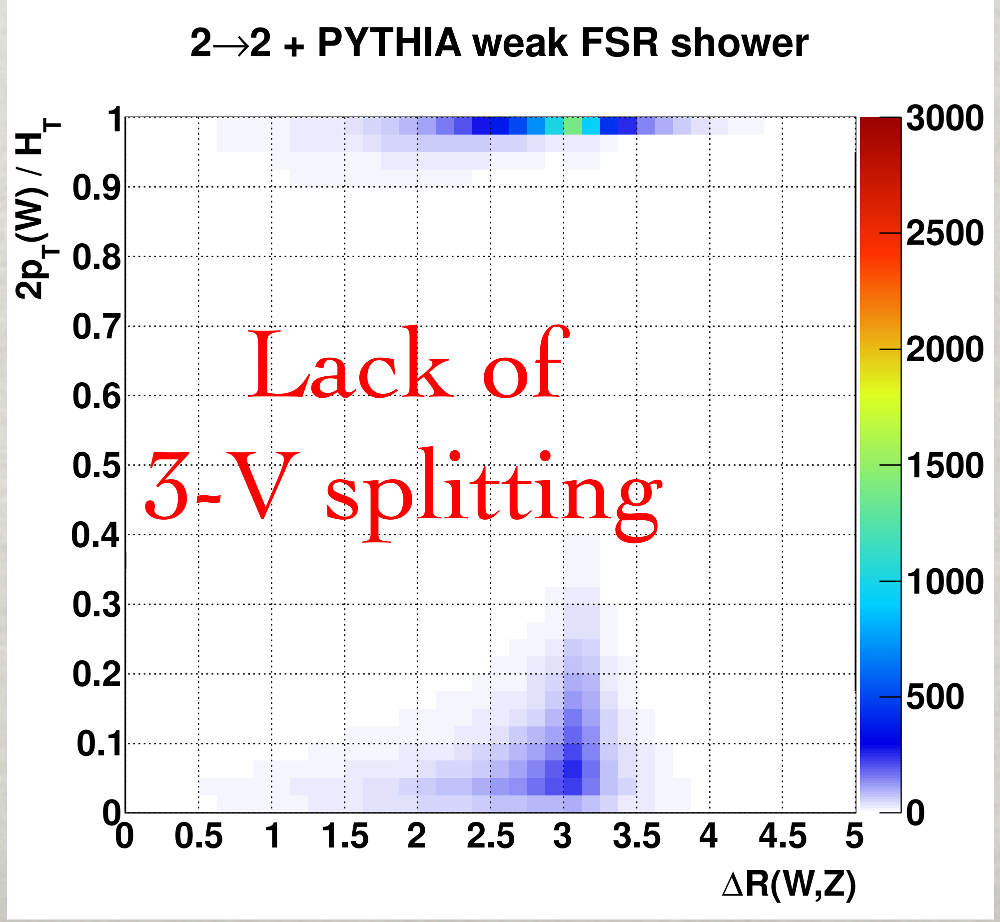
Each *W* costs you a factor of ~ 1/100 (EW coupling)

An Example: WZ+J @ 100 TeV

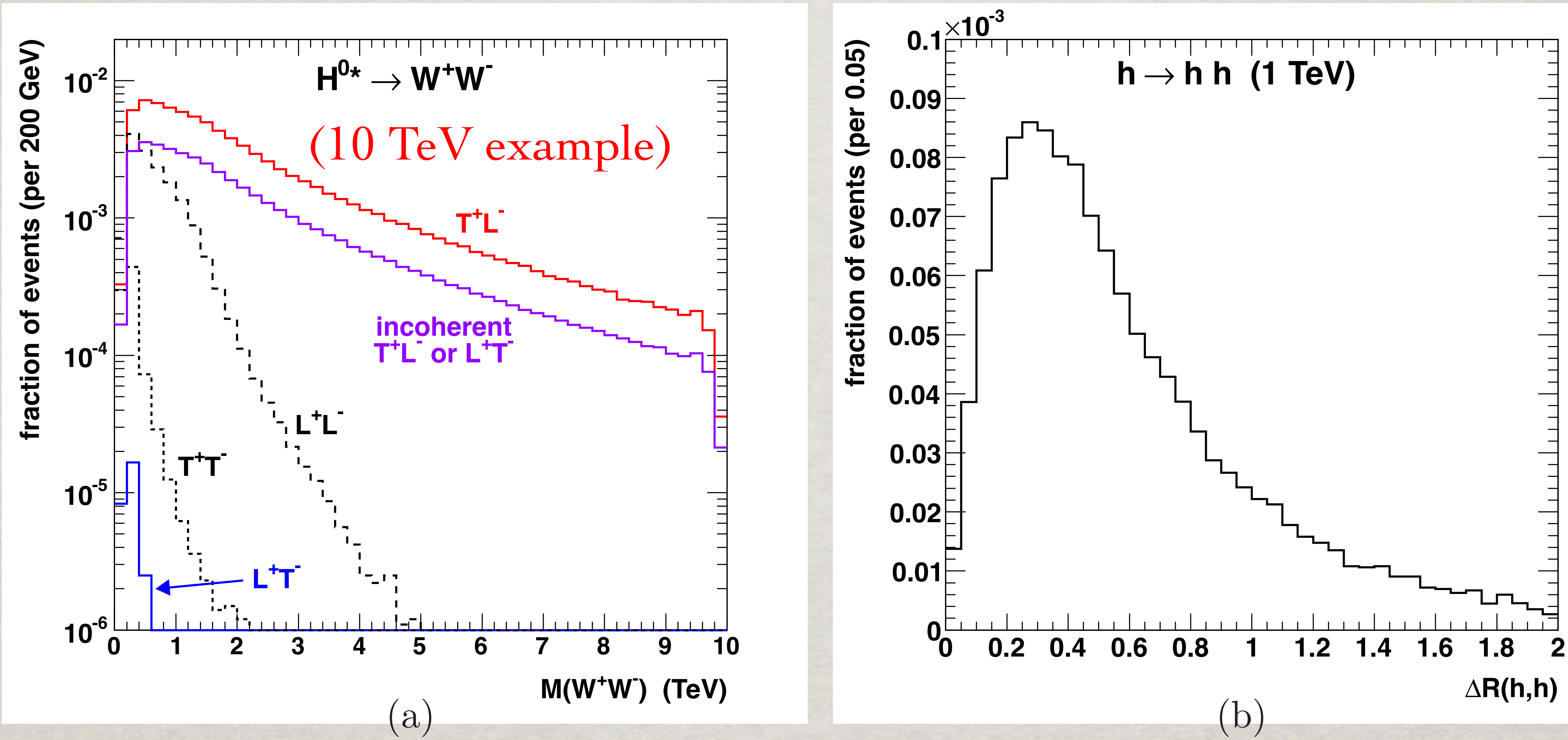
MadGraph 2→3 fixed order







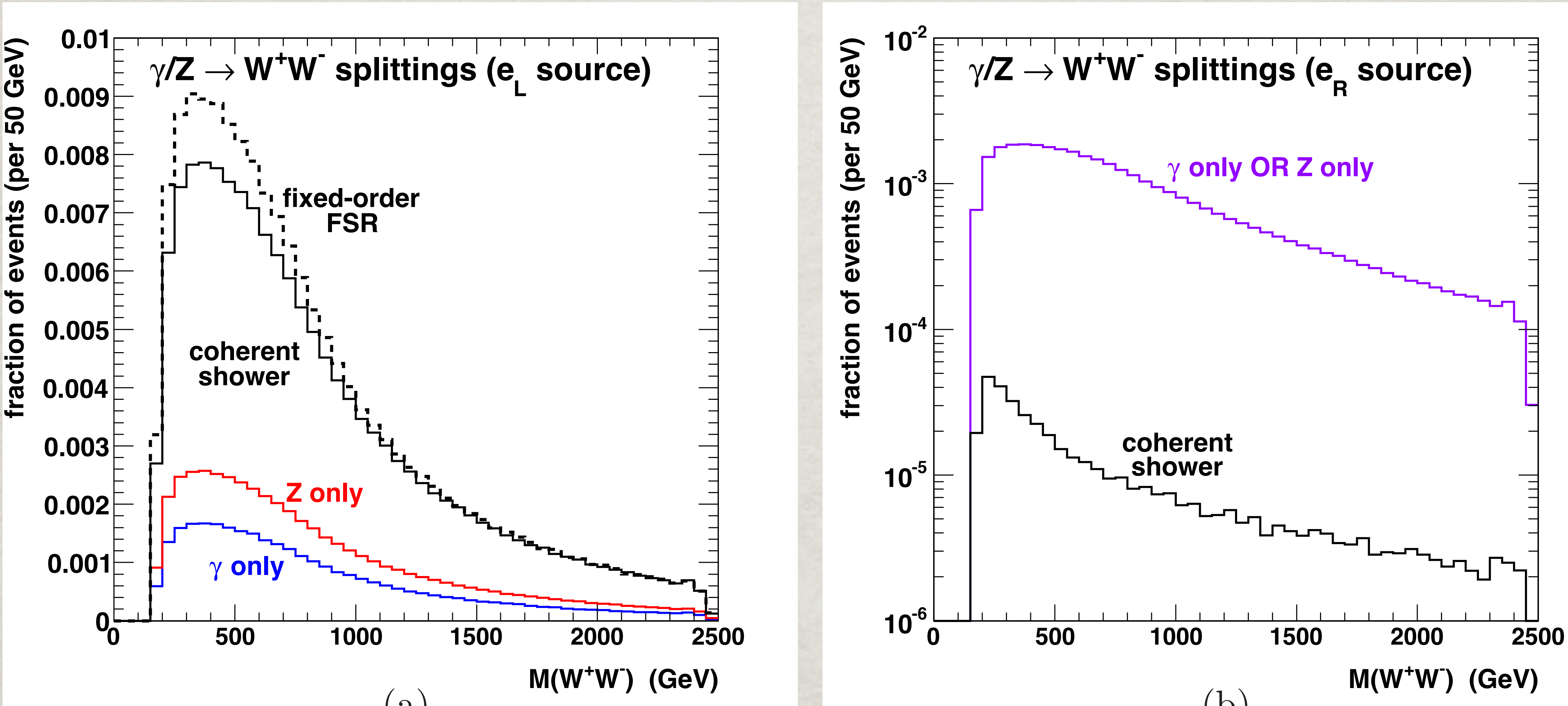
Higgs boson showering:



- $H^{0*} = h^0 - i\phi^0$ coherent:
  $W_T^+ h^- >> W_T^- h^+$
- h/Z_L separate wrong!

Ultra-collinear behavior:
Some guidance for h^3 search.

$e^-_L e^+_R$ & $e^-_R e^+_L \rightarrow W^+W^-$ + shower (e^+e^- E_{cm} = 5 TeV)



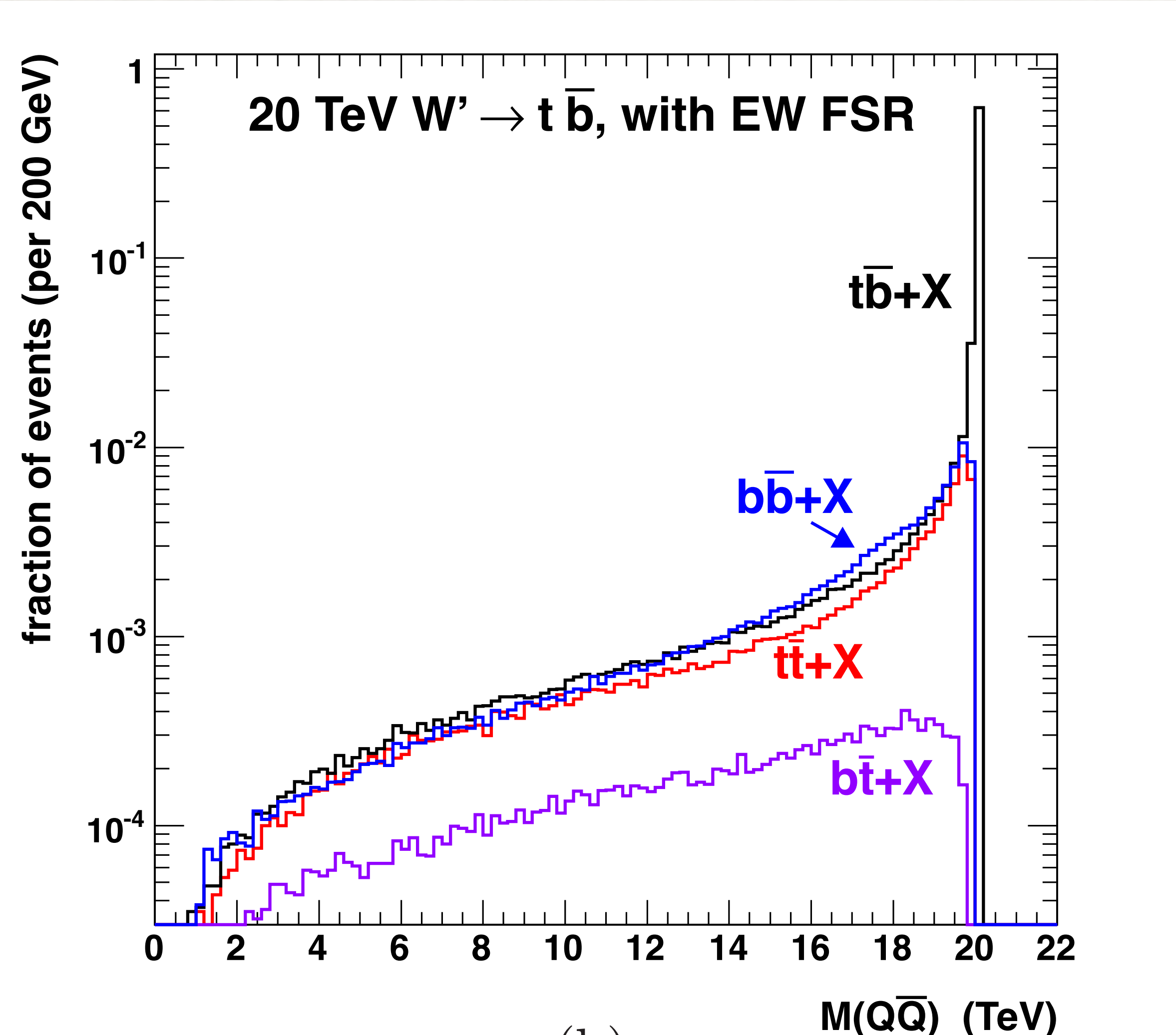
W/Z shower important;
Coherent treatment important.

Pure B^0 exchange:
Small.

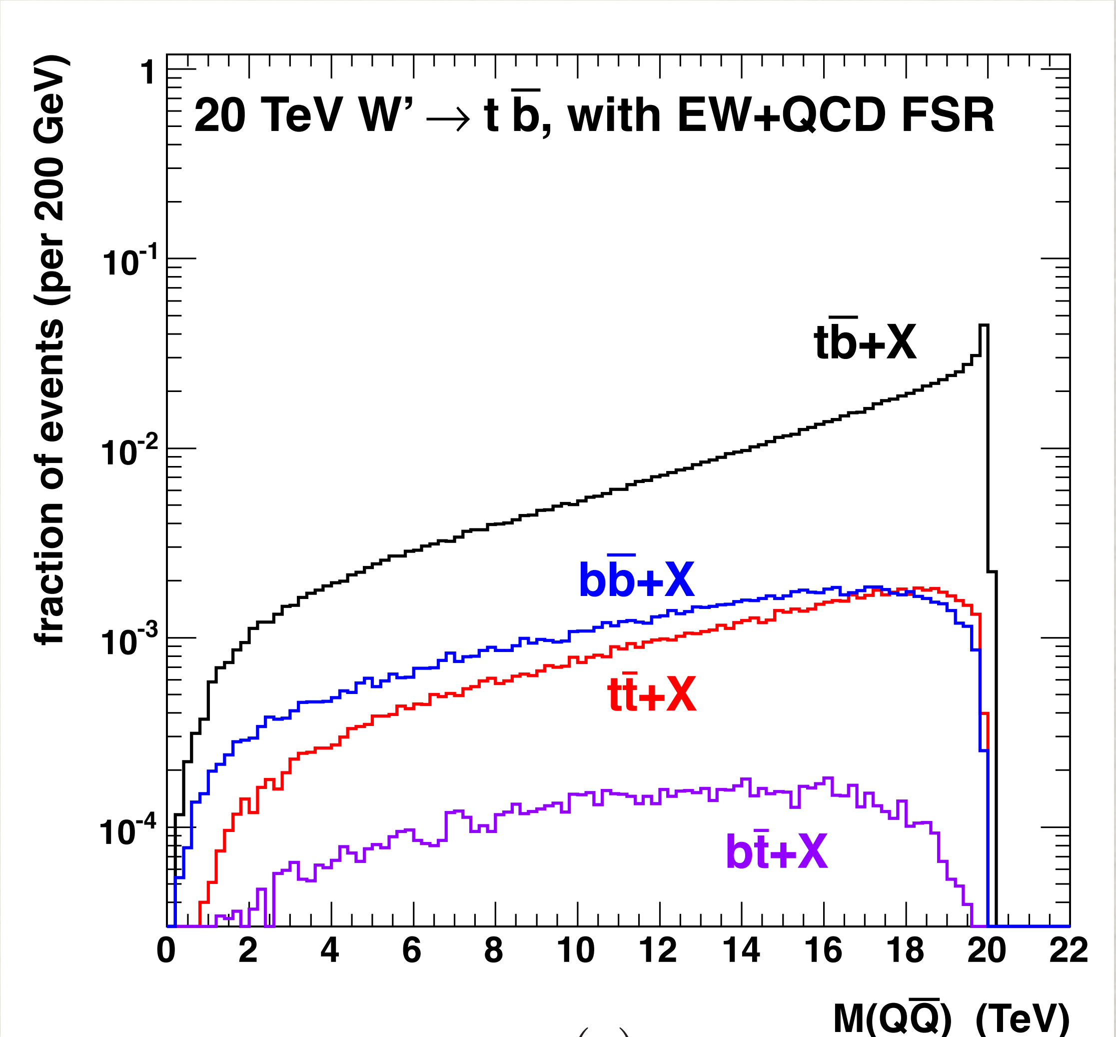
$SU(2)_L \times U(1)_Y$ interactions restored!

W^{+}' Shower examples:

$$W_L^{+'} \to t\bar{b},\ t\bar{t}(W^-),\ b\bar{b}(W^+),\ b\bar{t}(W^+W^+).$$



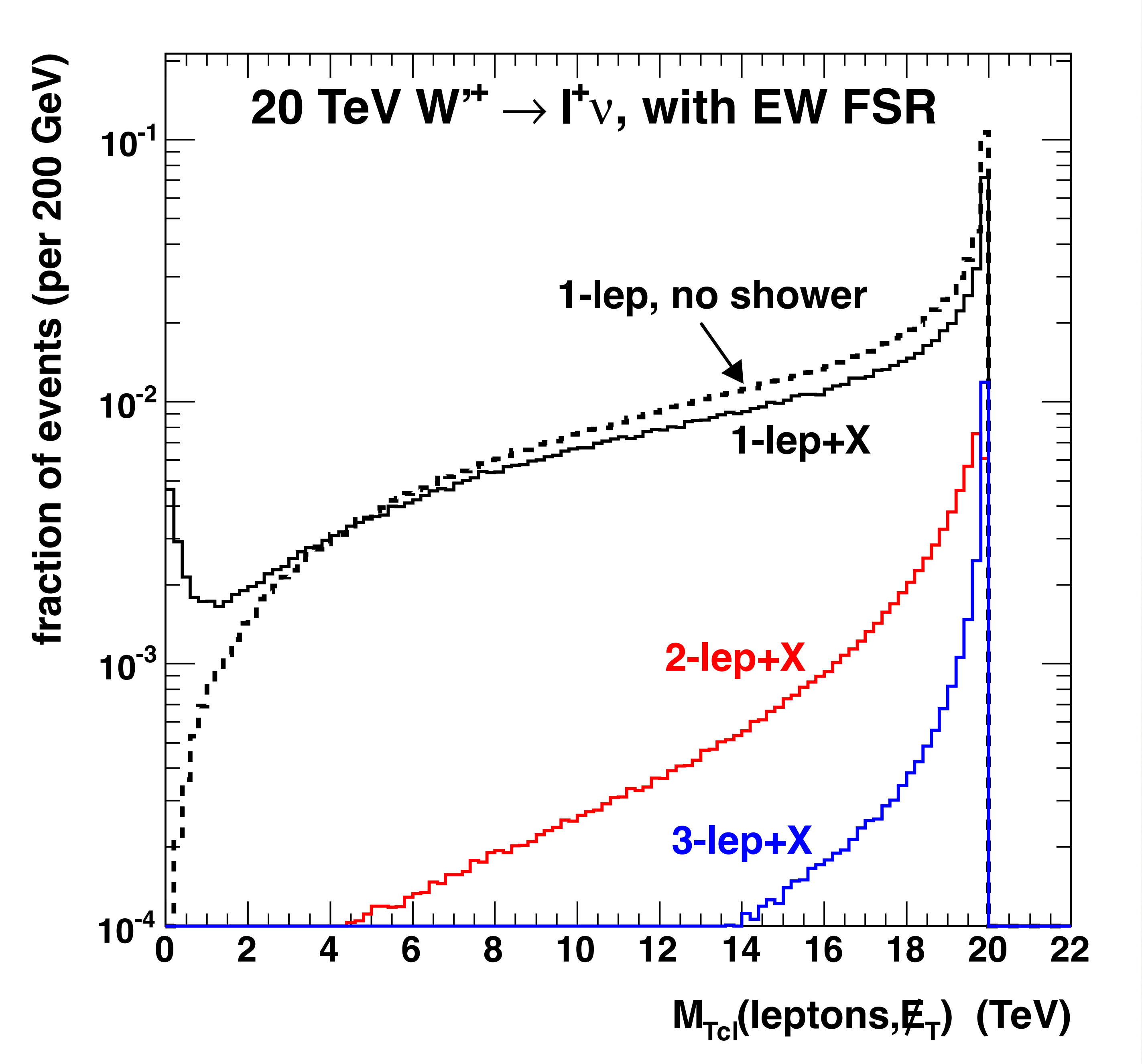
(b)



(c)

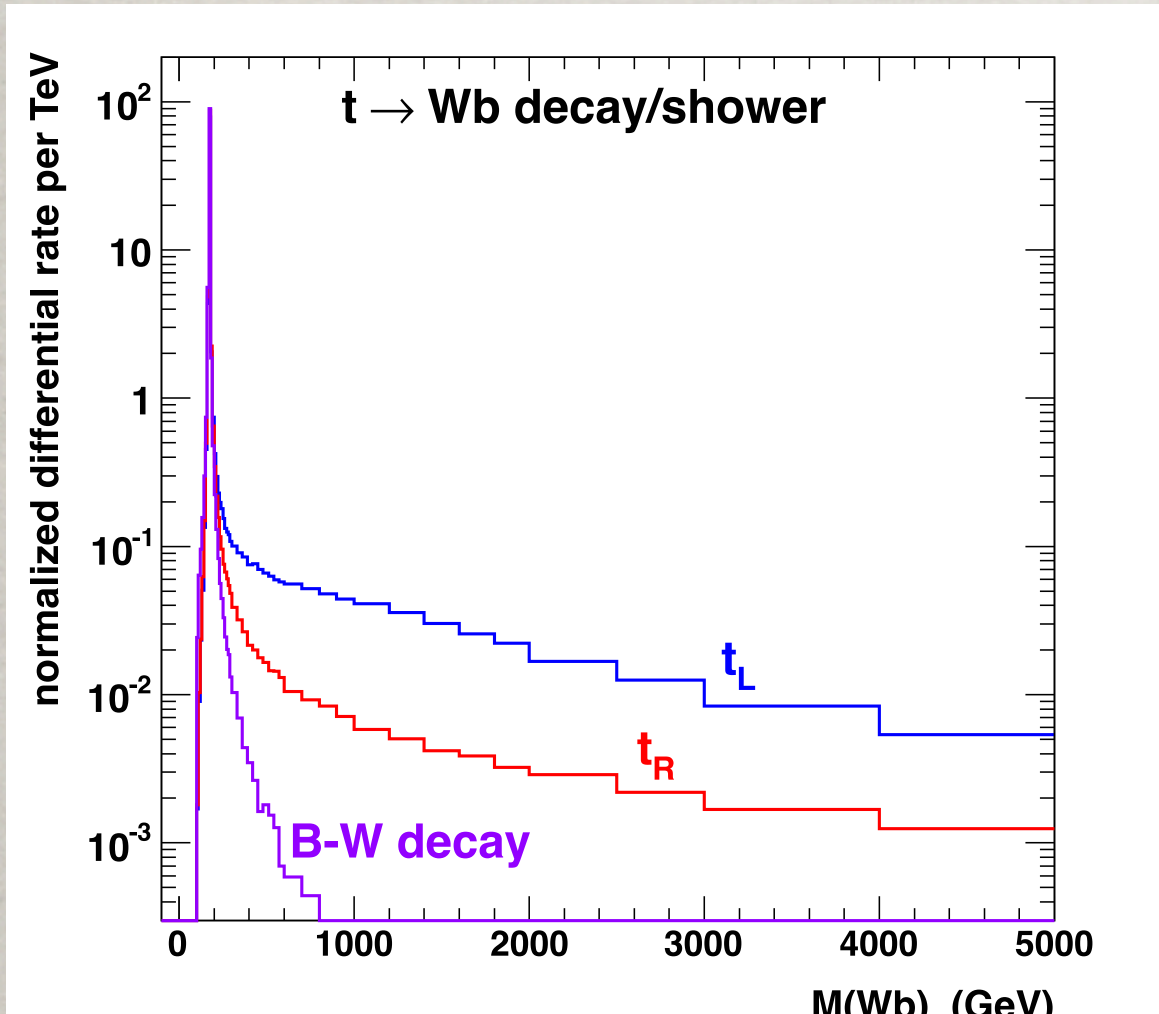
With W/Z showers, ALL t/b iso-spin components exist.

W^{+}' Shower example: Lepton final states

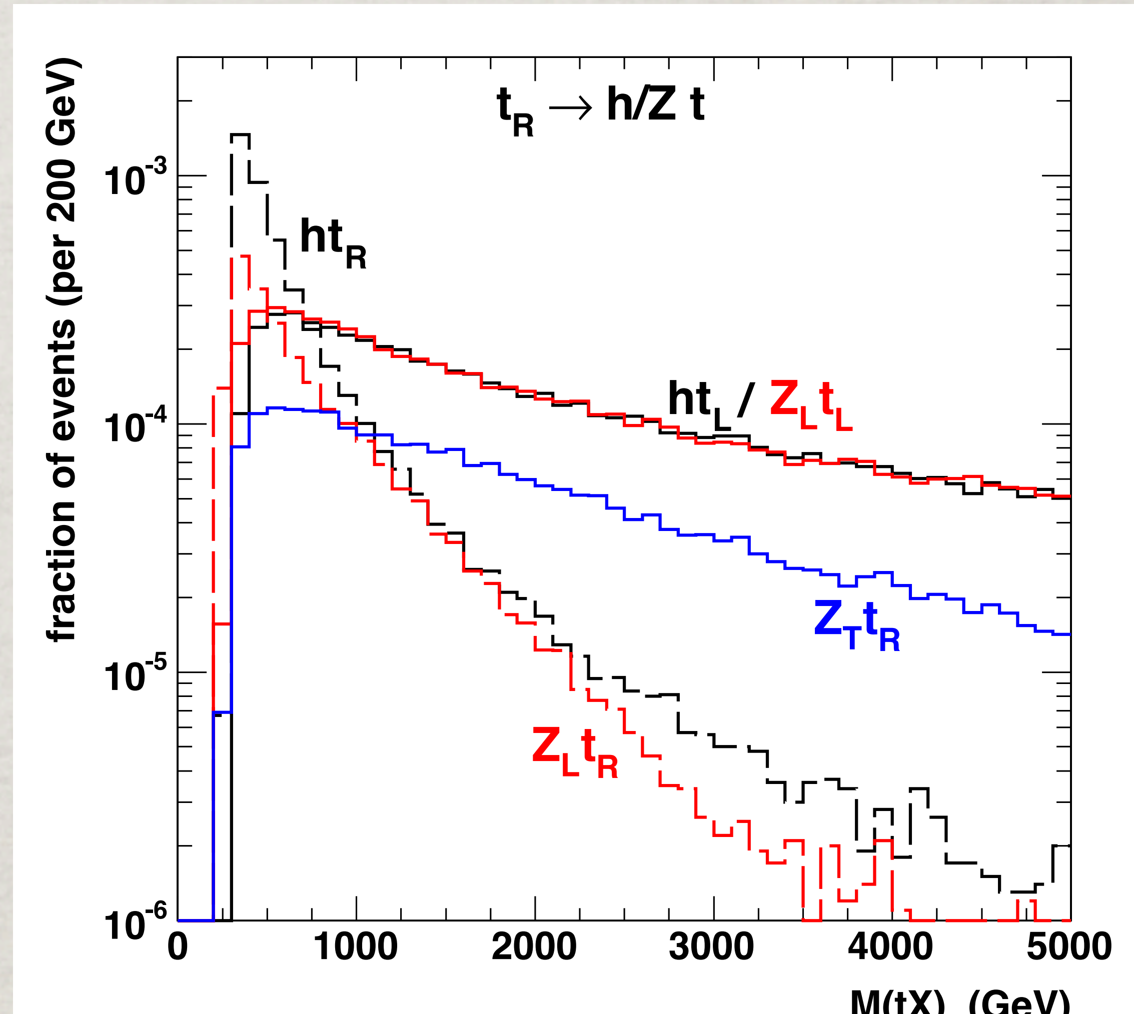


With W/Z showers, all leptons/neutrino components exist.

Top decay/showering (10 TeV):



(a)



(b)

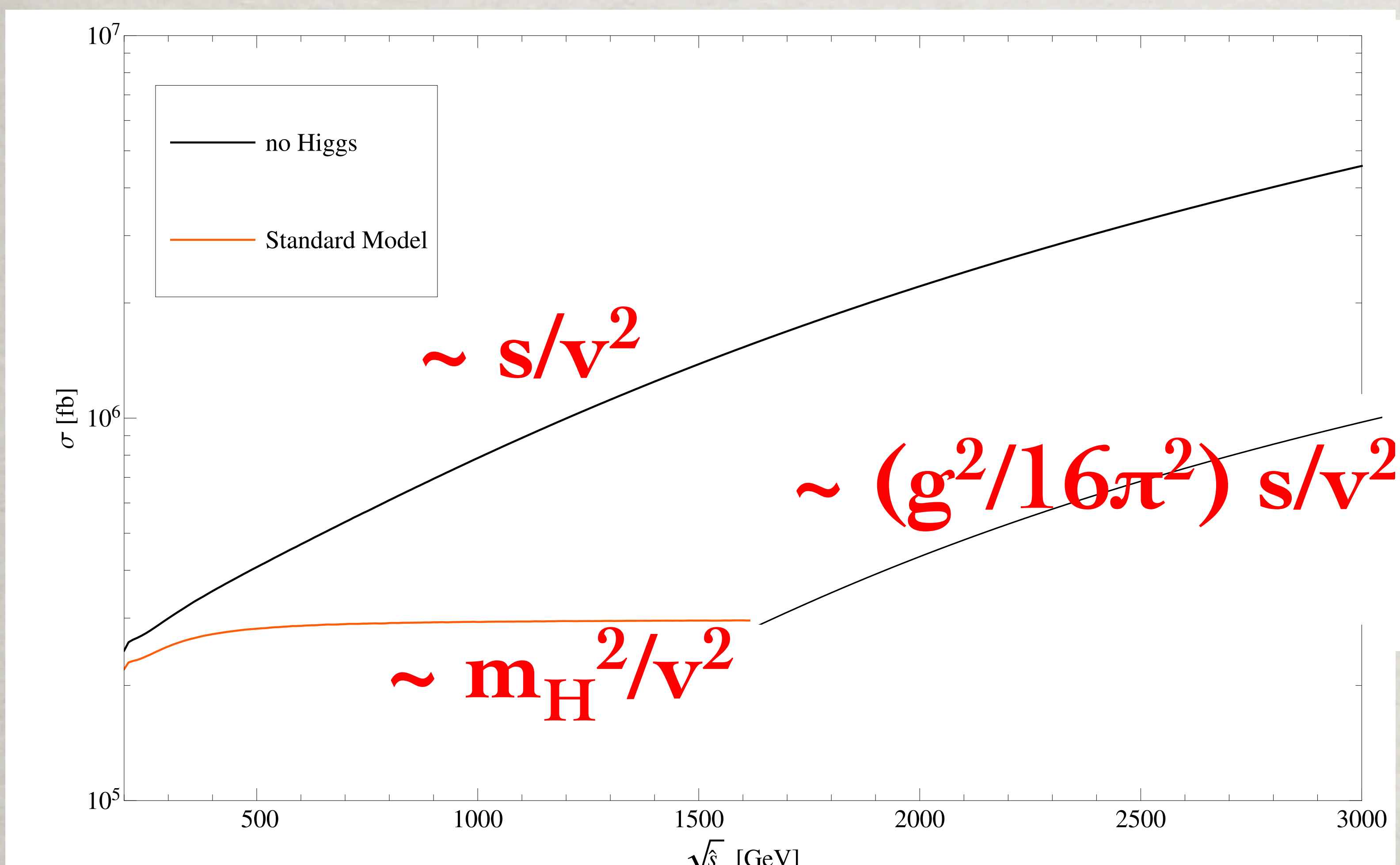
Yukawa: $\mathcal{P}(t_R \to ht_L) \simeq \mathcal{P}(t_R \to Z_L t_L) \approx 7.2 \times 10^{-3}$

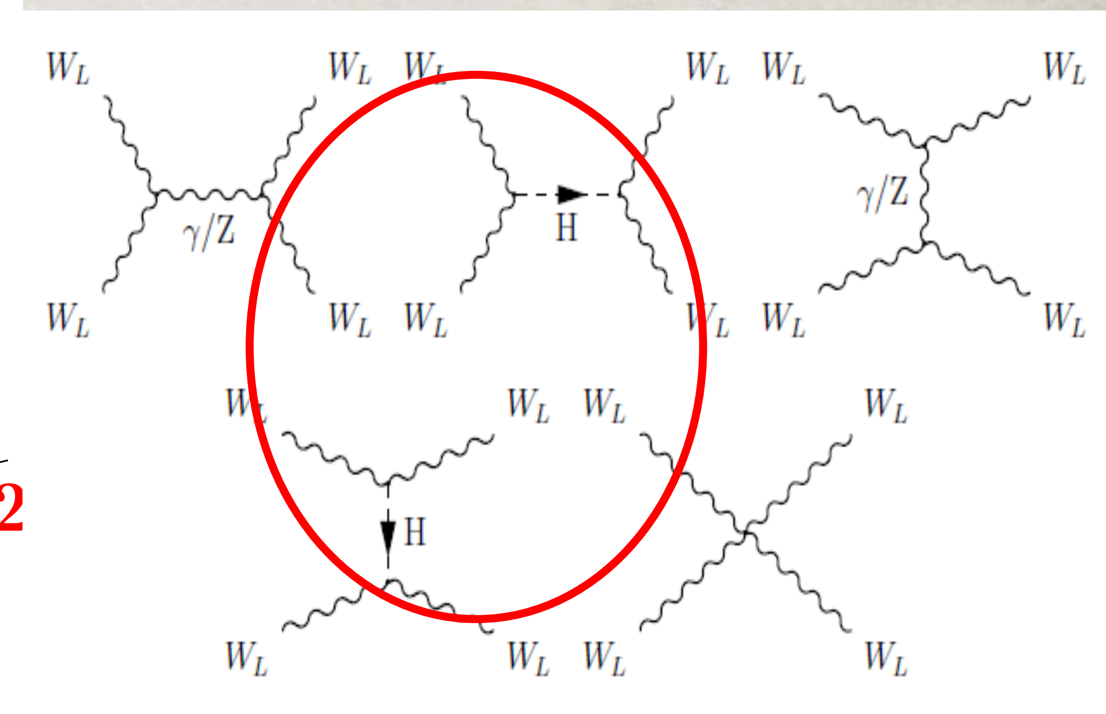
U(1) gauge: $\mathcal{P}(t_R \to Z_T t_R) \approx 4.5 \times 10^{-3}$

Ultra-collinear: $t_R \to ht_R,\ Z_L t_R$

$W_L W_L$ Scattering:

- The existence of a light, weakly coupled Higgs boson unitarize the WW amplitude:





- Consistent perturbative theory up to Λ (?)
- New strong dynamics effects may still exist, but “delayed” to v^2/Λ^2.

EW PDF's

QCD factorization: Colins, Soper, Sterman (1985).

$$\sigma(pp \to X + \text{anything}) = \int_{\tau_0}^{1} d\tau \sum_{ij} \frac{d\mathcal{L}_{ij}}{d\tau}\ \hat{\sigma}(ij \to X),$$

$$\frac{d\mathcal{L}_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{d\xi}{\xi} \left[f_{i/p}(\xi, Q_f^2) f_{j/p}\left(\frac{\tau}{\xi}, Q_f^2\right) + (i \leftrightarrow j) \right]$$

EW partons:

$$\Phi_{VV'}(\tau) = \frac{1}{(\delta_{VV'}+1)} \int_{\tau}^{1} \frac{d\xi}{\xi} \int_{\tau/\xi}^{1} \frac{dz_1}{z_1} \int_{\tau/\xi/z_1}^{1} \frac{dz_2}{z_2} \sum_{q,q'} \tag{7}$$

$$\times \left[f_{V/q}(z_2) f_{V'/q'}(z_1)\ f_{q/p}(\xi) f_{q'/p}\left(\frac{\tau}{\xi z_1 z_2}\right) + f_{V/q}(z_2) f_{V'/q'}(z_1)\ f_{q/p}\left(\frac{\tau}{\xi z_1 z_2}\right) f_{q'/p}(\xi) \right]$$

Chen, TH, Tweedie, arXiv:1611.00788;
Bauer, Ferland, Webber, arXiv:1703.08562, 1712.07147.

EW Evolution @ Leading Double Log

Bauer, Ferland, Webber, arXiv:1703.08562, 1712.07147;
Chen, TH, Tweedie, arXiv:18xx.

$\Rightarrow$ Sudakov factor : $\Delta_i \sim \exp[-C_i \frac{\alpha_2}{\pi} \ln^2(\frac{Q^2}{M_W^2})]$

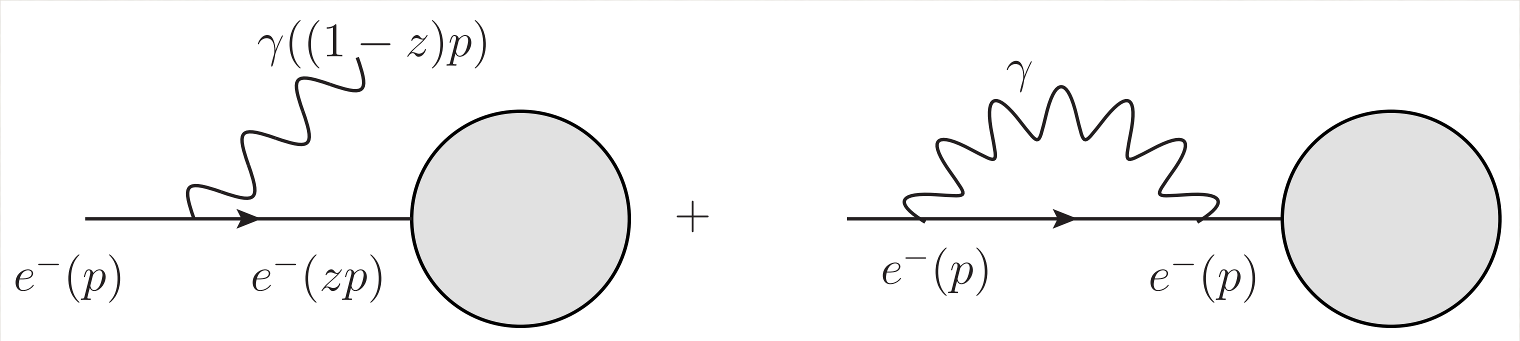
Following SU(2)xU(1) DGLAP equations.

e.g., iso-spin state evolution @ leading log:

$$f_e(x,\mu) \simeq f_e(x,0)\frac{1+e^{-(\alpha_2/\pi)\log^2(\mu/m_W)}}{2} + f_\nu(x,0)\frac{1-e^{-(\alpha_2/\pi)\log^2(\mu/m_W)}}{2}$$

with W/Z showers, leptons/neutrinos redistributed.

EW Evolution beyond Leading Log



Incomplete cancellation for non-inclusive process in SU(2)
→ Bloch-Nordsieck theorem violation

$$d\mathcal{P}_{\nu\leftarrow e} = d\mathcal{P}_{e\leftarrow\nu} \sim \frac{(T^{\pm})^2}{1-z} = \frac{(1/\sqrt{2})^2}{1-z}$$

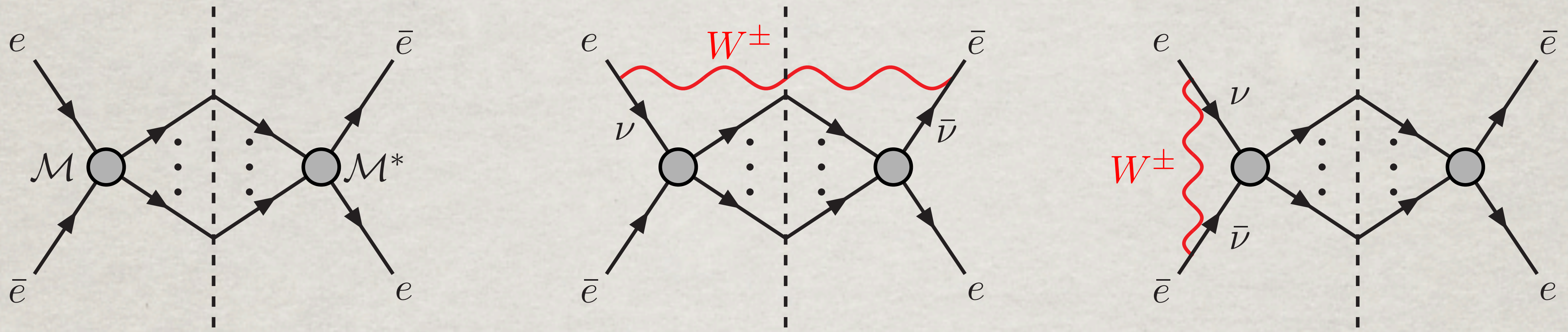
$$d\mathcal{P}_{e\leftarrow e} = d\mathcal{P}_{\nu\leftarrow\nu} \sim \frac{(T^{3})^2}{1-z} = \frac{(1/2)^2}{1-z}$$

$$dV_{\nu\leftarrow e} = dV_{e\leftarrow\nu} = 0$$

$$dV_{e\leftarrow e} = dV_{\nu\leftarrow\nu} \sim -\int dz\, \frac{C_2(\mathbf{2})}{1-z} = -\int dz\, \frac{3/4}{1-z}$$

→ non-cancelled sub-leading $\log(Q^2/M_w{}^2)$

Consider $e^+e^- \rightarrow X$



$$\Delta\sigma_{e\bar{e}\to X} \simeq \left[\frac{\alpha_2}{\pi}\log\left(\frac{Q}{m_W}\right)\mathcal{A}(e,e)\left(\frac{1}{\sqrt{2}}\right)^2\right] \times \sigma_{\nu\bar{e}\to X}$$

$$\Delta\sigma_{e\bar{e}\to X} \simeq \left[\frac{\alpha_2}{\pi}\log\left(\frac{Q}{m_W}\right)\mathcal{A}(e,\bar{e})\left(\frac{1}{\sqrt{2}}\right)^2\right] \times \sigma_{\nu\bar{\nu}\to X,\,\bar{e}e\to\bar{X}}$$

Ciafaloni et al., hep=ph/0007096.

$$\begin{aligned}\sigma \;=\; & F_{e\bar{e},\bar{e}e}\,\hat{\sigma}_{e\bar{e}\to X,\bar{e}e\to\bar{X}} + F_{\nu\bar{\nu},\bar{\nu}\nu}\,\hat{\sigma}_{\nu\bar{\nu}\to X,\bar{\nu}\nu\to\bar{X}} + \\ & F_{e\bar{\nu},\bar{e}\nu}\,\hat{\sigma}_{e\bar{\nu}\to X,\bar{e}\nu\to\bar{X}} + F_{\nu\bar{e},\bar{\nu}e}\,\hat{\sigma}_{\nu\bar{e}\to X,\bar{\nu}e\to\bar{X}} + \\ & F_{e\bar{e},\bar{\nu}\nu}\,\hat{\sigma}_{e\bar{e}\to X,\bar{\nu}\nu\to\bar{X}} + F_{\nu\bar{\nu},\bar{e}e}\,\hat{\sigma}_{\nu\bar{\nu}\to X,\bar{e}e\to\bar{X}} + \cdots\end{aligned}$$

→ State ensembles:
Parton-Luminosity Ensembles (PLE).

Our Approach

- Decompose an incoming state into gauge multi-plets: $SU(2)\ f_L \rightarrow \mathbf{1} + \mathbf{3}$.

$$\mathbf{1}:\ (e\nu - \nu e)/\sqrt{2}$$

$$\mathbf{3}:\ ee,\ \nu\nu,\ (e\nu + \nu e)/\sqrt{2}$$

- Gauge eigenstates properly evolve with Q^2; and the off-diagonal terms never develop: $\mathbf{1}_{in}$ or $\mathbf{3}_{in}$ would not fix.

- At which level would it break down?

More to come …

Conclusions

- With the discovery of the Higgs boson, we have a consistent QM, relativistic, unitary theory up to (possibly exponentially) high scales, but where is it? We wish $\Lambda \sim 4\,\pi\, v$ (?)

- EW sector @ high scale holds the hope for the probe!

- First, bread & butter rich physics:
  - Perturbative cutoff via SSB
  - Longitudinals/scalars
  - Chirality
  - Yukawa showers
  - Neutral boson interference
  - Weak isospin self-averaging

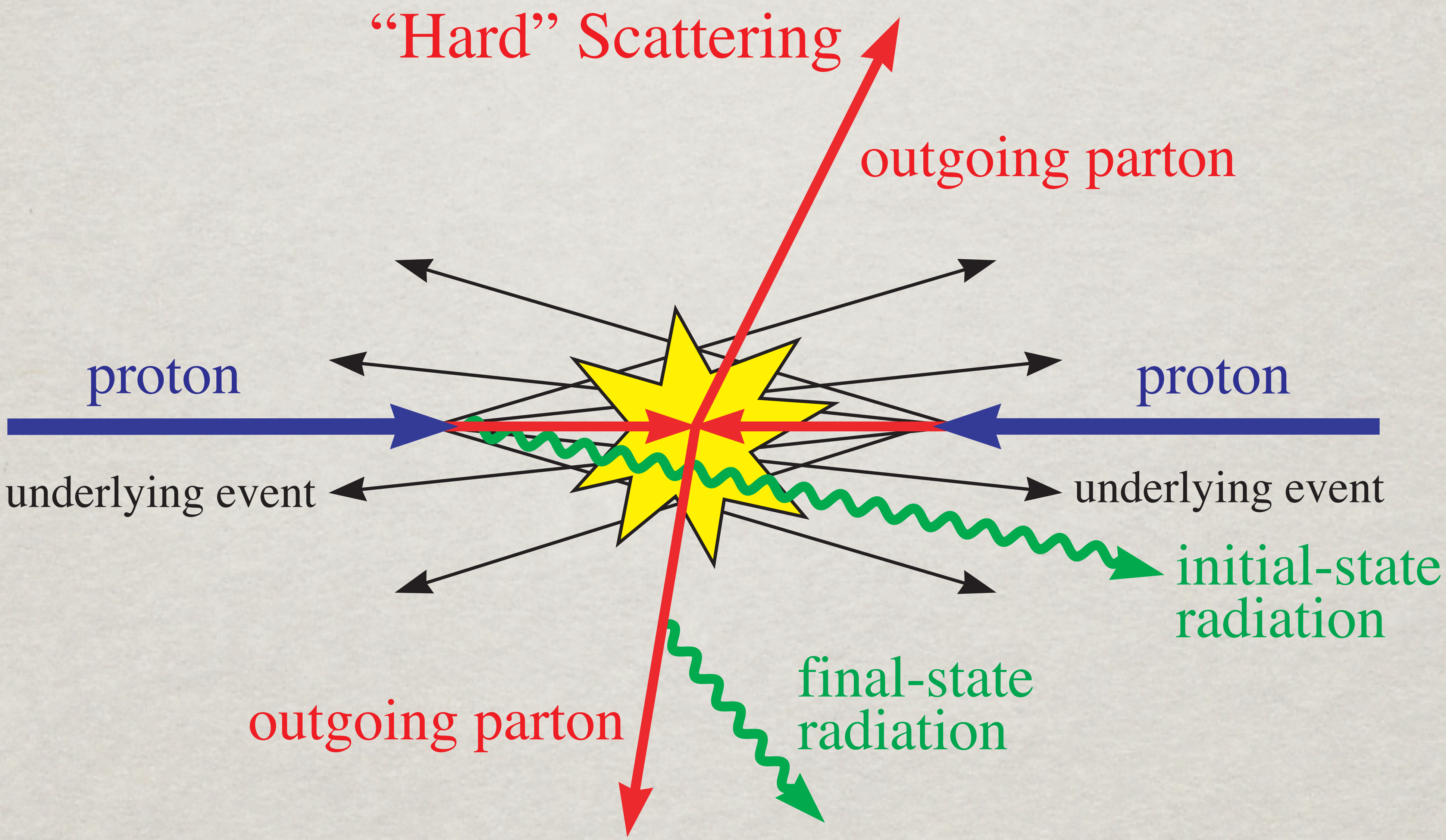
Conclusions

- EW splitting/showering will become an increasingly important part at higher energies.

- It still has technical & conceptual challenges at higher energies.

- Be prepared:
  Very high-energy W, Z, h, t may serve as tools for the next discovery !

Reality in Hadronic Collisions



Collinear splitting, ISR & FSR,
is one of the dominant phenomena.

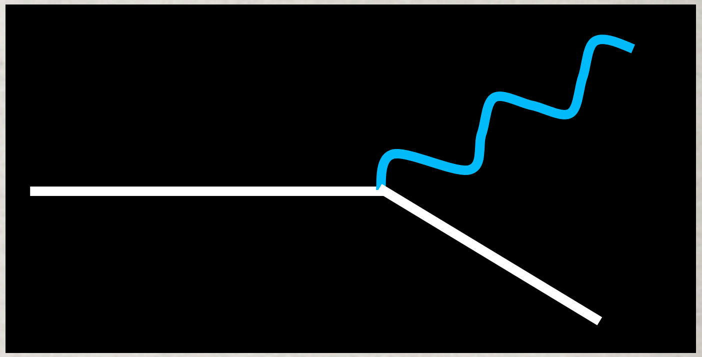
EW Splitting Functions

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.

Gauge-boson Initiated Processes

At colliding energies E >> M_W,
EW gauge bosons are new "gluons"!



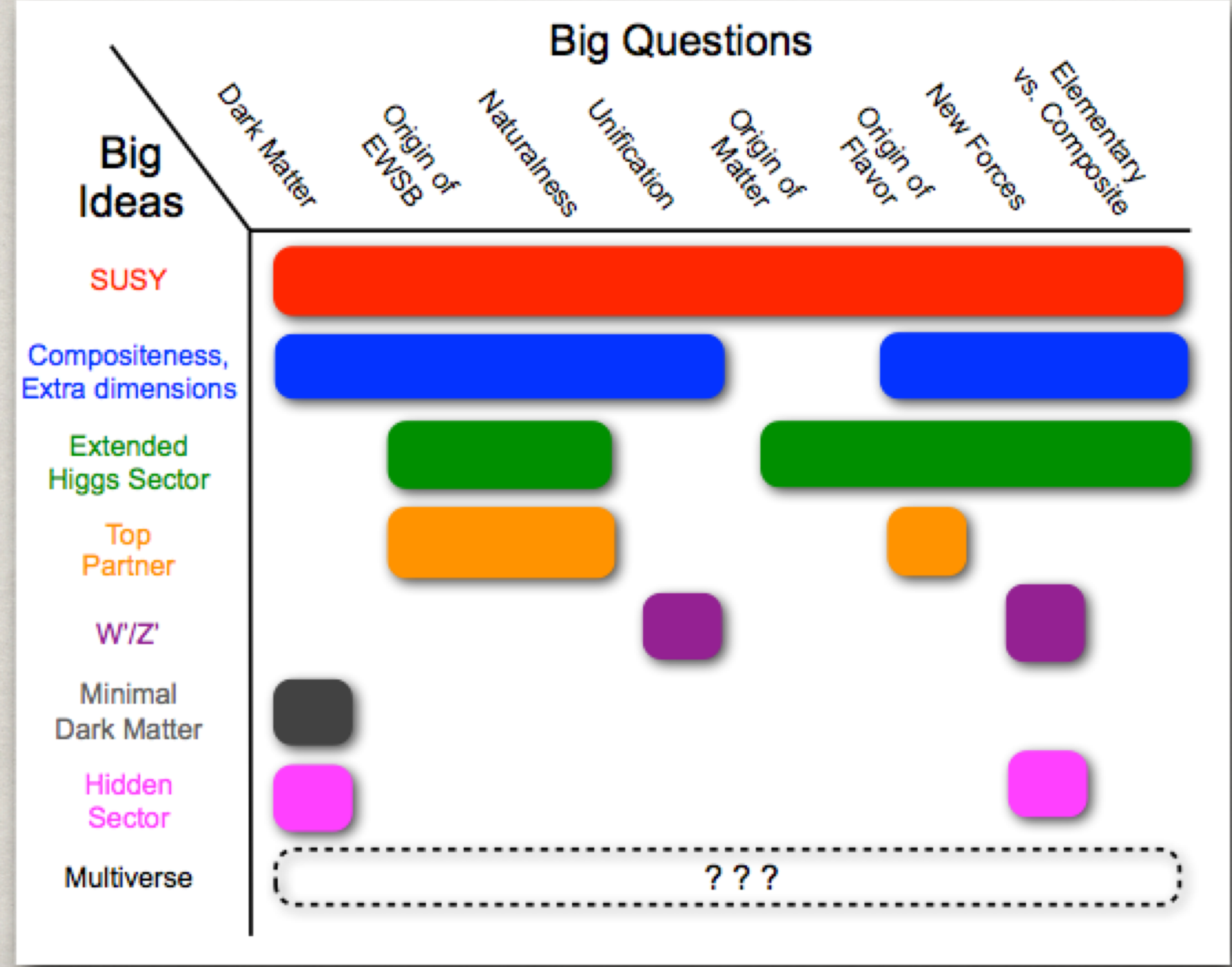
In the EW theory:

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

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

- V_T radiation the same as *g*, γ : $|\mathcal{M}|^2 \sim p_T^2$:
  - "dead cone" at $k_T \to 0$: $\sim k_T\, dk_T/m_W^2$
  - log-enhancement at high p_T & soft x
- V_L radiation no collinear enhancement/suppression, no log-running at leading order.

Snowmass NP report, 1311.0299



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', …*

Heavy W', Z' decays.

Heavy DM annihilation in indirect searches

… …

Ciafaloni, Riotto, Strumia, et al., 1009.0224;
Hook, Katz, 1407.2607;
M. Bauer, T. Cohen, et al., 1409.7492;
Baumgart, Rothstein, Vaidya (2014 - 2015)
… …

→ Energetic $W^\pm$, *Z, H, t* from new radiation sources and decays.