New physics at muon collider

Li, Tong (李佟)

Nankai University

in collaboration with Tao Han (Pitt),
Han Qin (Pitt) and Xing Wang (UCSD)

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Outline

- Why a muon collider?
- Production features and new physics at muon collider
- Summary

Why a muon collider?

- The past and ongoing particle colliders (LEP, Sp$\bar{p}$S, PETRA, SPEAR, SLC, Tevatron, and LHC) made important measurements for the SM and BSM. They have so far seen no conclusive evidence of BSM phenomena.
- The quest for discovery in particle physics has always required higher energy experiments.

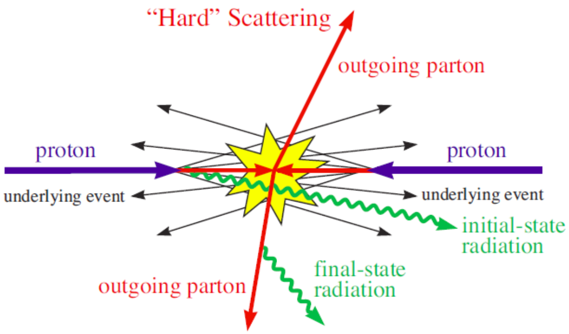
What kind of environment is ideal?

- The key factor to the collider energy: energy loss

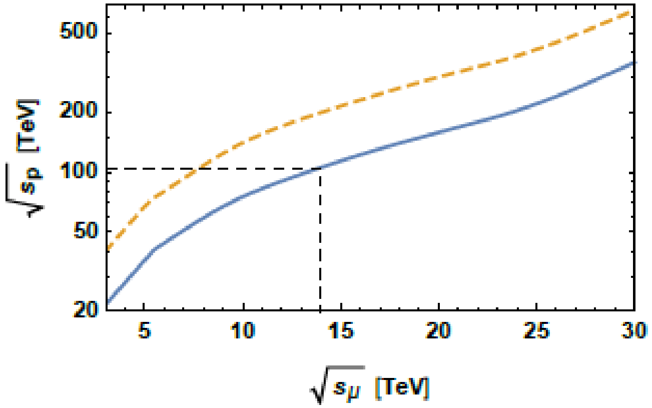
$$\Delta E \propto \left(\frac{E}{m}\right)^4$$

- An accelerator is more efficient for a more massive beam particle.
- Large muon mass ($^{m_\mu}/_{m_e} \approx 207$) suppresses the synchrotron radiation by a factor of 10^9, compared with electron beams.
- Circular muon colliders with smaller ring size have the potential to reach tens of TeV c.m. energies.

- In hadronic collisions, only a fraction of the total c.m. energy is carried by the partons.



- The muon collider c.m. energy can be fully converted into the physics threshold.
- A 14 TeV muon collider has potential similar to that of a 100 TeV pp collider.
- Lower background



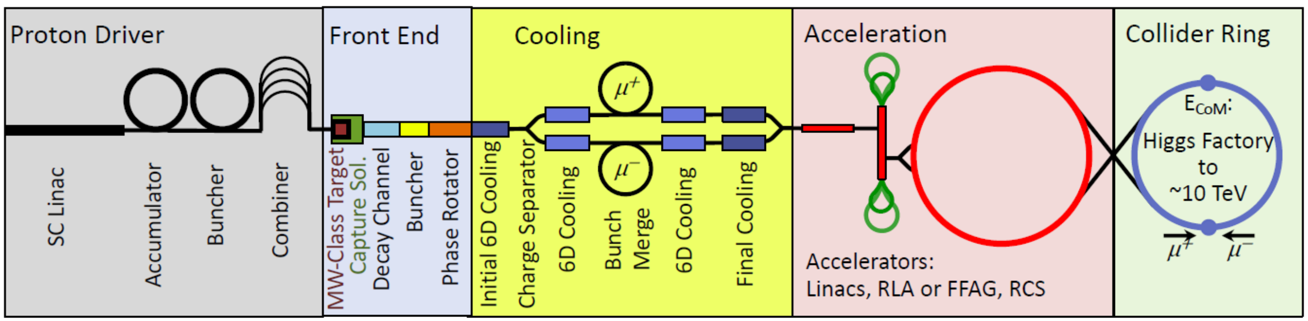
1901.06150

- The idea of muon collider introduced in 1980's.

  Skrinsky, Parkhomchuk, Sov.J.Part.Nucl.12(1981)223
  Neuffer, Part.Accel.14 (1983) 75-90, AIP Conf.Proc.156(1987)201-208
  Barger, Berger, Gunion, Han, PRL75(1995)1462-1465, Phys.Rept.286(1997)1-51

- Proton/positron driver scheme, e.g. proton

1901.06150



Muon Accelerator Program (MAP)

- Short lifetime (2 μs) and cooling

MICE collaboration, Nature 578(2020)53

- Luminosity scaling scheme: $\sigma L \sim$const. and luminosity goals

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

1 ab^-1/yr

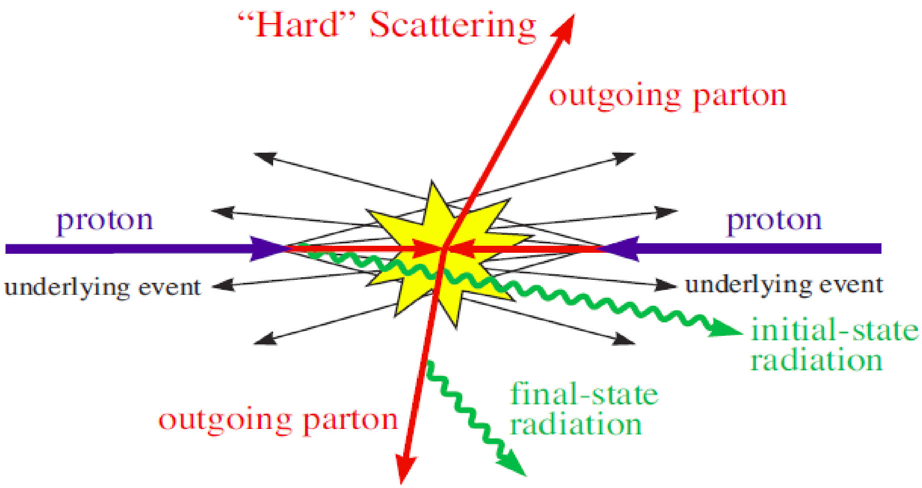
1901.06150

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Production at high-energy lepton colliders

- Recall the hadron colliders: pp($p\bar{p}$) collision at Tevatron or LHC



Factorization formalism: PDFs $\otimes$ partonic cross sections

$$\sigma(AB \to X) = \sum_{a,b} \int dx_a dx_b f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \hat{\sigma}(ab \to X)$$

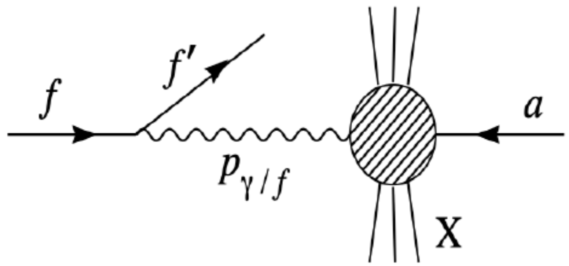
- a, b are the "partons" from the beam particles A, B
- $f_{a/A}(f_{b/B})$ are PDFs, defined as the probabilities of finding partons a (b) from the beam particles A (B) with the momentum fractions $x_a(x_b)$

- The simplest parton of a lepton: photon
- "Equivalent photon approximation (EPA)": collinear photon radiation off the high-energy leptons

C.F.von Weizsacker, Z.Phys.88,612(1934), E.J.Williams, Phys.Rev.45,729(1934)

$$\sigma(\ell^- + a \to \ell^- + X) = \int \mathrm{d}x\, f_{\gamma/\ell}\, \hat{\sigma}(\gamma a \to X)$$

$$f_{\gamma/\ell,\mathrm{EPA}}(x_\gamma, Q^2) = \frac{\alpha}{2\pi} \frac{1+(1-x_\gamma)^2}{x_\gamma} \ln \frac{Q^2}{m_\ell^2}$$



- Production cross section at lepton colliders

$$\sigma(\ell^+\ell^- \to F + X) = \int_{\tau_0}^{1} d\tau \sum_{ij} \frac{d\mathscr{L}_{ij}}{d\tau}\, \hat{\sigma}(ij \to F),\ \tau = \hat{s}/s$$

Partonic luminosities

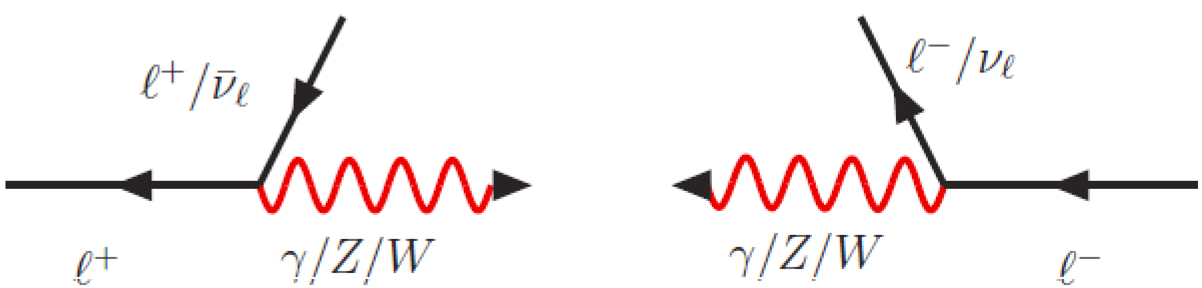
$$\frac{d\mathscr{L}_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{d\xi}{\xi} \left[f_i(\xi, Q^2) f_j\left(\frac{\tau}{\xi}, Q^2\right) + (i \leftrightarrow j) \right]$$

beyond the EPA

- Ultra-high energy Q>MZ: $\frac{v}{E} = \frac{v}{10\ TeV} \rightarrow 0$
- The SM gauge symmetry is restored and all EW states are dynamically activated.
- We should take into account the four EW gauge bosons (B, W^i), EW partons emerge

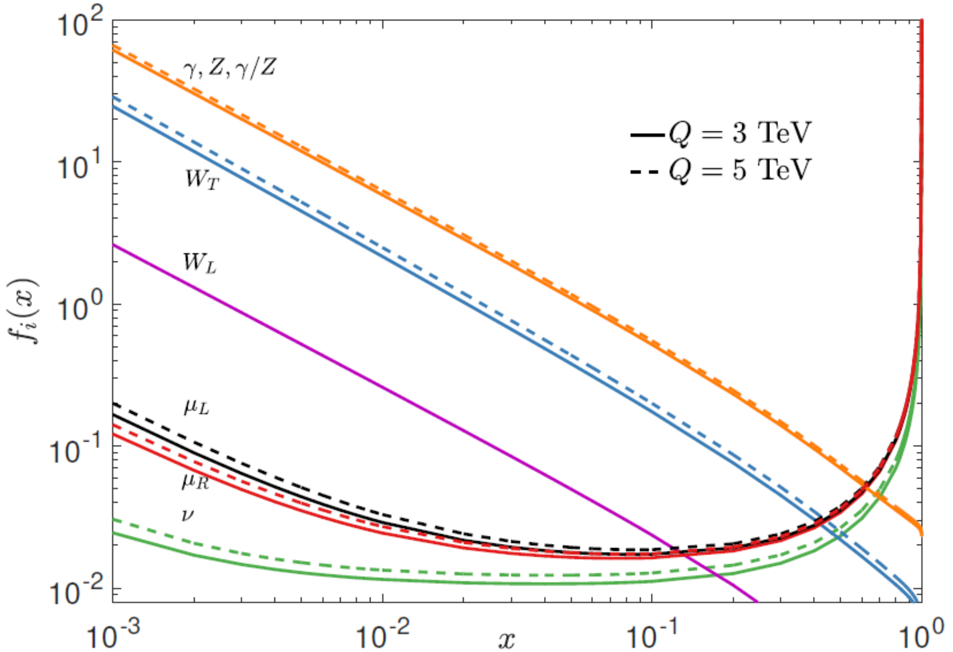
"Effective W Approximation (EWA)": EW PDF

G.Kane, W.Repko, W.Rolnick, PLB148(1984)367; S.Dawson NPB 249(1985)42



• EW PDFs for muon collider

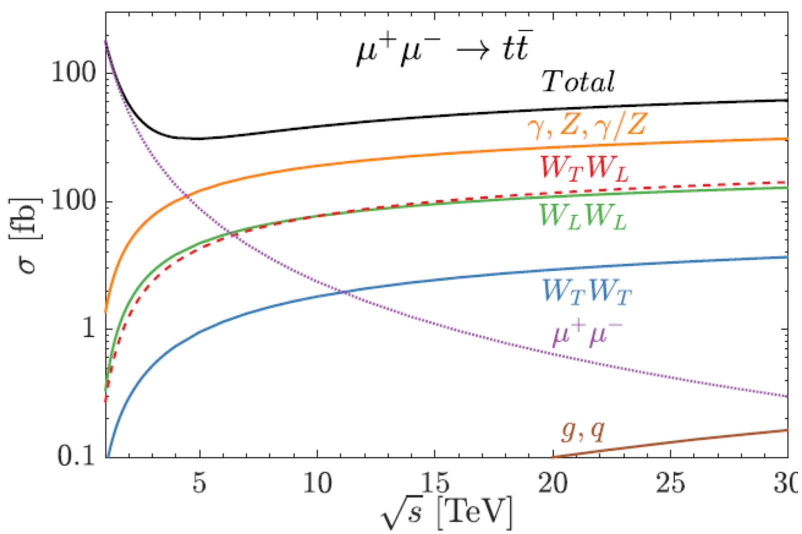
T. Han, Y. Ma, K. Xie, 2007.14300

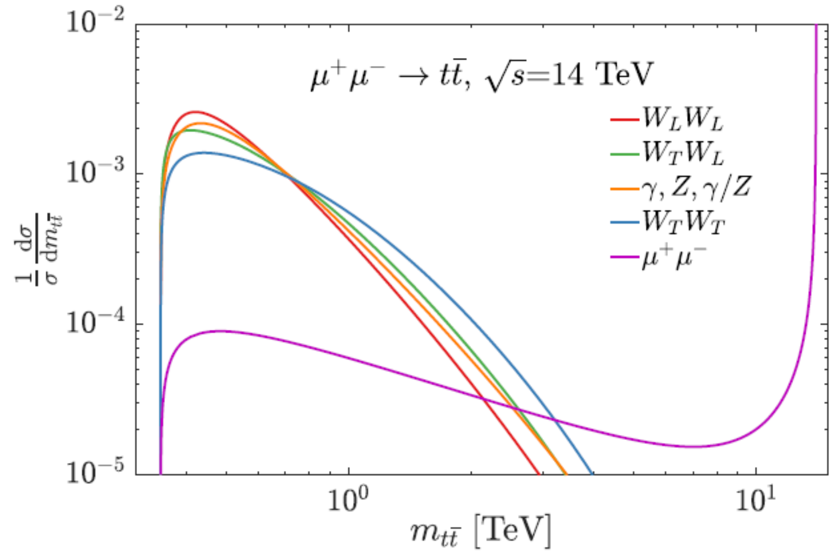


- The muon PDF peaks at collider energy $x \approx 1$.
- The gauge boson PDFs are dominant at low partonic energy.

Inclusive production cross section

T. Han, Y. Ma, K. Xie, 2007.14300





- sum over all partonic contributions and calculate the inclusive production cross section, e.g. $t\bar{t}$
- The direct annihilation falls as 1/s and VBF takes over it at high energies
- The invariant mass peaks at collider energy for annihilation and the VBF peaks above the threshold
- The contributions from polarized initial states are available to explore the underlying physics.

New physics examples at muon collider

- A high-energy muon collider allows to probe unprecedented energy scales and explore many different directions
- Great interest in the theory community:

High-energy searches:
resonances,
di-boson, di-fermion,
Dark Matter, etc

High-rate measurement:
single Higgs, self coupling,
rare Higgs decays, EFT, etc

Muon physics:
lepton flavor universality,
muon g-2, b->$s\mu\mu$, etc

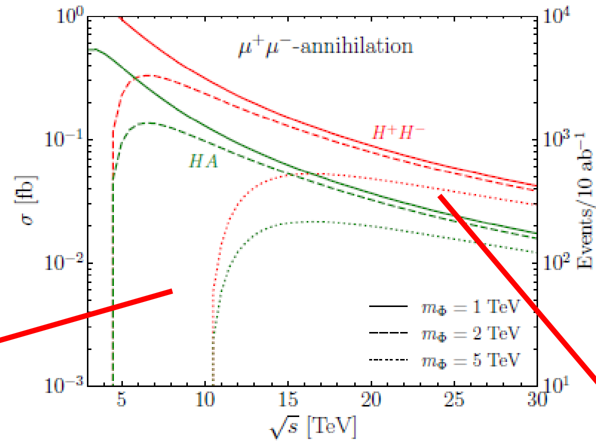
Dario Buttazzo's slides

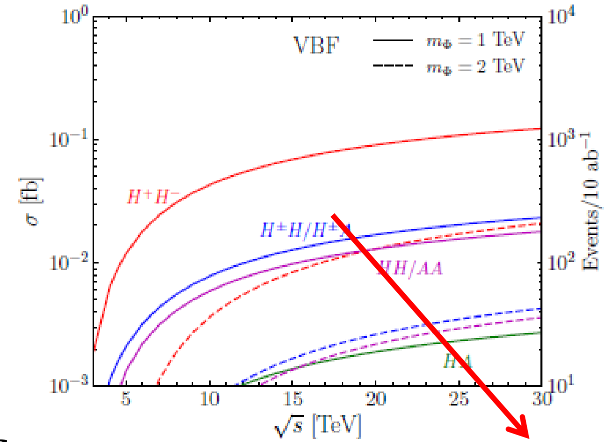
See e.g. TL, M.A. Schmidt, C.-Y. Yao, M. Yuan, arXiv: 2104.04494

Example 1: heavy particle search

- heavy higgs bosons

arXiv: 2102.08386



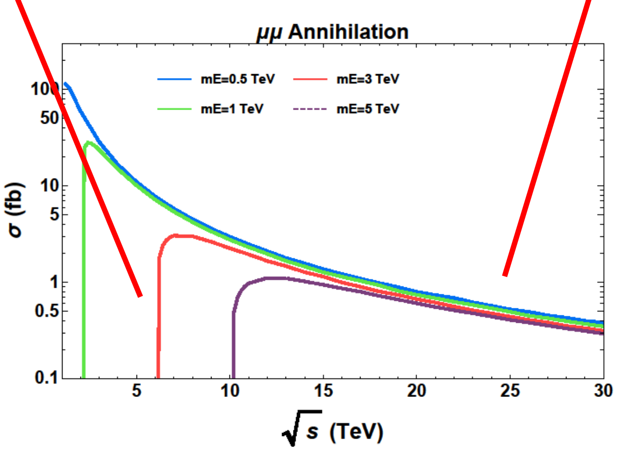


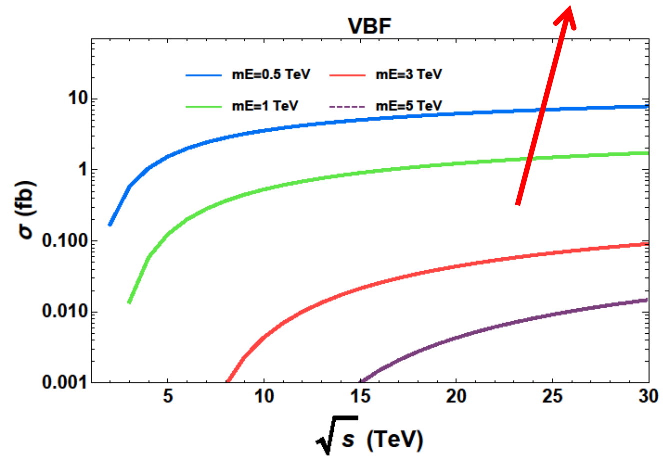
threshold behavior:
β^3 or β with
$\beta=\sqrt{1-M^2/s}$

$\sigma \sim 1/s$

EW PDF threshold
suppression: 1/M^2

- heavy charged leptons

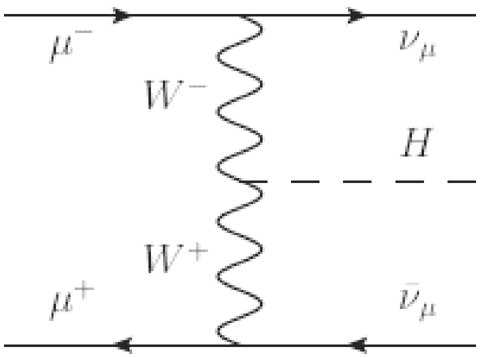




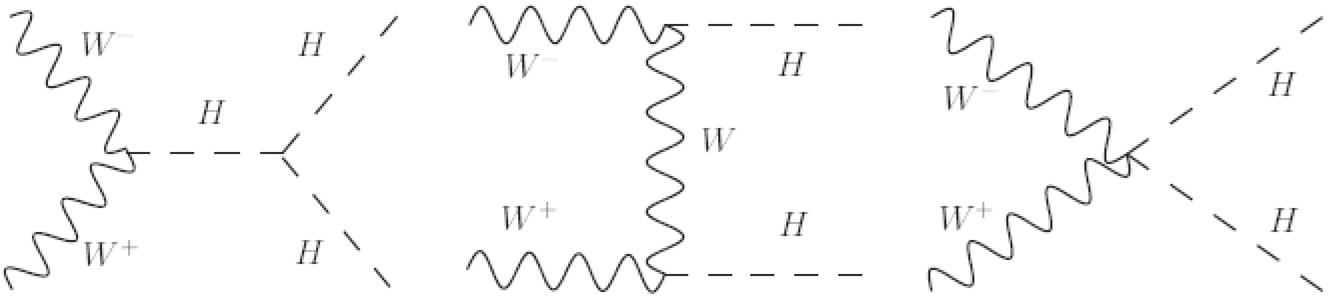
Example 2: precision Higgs measurement

arXiv: 2008.12204

- WWH/ZZH couplings: single production



- HHH/WWHH couplings: pair production



$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

- Compared with the precision of other proposed colliders, muon collider can improve the measurements substantially

See also Junmou Chen's talk

Summary

- High-energy muon colliders are potentially ideal machines in both energy and precision frontiers.
- Muon collider can become good candidate of future colliders and comprehensively cover SM and BSM physics of interest.

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- High-energy muon colliders are potentially ideal machines in both energy and precision frontiers.
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Thank you!

- EW DGLAP equations

$$\frac{\mathrm{d}f_i}{\mathrm{d}\log Q^2} = \sum_I \frac{\alpha_I}{2\pi} \sum_j P^I_{ij} \otimes f_j$$

- EW PDFs: $f_i(x, Q^2)$
- I: gauge group
- P: splitting function