The partonic picture at high-energy lepton colliders

Yang Ma

Pittsburgh Partcile-physics, Astrophysics, and Cosmology Center,
Department of Physics and Astronomy,
University of Pittsburgh, PA 15260, USA

August 24, 2021

In collaboration with **Tao Han** and **Keping Xie**

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

[T. Han, Y. Ma, K.Xie 2103.09844]

[D. Franzosi, *et al.*, 2106.01393]

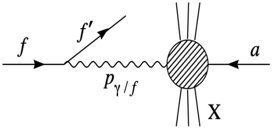
What is the PDF of a lepton?

"Equivalent photon approximation (EPA)" [C. F. von Weizsacker, Z. Phys. 88, 612 (1934)]

Treat photon as a parton constituent in the electron [E. J. Williams, Phys. Rev. 45, 729 (1934)]

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

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



Extra terms:

[Frixione, Mangano, Nason, Ridolfi 2103.09844]
[Budnev, Ginzburg, Meledin, Serbo, Phys. Rept.(1975)]

Applications at muon collider

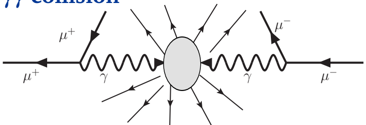
- Production cross sections

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

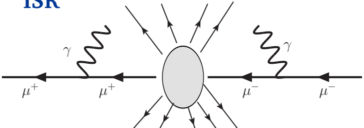
- Partonic luminosities

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

$\gamma\gamma$ collision



ISR



A possible high-energy lepton collider: Why?

Why lepton colliders?

- **Leptons** are the ideal probes of short-distance physics
  - Cleaner background comparing to hadron colliders
  - High-energy physics probed with much smaller collider energy
- **ee colliders**
  - A glorious past: discovery of charm, τ, and gluon
  - Important future: Precision EW constraints on BSM physicss, Higgs physics
- **Muon colliders**
  - A s-channel Higgs factory: Higgs production enhanced by $m_\mu^2/m_e^2 \sim 40000$
    - Direct measurements on y_μ and Γ_H
  - Multi-TeV muon colliders: Less radiations then electron
    - Center of mass energy $3-15$ TeV and the more speculative $E_{\rm cm} = 30$ TeV
    - New particle mass coverage $M \sim (0.5-1)E_{\rm cm}$
    - Great accuracies for WWH, $WWHH$, H^3, H^4
    - $\cdots$

Muon Collider Physics Potential Pillars

Direct search of heavy particles	High rate indirect probes	High energy probes
SUSY-inspired, WIMP, VBF production, 2->1	Higgs single and self-couplings, rare Higgs decays, exotic decays	difermion, diboson, EFT, Higgs compositeness

A high-energy muon collider at first glance

What are the dominant processes at a high-energy muon collider?

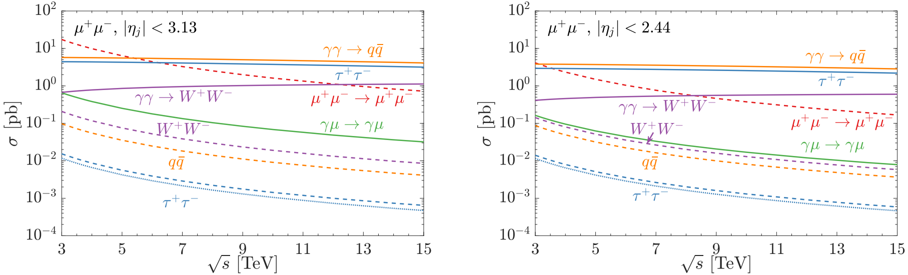
- Leading-order: $\mu^+\mu^- \to \mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, W^+W^-, and $\gamma\mu \to \gamma\mu$
- $\gamma\gamma$ scatterings: $\gamma\gamma \to \tau^+\tau^-$, $q\bar{q}$, W^+W^-

Need some cuts:

- Detector angle: $\theta > 5^\circ\,(10^\circ) \Longleftrightarrow |\eta| < 3.13(2.44)$
- Threshold: $m_{ij} > 20$ GeV
- Need a p_T cut to separate from the nonperturbative hadronic production

[Chen, Barklow, and Peskin, hep-ph/9305247; Drees and Godbole, PRL 67, 1189,T. Barklow, etal, LCD-2011-020]

$$p_T > \left(4 + \sqrt{s}/3\,\mathrm{TeV}\right)\,\mathrm{GeV}$$

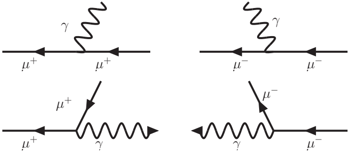


Go beyond the EPA at a high-energy muon collider

We have been doing:

- $\ell^+\ell^-$ annihilation

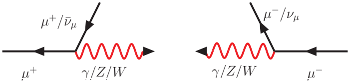
- EPA and ISR



- "Effective W Approx." (EWA)

[G. Kane, W. Repko, and W. Rolnick, PLB 148 (1984) 367]

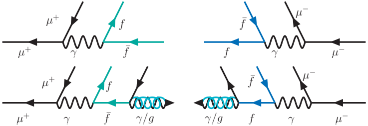
[S. Dawson, NPB 249 (1985) 42]



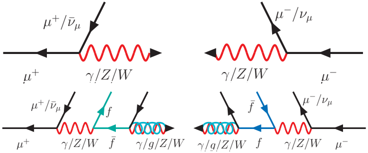
We will add:

[T. Han, Y. Ma, K.Xie 2007.14300, 2103.09844]

- Above $\mu_{\rm QCD}$: QED⊗QCD
  q/g emerge



- Above $\mu_{\rm EW} = M_Z$: EW⊗QCD
  EW partons emerge

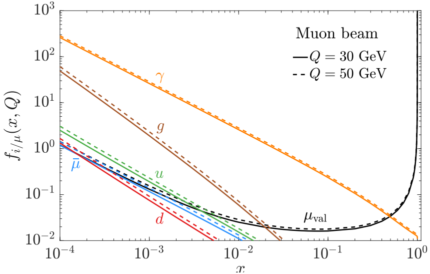


In the end, everything is parton, i.e. the full SM PDFs.

The PDFs for a muon collider

- **QED⊗QCD PDFs**:
  $f_{\mu_{\rm val}}, f_\gamma, f_{\ell_{\rm sea}}, f_q, f_g$
- Scale uncertainty: 20% for $f_{g/\mu}$
- The averaged momentum fractions $\langle x_i \rangle = \int x f_i(x) \mathrm{d}x$

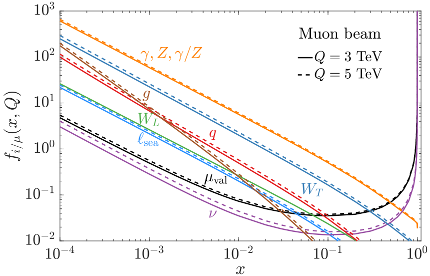
$Q(\mu^\pm)$	$\mu_{\rm val}$	γ	ℓsea	q	g
30 GeV	98.2	1.72	0.019	0.024	0.0043
50 GeV	98.0	1.87	0.023	0.029	0.0051
M_Z	97.9	2.06	0.028	0.035	0.0062



- **EW PDFs: All SM particles**

Q	μ	$\gamma, Z, \gamma Z$	$W^\pm$	ν	ℓsea	q	g
M_Z	97.9	2.06	0	0	0.028	0.035	0.0062
3 TeV	91.5	3.61	1.10	3.59	0.069	0.13	0.019
5 TeV	89.9	3.82	1.24	4.82	0.077	0.16	0.022

- Scale uncertainty: $\sim 20\%$ between $Q = 3$ TeV and $Q = 5$ TeV
- The EW correction is not small: $\sim 100\%$ for $f_{d/\mu}$ due to **relatively large SU(2) gauge coupling**.
- W_L does not evolve

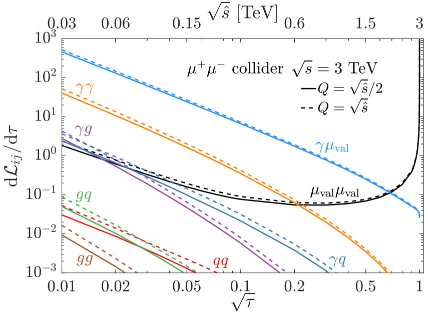


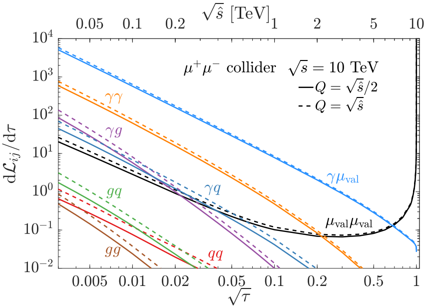
Parton luminosities at a possible muon collider

Consider a 3 TeV and a 10 TeV machine

- Partonic luminosities for

$$\mu^+\mu^-, \gamma\mu, \gamma\gamma, qq, \gamma q, \gamma g, gq, \text{ and } gg$$





- The partonic luminosity of $\gamma g + \gamma q$ is $\sim 20\%$ of the $\gamma\gamma$ one
- The partonic luminosities of qq, gq, and gg are $\sim 0.5\%$ of the $\gamma\gamma$ one
- Given the stronger QCD coupling, **sizable QCD cross sections are expected**.
- Scale uncertainty is $\sim 20\%(\sim 50\%)$ for photon (gluon) initiated processes.

Jet production of possible lepton colliders (I)

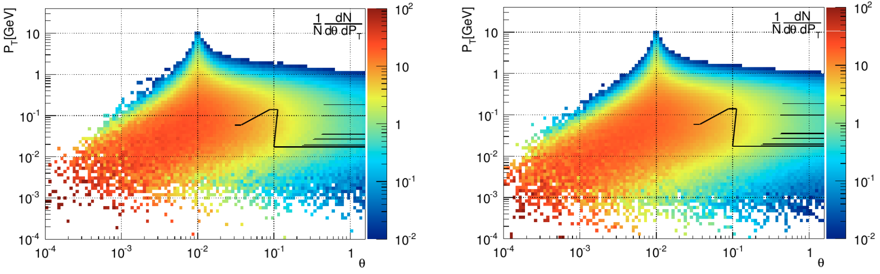
- Large photon induced non-perturbative hadronic production

  [Drees and Godbole, PRL 67 1189, hep-ph/9203219]

  [Chen, Barklow, and Peskin, hep-ph/9305247; Godbole, Grau, Mohan, Pancheri, SrivastavaNuovo Cim. C 034S1]

  - $\sigma_{\gamma\gamma}$ may reach micro-barns level at TeV c.m. energies
  - $\sigma_{\ell\ell}$ may reach nano-barns, after folding in the $\gamma\gamma$ luminosity

- The events populate at low p_T regime
  So we can separate from this non-perturbative range via a p_T cut.



(a) Pythia sample

(b) SLAC sample

[T. Barklow, D. Dannheim, M. O. Sahin, and D. Schulte, LCD-2011-020]

Jet production at a possible lepron collider (II)

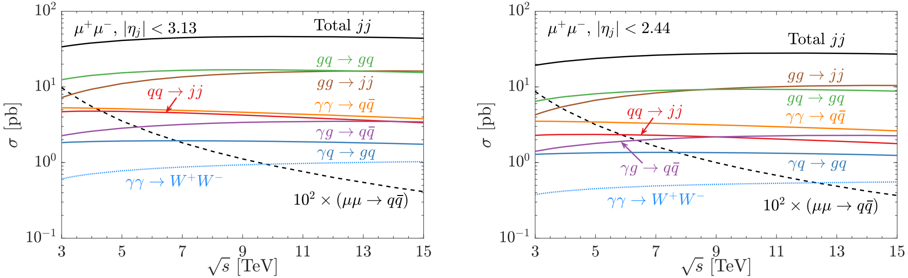
- Low-p_T range: photon induced non-perturbative hadronic production

  [Chen, Barklow, and Peskin, hep-ph/9305247; Drees and Godbole, PRL 67, 1189,T. Barklow, etal, LCD-2011-020]

- High-p_T range [$p_T > (4 + \sqrt{s}/3\,\mathrm{TeV})$ GeV]: perturbatively computable

$$\gamma\gamma \to q\bar{q},\ \gamma g \to q\bar{q},\ \gamma q \to gq,$$
$$qq \to qq\ (gg),\ gq \to gq \text{ and } gg \to gg\ (q\bar{q}).$$

- $Q = \sqrt{\hat{s}}/2$, due to large $\alpha_s \ln(Q^2)$, a $30 \sim 40\%$ enhancement if $Q = \sqrt{\hat{s}}$



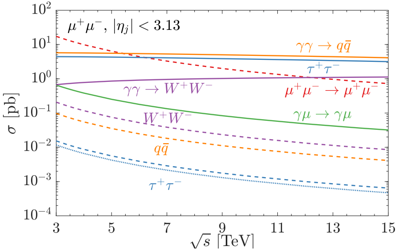
- Including the QCD contribution leads to much larger total cross section.
- gg initiated cross sections are large for its large multiplicity;
- gq initiated cross sections are large for its large luminosity.
- $\gamma\gamma$ initiated cross sections here are smaller than the EPA results.

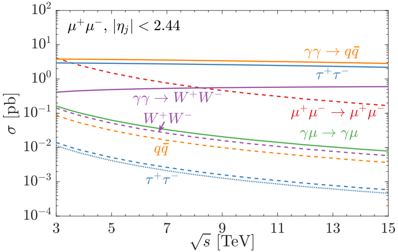
Refresh the picture of high-energy muon colliders

What is the dominant process at a high-energy muon collider?

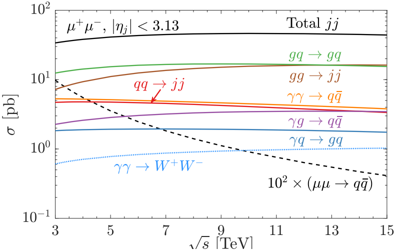
- **Quark/gluon initiated jet production dominates**

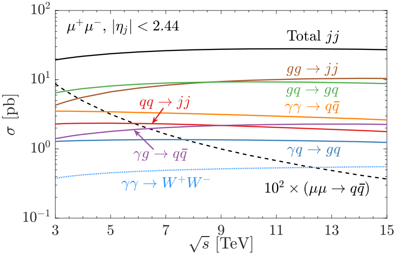
Before:





After:

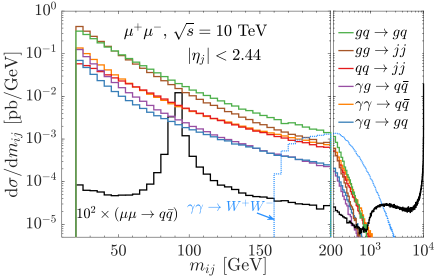


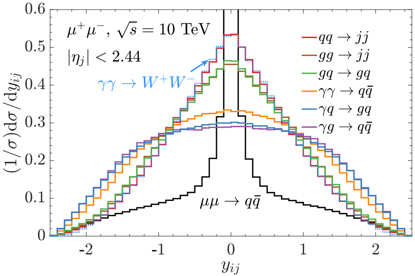


Di-jet distributions at a muon collider

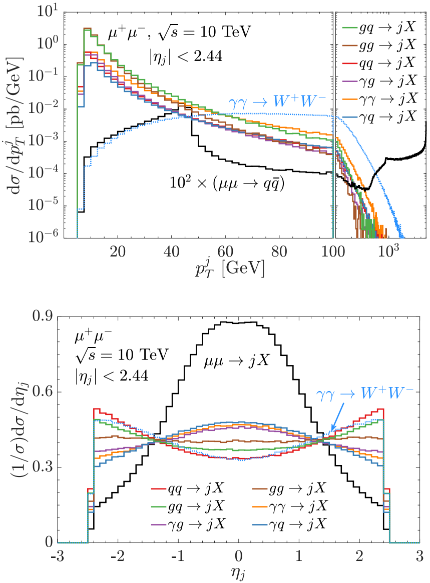
Rather a conservative set up: $\theta = 10^\circ$

- Some physics:
  Two different mechanisms: $\mu^+\mu^-$ **annihilation** VS **Fusion processes**
  - Annihilation is more than 2 orders of magnitude smaller than fusion process.
  - Annihilation peaks at $m_{ij} \sim \sqrt{s}$;
  - Fusion processes peak near m_{ij} threshold.
  - Annihilation is very central, spread out due to ISR;
  - Fusion processes spread out, especially for γq and γg initiated ones.





Inclusive jet distributions at a muon collider

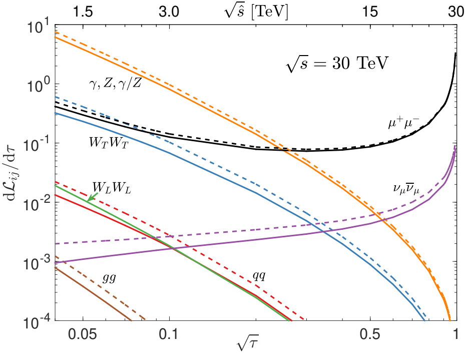


- Jet production dominates over WW production until $p_T > 60$ GeV;
- WW production takes over around energy ~ 200 GeV.
- QCD contributions are mostly forward-backward; $\gamma\gamma$, γq, and γg initiated processes are more isotropic.

An EW version of HE LHC

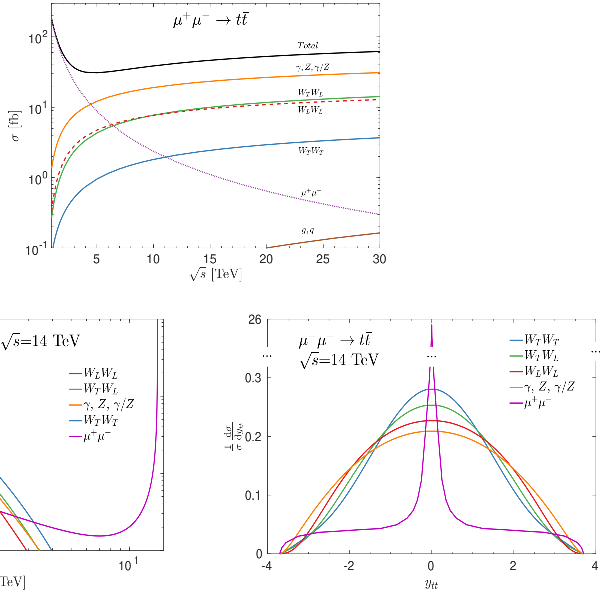
- All SM particles are partons when the machine energy is high
- We are able to determine the partons with their different polarizations

The EW parton luminosities of a 30 TeV muon collider



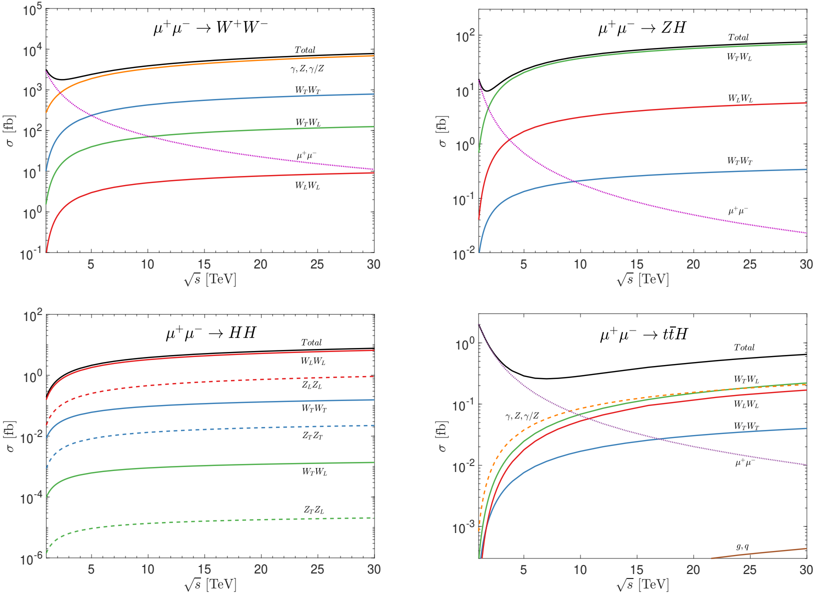
[T. Han, Y. Ma, K.Xie 2007.14300]

One example: $t\bar{t}$ production at a muon collider



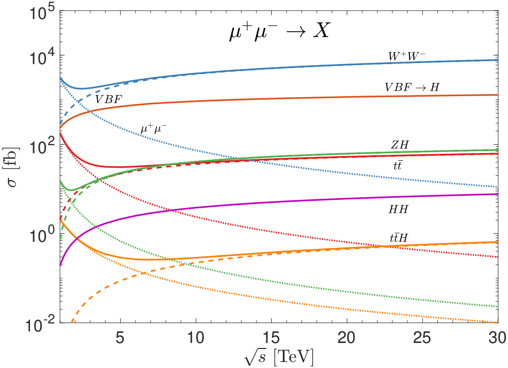
[T. Han, Y. Ma, K.Xie 2007.14300]

Other processes: $W^+W^-, ZH, HH, t\bar{t}H$



The full picture: Semi-inclusive processes

Just like in hadronic collisions: $\mu^+\mu^- \to$ exclusive particles + remnants



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

Some observations:

- The annihilations decrease as $1/s$.
- ISR needs to be considered, which can give over 10% enhancement.
- The fusions increase as $\ln^p(s)$, which take over at high energies.
- The large collinear logarithm $\ln\left(s/m_\mu^2\right)$ needs to be resummed, set $Q = \sqrt{\hat{s}}/2$.

Summary and prospects

EWPDF is important and necessary:

- At very high energies, the collinear splittings dominate. **All SM particles should be treated as partons that described by proper PDFs.**
  - The large collinear logarithm needs to be resummed via solving the DGLAP equations, so the **QCD partons (quarks and gluons) emerge**.
  - When $Q > M_Z$, the EW splittings are activated: the EW partons appear, and the existing QED$\otimes$QCD PDFs may receive big corrections.

A high-energy muon collider is an EW version of HE LHC

- There are many things to work on: SUSY, DM, Higgs, etc.
- Two classes of processes: $\mu^+\mu^-$ annihilation VS fusions

  [T. Han, Y. Ma, K.Xie 2007.14300]
- **The main background of is the jet production**:
  - Low p_T range: non-perturbative $\gamma\gamma$ initiated hadronic production dominates

    [Chen, Barklow, and Peskin, hep-ph/9305247; Drees and Godbole, PRL 67, 1189,T. Barklow, etal, LCD-2011-020]
  - High p_T range, q and g initiated jet production dominates

    [T. Han, Y. Ma, K.Xie 2103.09844]
- EWPDF allows to determine the contributions from different partons and their different ploarizations.