

# HIGH ENERGY LEPTON COLLISIONS & EW PDFs

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TF07: EW Effects at High Energies,  
Sept. 15, 2020

- EW physics @ high energies
- EW PDF approach
- Semi-inclusive processes @ a  $\mu^+\mu^-$  collider
- Further topics/issues

J.M. Chen, TH & B. Tweedie, arXiv:1611.00788;  
TH, Y. Ma & K. Xie, arXiv:2007.14300

# EW PHYSICS AT HIGH ENERGIES

$$\frac{v}{E} \dot{\sim} \frac{v}{100 \text{ TeV}} \sim \frac{\Lambda_{QCD}}{100 \text{ GeV}}$$

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

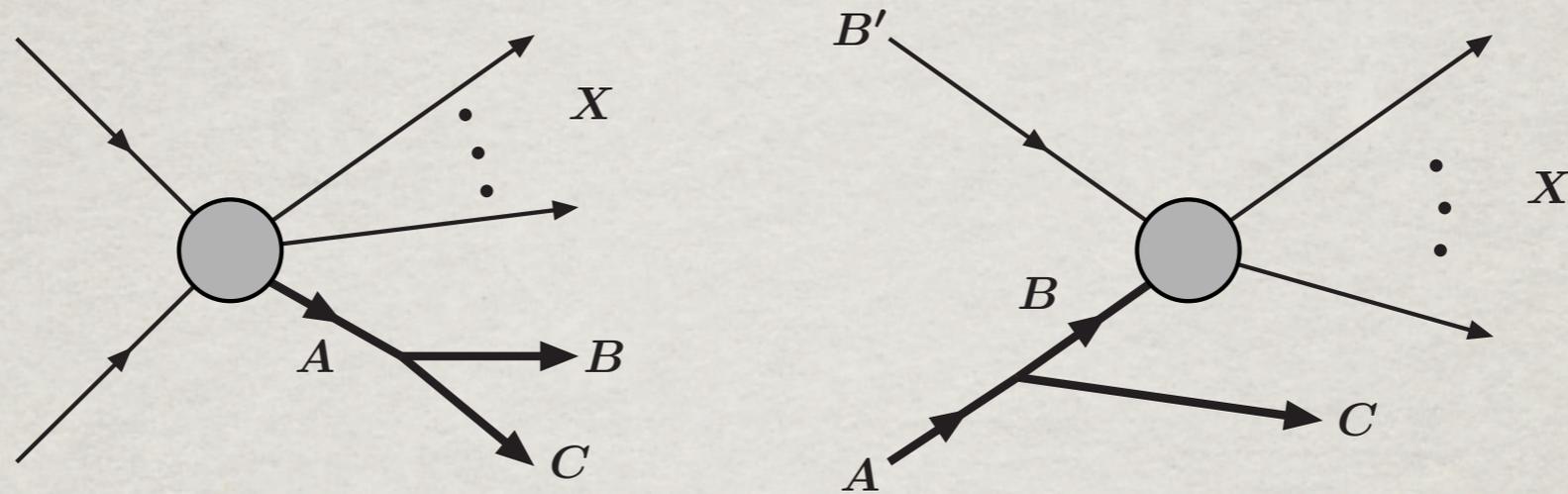
- A massless theory:
  - splitting phenomena dominate
- EW symmetry restored:
  - $SU(2)_L \times U(1)_Y$  unbroken
- Goldstone boson Equivalence

& its violation:  $\epsilon(k)_L^\mu = \frac{E}{m_W} (\beta_W, \hat{k}) \approx \frac{k^\mu}{m_W} + O(M_W/E)$

$v/E$  power counting  $\rightarrow$  Higher twist effects.

G. Cuomo, A. Wulzer, arXiv:1703.08562; 1911.12366

# EW SPLITTING & PDF



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

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

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

- On the dimensional ground:  $|\mathcal{M}_{split}|^2 \sim k_T^2$  or  $m^2$
- For the factorized formalism to be valid:  
infra-red safe & leading behavior

Ciafaloni et al., hep-ph/0004071; 0007096

C. Bauer, Ferland, B. Webber et al., arXiv:1703.08562; 1808.08831.

A. Manohar et al., 1803.06347.

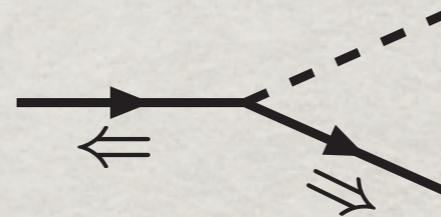
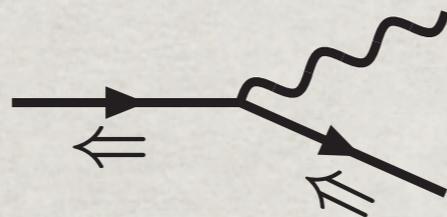
# SPLITTING FUNCTIONS: EW

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

e.g.: fermion splitting:



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

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

$$\rightarrow V_T f_s^{(\prime)} \quad [BW]_T^0 f_s$$

$$H^{0(*)} f_{-s} \text{ or } \phi^\pm f'_{-s}$$

Ciafaloni et al.,  
Hep-ph/0505047.

$f_{s=L,R}$

$$g_V^2 (Q_{f_s}^V)^2$$

$$g_1 g_2 Y_{f_s} T_{f_s}^3$$

$$y_{f_R}^2$$

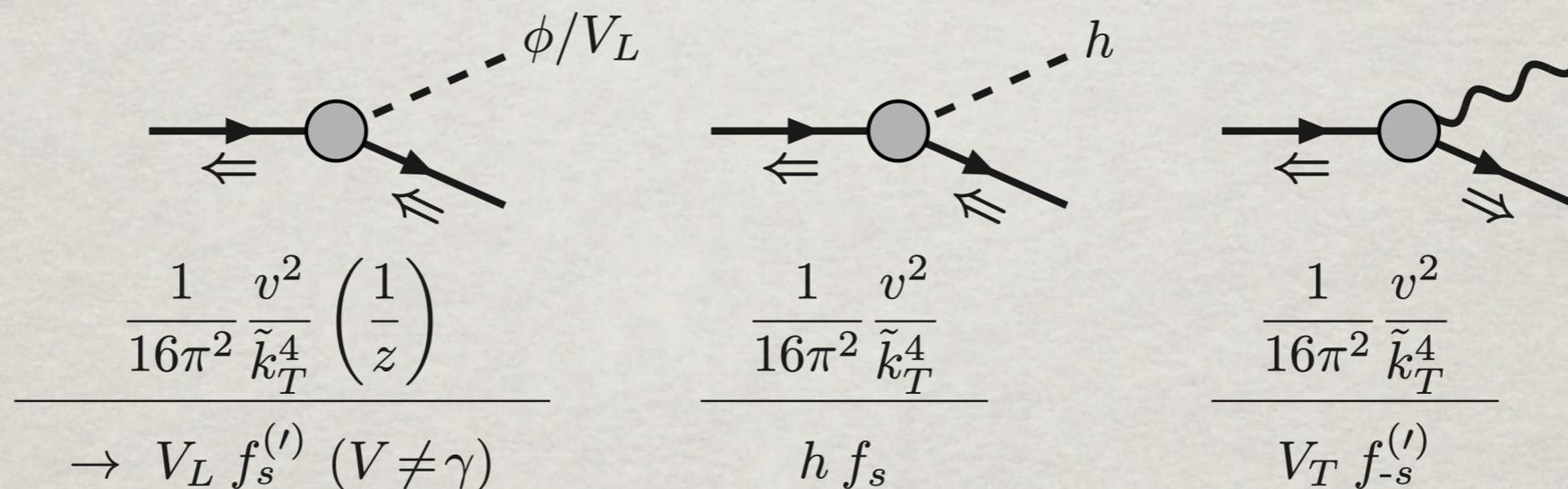
Infrared & collinear singularities ( $P_{gq}$ )

Collinear singularity,  
Chirality-flip, Yukawa

# SPLITTING IN THE BROKEN GAUGE CORRECTIONS TO GET

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

$V_L$  is of IR, h no IR



Chirality conserving:  
Non-zero for massless f

Chirality flipping:  
 $\sim m_f$

The DPFs for  $W_L$  thus don't run at leading log:  
"Bjorken scaling" restored (higher-twist effects)!

# ISR, PDF (DGLAP):

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

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

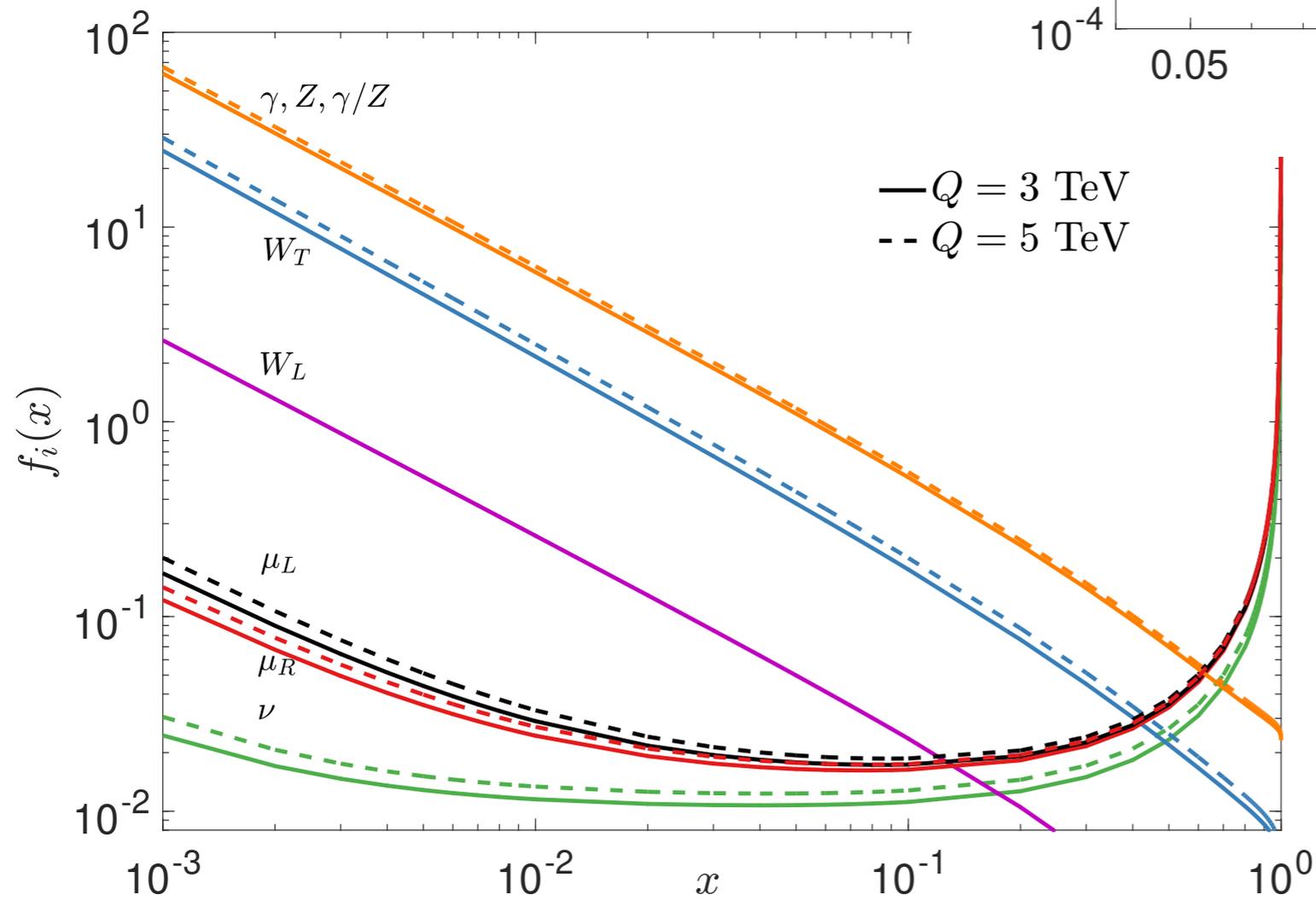
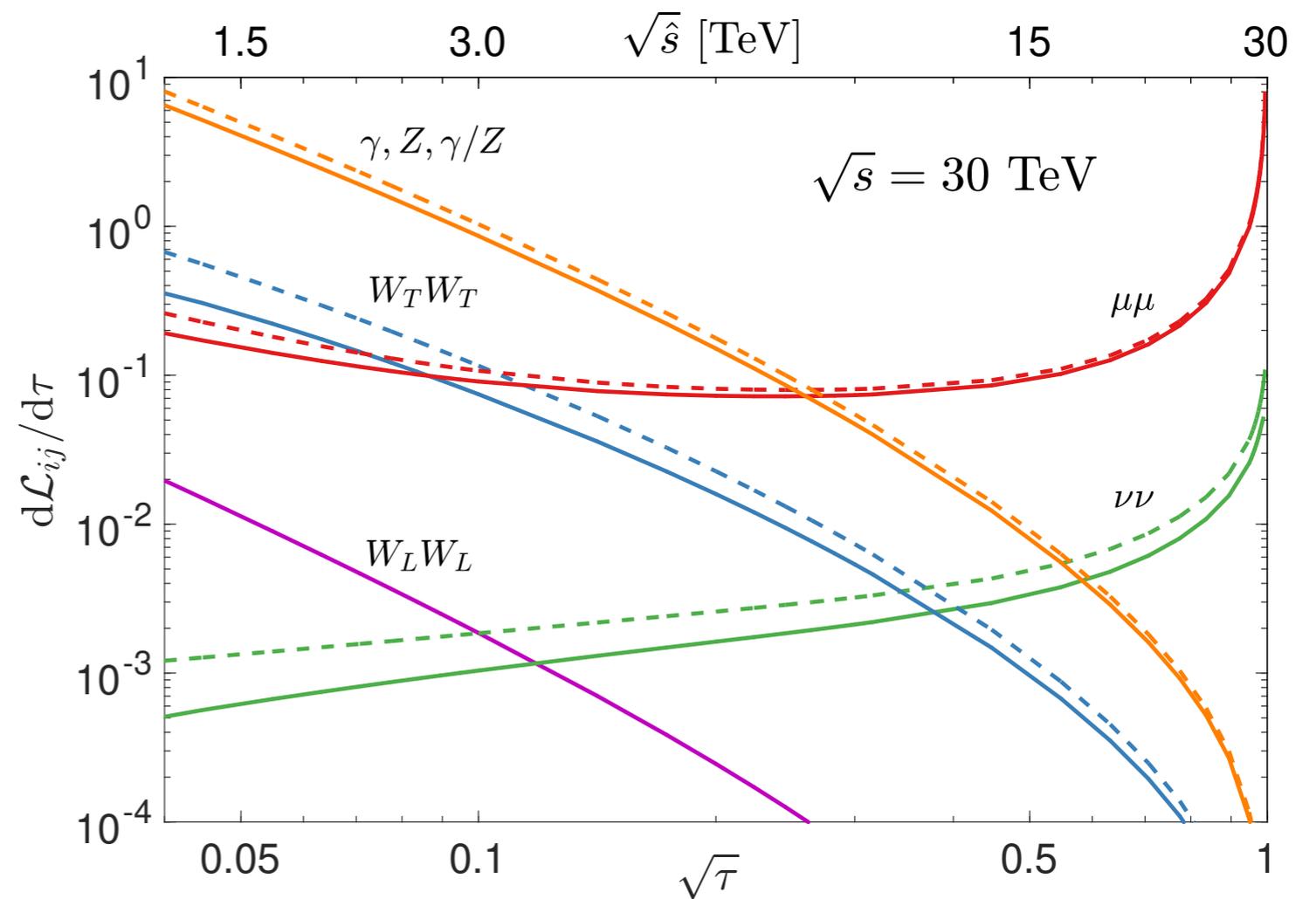
# FSR, parton showers:

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

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

**Very important formulation for LHC physics,  
will remain so for future colliders.**

EW PDFs  
at a muon collider:  
 $W_L$  doesn't involve

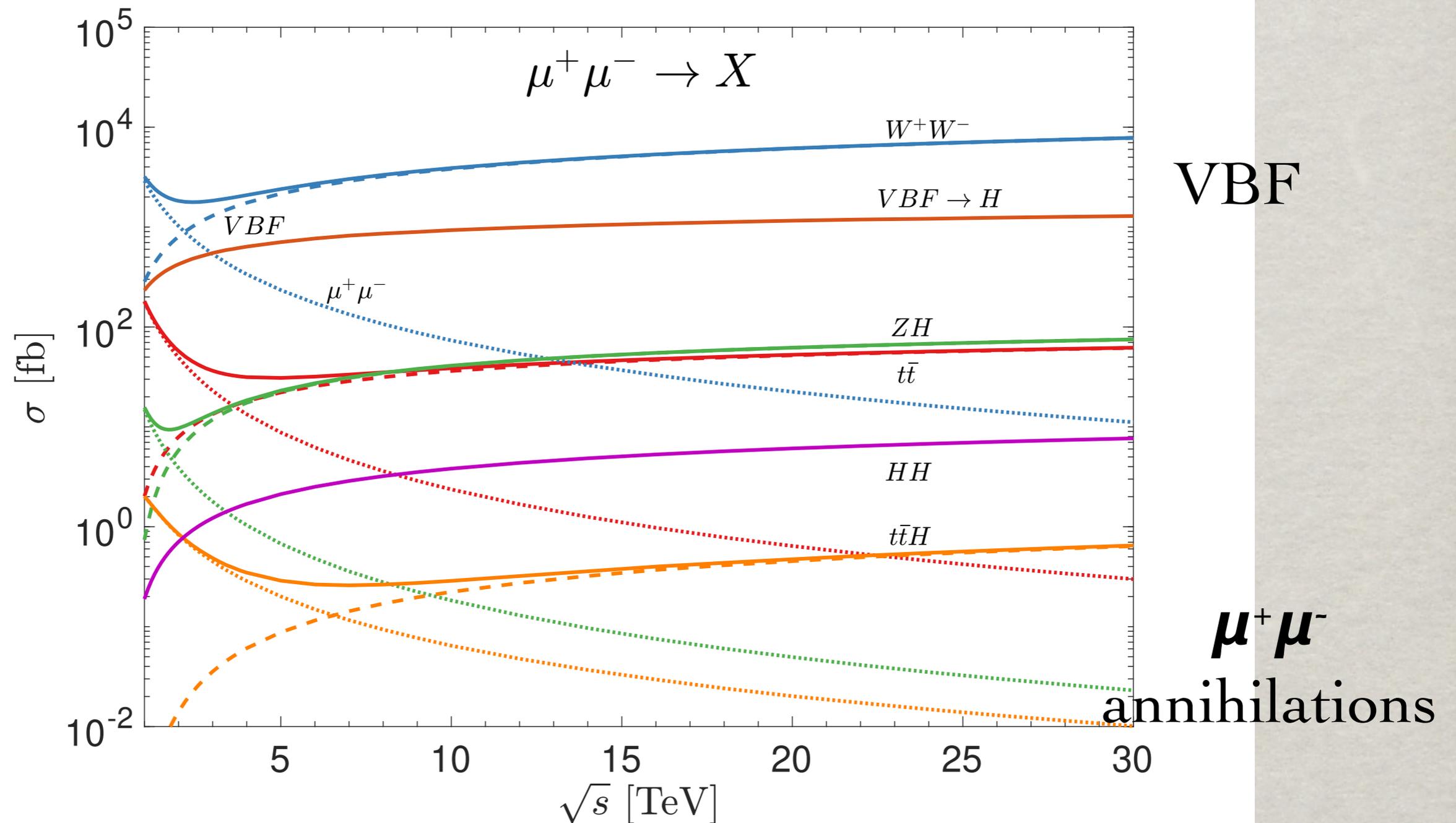


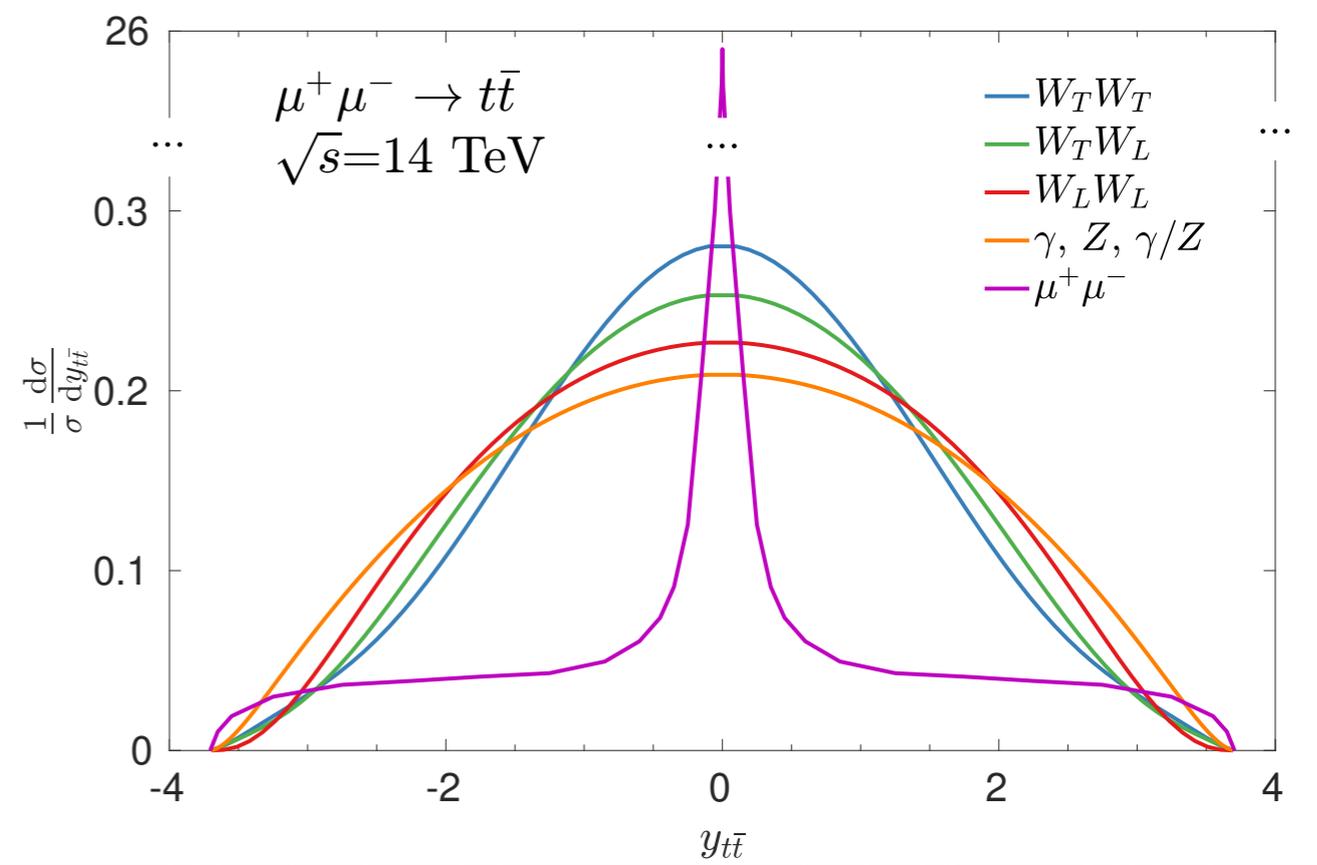
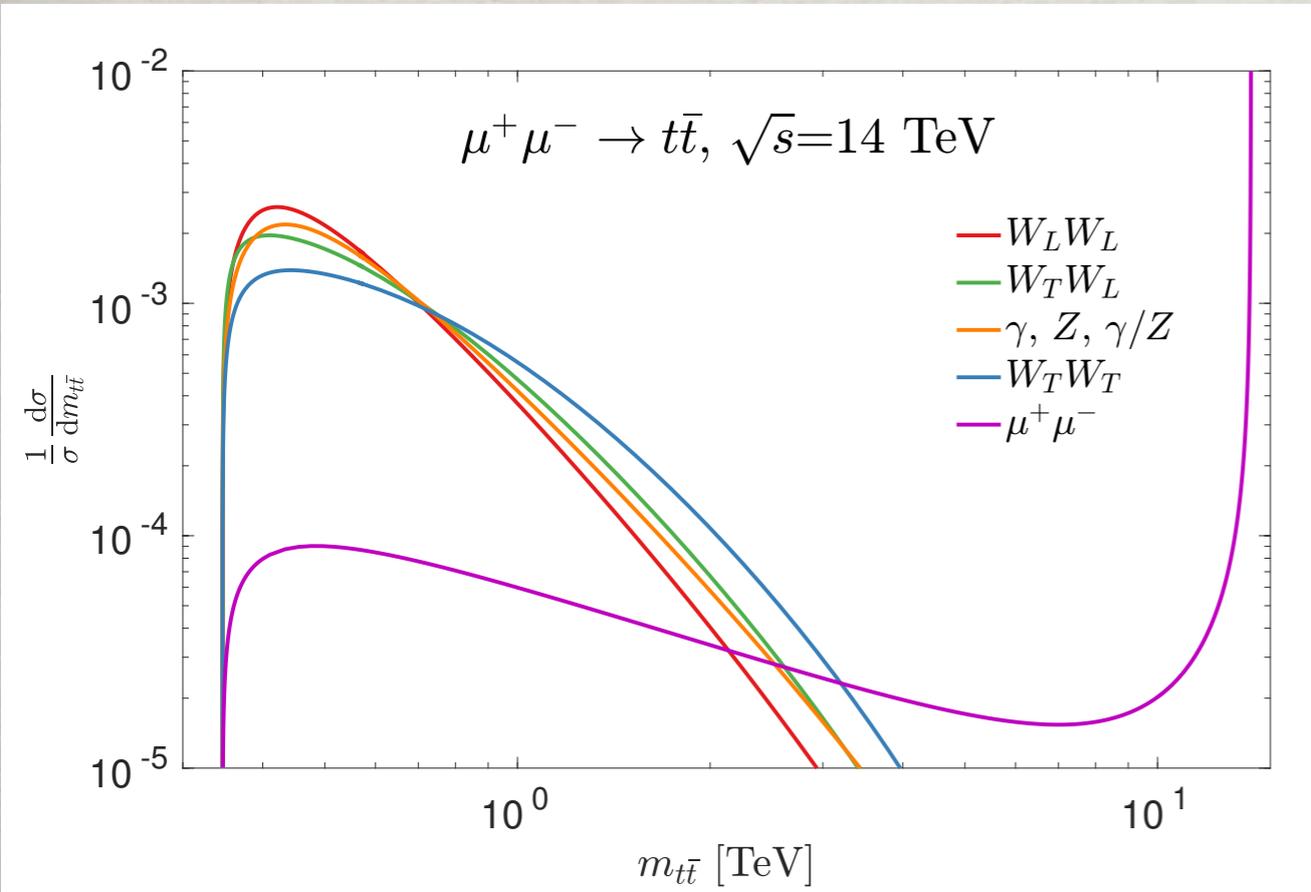
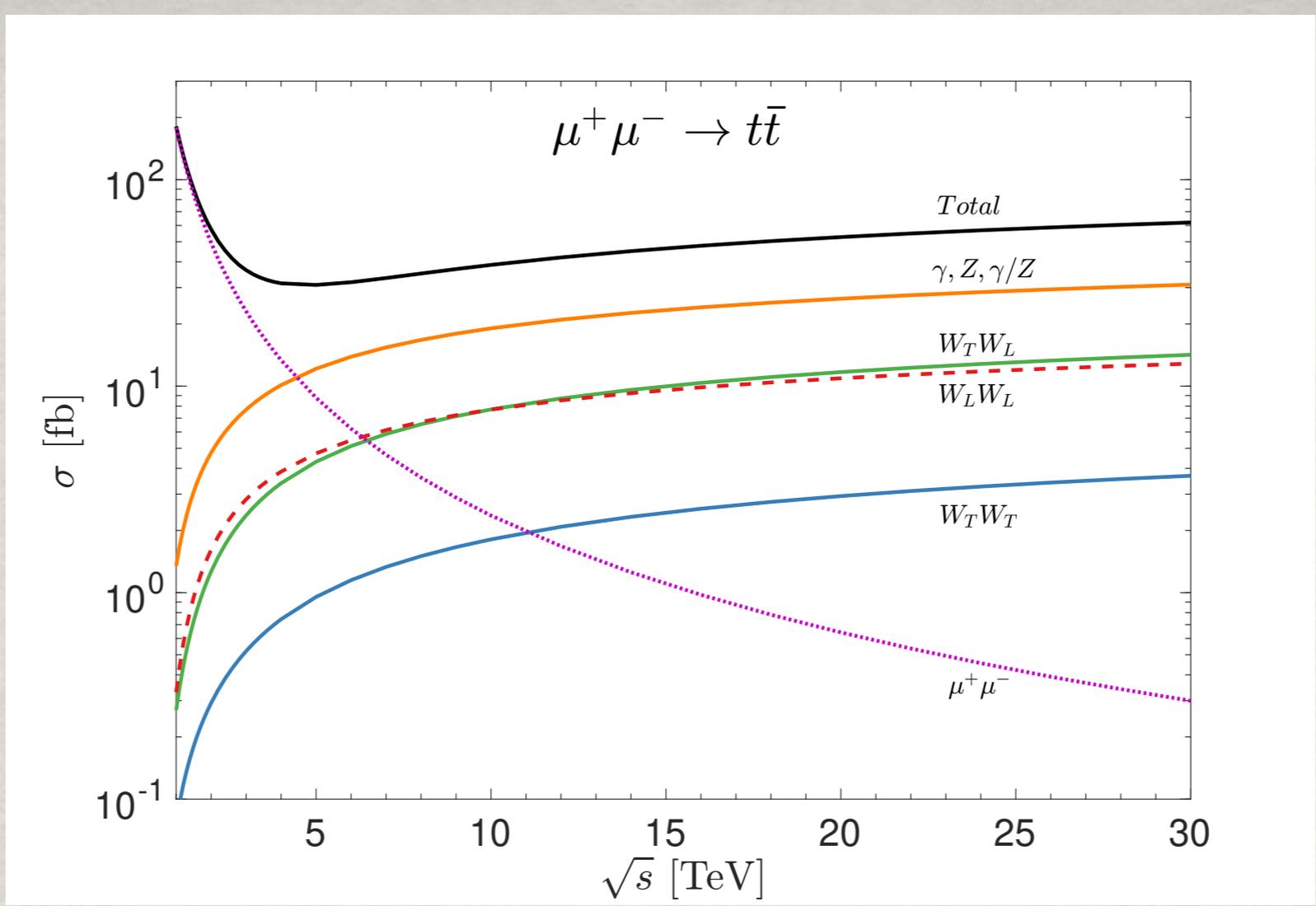
Partonic luminosities  
There are neutrinos,  
and everything!

# SEMI-INCLUSIVE PROCESSES

Just like in hadronic collisions:

$\mu^+\mu^- \rightarrow$  exclusive particles + remnants





# FURTHER TOPICS/ISSUES

- 😊 EW PDF approach allows for decomposition of polarized partonic sub-processes; including mixed states  $\gamma$ - $Z_T$  &  $h$ - $Z_L$
- 🤔 Low  $Q^2$ /near-threshold invalid
- 🤔 Fragmentation/FSR next target:  
An optimal gauge?
- 😓 Bloch-Nordsieck theorem violation: Factorization breaks down for insufficiently inclusive processes.  
Solutions: cutoff or “inclusive” ?