Electroweak and Higgs physics at high energies

Yang Ma

Department of Physics and Astronomy
University of Pittsburgh

April 19, 2022

University of Pittsburgh

Publications

- T. Han, Y. Ma and K. Xie, *Electroweak fragmentation at high energies: A Snowmass White Paper*, in *2022 Snowmass Summer Study*, 3, 2022, `2203.11129`.
- T. Han, A. K. Leibovich, Y. Ma and X.-Z. Tan, *Higgs boson decay to charmonia via c-quark fragmentation*, `2202.08273`.
- T. Han, W. Kilian, N. Kreher, Y. Ma, J. Reuter, T. Striegl et al., *Precision test of the muon-Higgs coupling at a high-energy muon collider*, *JHEP* **12** (2021) 162 [`2108.05362`].
- D. Buarque et al., *Vector Boson Scattering Processes: Status and Prospects*, *Rev. Phys.* **8** (2022) 100071 [`2106.01393`].
- T. Han, Y. Ma and K. Xie, *Quark and gluon contents of a lepton at high energies*, *JHEP* **02** (2022) 154 [`2103.09844`].
- T. Han, Y. Ma and K. Xie, *High energy leptonic collisions and electroweak parton distribution functions*, *Phys. Rev. D* **103** (2021) L031301 [`2007.14300`].
- Z. Sun and Y. Ma, *Inclusive productions of $\Upsilon(1S, 2S, 3S)$ and $\chi_b(1P, 2P, 3P)$ via the Higgs boson decay*, *Phys. Rev. D* **100** (2019) 094019 [`1909.08548`].
- Z. Sun, X.-G. Wu, Y. Ma and S. J. Brodsky, *Exclusive production of $J/\psi + \eta_c$ at the B factories Belle and Babar using the principle of maximum conformality*, *Phys. Rev. D* **98** (2018) 094001 [`1807.04503`].
- Y. Ma and X.-G. Wu, *Renormalization scheme dependence of high-order perturbative QCD predictions*, *Phys. Rev. D* **97** (2018) 036024 [`1707.09886`].
- J.-M. Shen, X.-G. Wu, Y. Ma and S. J. Brodsky, *The Generalized Scheme-Independent Crewther Relation in QCD*, *Phys. Lett. B* **770** (2017) 494 [`1611.07249`].

Presentations

Seminar and Colloquium (Invited)

- *Higgs decay to charmonia and the Charm Yukawa coupling* — UCLA, (scheduled) May 2022
- *Multi-boson production and the muon Yukawa coupling* — Univ. of Utah, Oct. 2021
- *Parton contents of a lepton at high energies* — Carleton Univ. May 2021
- *The partonic picture at high-energy lepton colliders* — SLAC, Apr. 2021
- *Parton contents of a lepton at high energies* — Oklahoma State Univ. Apr. 2021
- *High energy lepton collisions and electroweak PDFs* — Carleton Univ. Oct. 2020

Talks given at conferences

- 2022: *APS April Meeting 2022*
- 2021: *Higgs 2021, SUSY 2021, EPS-HEP 2021, DPF 2021, Pheno 2021, PPC 2021, etc.*
- 2020: *Pheno 2020*

Outline

The partonic picture of high-energy colliders

- Parton Distribution Functions (PDF)
- Future high-energy lepton colliders
- Electroweak PDF (EW PDF) and its evolution
- The Standard Model expectation for future high-energy lepton colliders

Multi-boson productions at a high-energy muon collider and the Muon-Higgs coupling

- Multi-boson physics at future high-energy lepton collider
- Muon-Higgs coupling

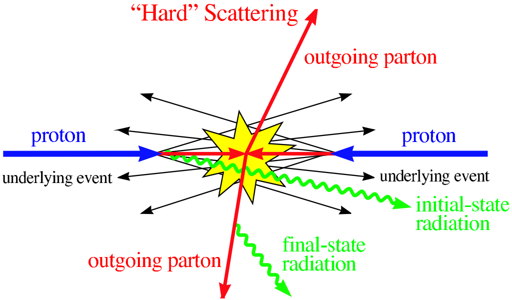
Higgs decay to charmonia and the Charm Yukawa

- Non-relatisvistic Quantum chromodynamics (NRQCD) calculation formalism
- Probe the Charm-Higgs coupling

Conclusion

Hadron colliders and the Parton Distribution Function (PDF)

- **Recall the hadron colliders: the $\mathrm{Sp\bar{p}S}$, the Tevatron or the LHC**



- **Hadrons are composite**
  a, b are the "partons" from the beam particles A and B.
- **PDFs**
  $f_{a/A}, f_{b/B}$ are the probabilities to find a parton a (b) from the beam particle A (B) with a momentum fraction x_a (x_b).

- **Factorization formalism : PDFs $\otimes$ partonic cross sections**

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

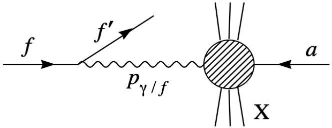
Lepton colliders and Equivalent Photon Appromation (EPA)

- **Leptons are elementary particles** $\Rightarrow$ **"Equivalent photon approximation (EPA)"**

- Treat photon as a parton constituent in the electron

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

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



[C. F. von Weizsacker, Z. Phys. 88, 612 (1934)]

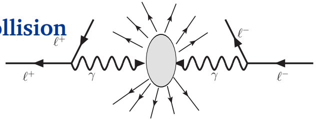
[E. J. Williams, Phys. Rev. 45, 729 (1934)]

- At lepton colliders

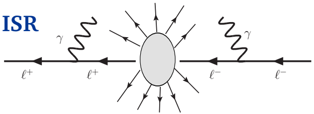
$$\sigma(\ell^+\ell^- \to F + X) = \int_{\tau_0}^{1} d\tau \sum_{ij} \frac{d\mathcal{L}_{ij}}{d\tau}\hat{\sigma}(ij \to F),\ \tau = \hat{s}/s$$

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

$\gamma\gamma$ **collision**



ISR



A possible high-energy lepton collider in the future

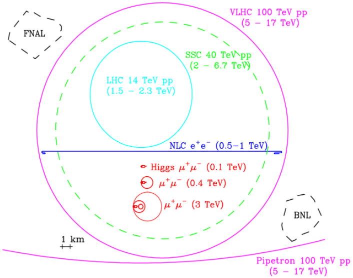
Why lepton colliders?

- **Leptons** are the ideal probes of short-distance physics
  - Cleaner background comparing to hadron colliders
  - The collision particles can carry the full machine 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 than 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
    - $\ldots$

The dream machine: A possible high-energy muon collider

International
MUON Collider
Collaboration

- **Size and Benchmarks**



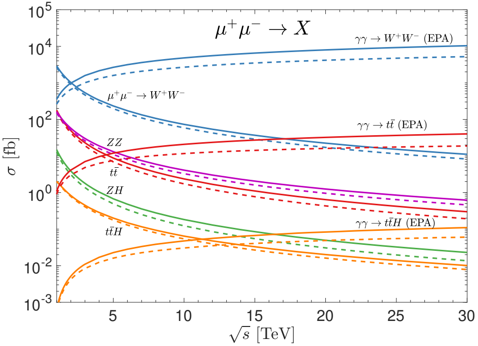
[Ankenbrandt et al. arXiv:physics/9901022]

- **Luminosity**: $\mathcal{L} = (E_{\rm cm}/10\,\text{TeV})^2 \times 10\text{ab}^{-1}$

$\sqrt{s}$ [TeV]	1	3	6	10	14	30	50	100
$\mathcal{L}_{\rm int}^{\rm opt}$ [ab^{-1}]	0.2	1	4	10	20	90	250	1000
$\mathcal{L}_{\rm int}^{\rm con}$ [ab^{-1}]	0.2	1	4	10	10	10	10	10

A high-energy muon collider at first glance

What do people expect from a high-energy lepton (muon) collider?



[T. Han, YM, K.Xie 2007.14300]

Some "commonsense":

- 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 $\ln(s/m_\ell^2)$ needs to be resummed, set $Q = \sqrt{\hat{s}}/2$,
- $\gamma\gamma \to W^+W^-$ production has the largest cross section.

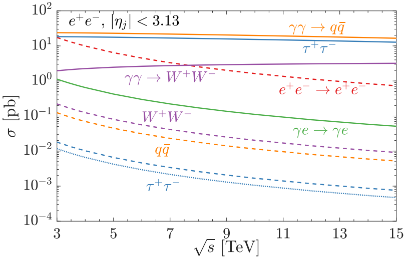
What are the dominant processes at a high-energy lepton collider?

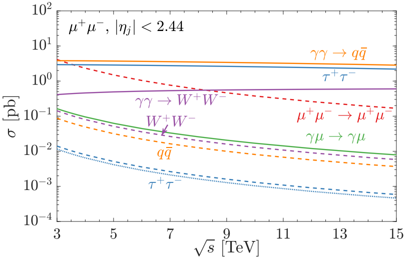
- Leading-order: $\ell^+\ell^- \to \ell^+\ell^-,\ \tau^+\tau^-,\ q\bar{q},\ W^+W^-$, and $\gamma\ell \to \gamma\ell$
- $\gamma\gamma$ scatterings: $\gamma\gamma \to \tau^+\tau^-,\ q\bar{q},\ W^+W^-$

Need some cuts:

- Detector angle & Threshold: $\theta_{\rm cut} = 5^\circ\ (10^\circ) \Longleftrightarrow |\eta| < 3.13(2.44)$, $m_{ij} > 20$ GeV
- To separate from the nonperturbative hadronic production: $p_T > \left(4 + \frac{\sqrt{s}}{3\,\mathrm{TeV}}\right)$ GeV

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

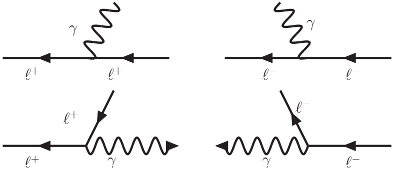




People have been doing:

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

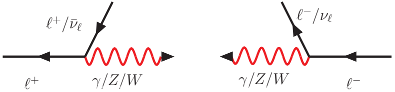
- EPA and ISR



- "Effective W Approx." (EWA)

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

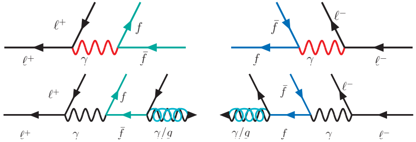
[S. Dawson, NPB 249 (1985) 42]



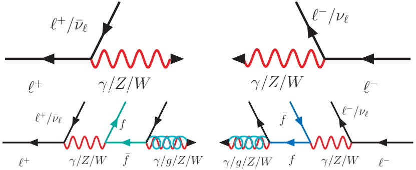
We will add:

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

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



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



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

The PDF evolution: DGLAP

- The DGLAP equations

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

- The initial conditions

$$f_{\ell/\ell}(x, m_\ell^2) = \delta(1-x)$$

- Three regions and two matchings
  - $m_\ell < Q < \mu_{\mathrm{QCD}}$: QED
  - $Q = \mu_{\mathrm{QCD}} \lesssim 1$ GeV: $f_q \propto P_{q\gamma} \otimes f_\gamma, f_g = 0$
  - $\mu_{\mathrm{QCD}} < Q < \mu_{\mathrm{EW}}$: QED$\otimes$QCD
  - $Q = \mu_{\mathrm{EW}} = M_Z$: $f_\nu = f_t = f_W = f_Z = f_{\gamma Z} = 0$
  - $\mu_{\mathrm{EW}} < Q$: EW$\otimes$QCD.

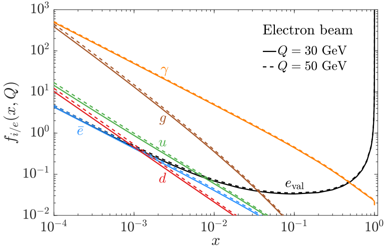
$$\begin{pmatrix} f_B \\ f_{W^3} \\ f_{BW^3} \end{pmatrix} = \begin{pmatrix} c_W^2 & s_W^2 & -2c_W s_W \\ s_W^2 & c_W^2 & 2c_W s_W \\ c_W s_W & -c_W s_W & c_W^2 - s_W^2 \end{pmatrix} \begin{pmatrix} f_\gamma \\ f_Z \\ f_{\gamma Z} \end{pmatrix}$$

- We work in the (B, W) basis. The technical details can be referred to the backup slides.

The QED⊗QCD PDFs for lepton colliders

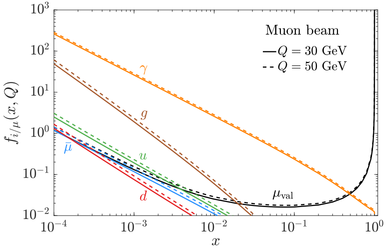
- **Electron PDFs**: $f_{e_{\rm val}},\ f_\gamma,\ f_{\ell_{\rm sea}},\ f_q,\ f_g$
- Scale uncertainty: 10% for $f_{g/e}$
- The averaged momentum fractions $\langle x_i\rangle = \int x f_i(x)\mathrm{d}x$

$Q(e^\pm)$	$e_{\rm val}$	γ	ℓsea	q	g
30 GeV	96.6	3.20	0.069	0.080	0.023
50 GeV	96.5	3.34	0.077	0.087	0.026
M_Z	96.3	3.51	0.085	0.097	0.028



- **Muon 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



The PDFs of a lepton beyond the EW scale

- **All SM particles are partons**

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

  - The sea leptonic and quark PDFs show up

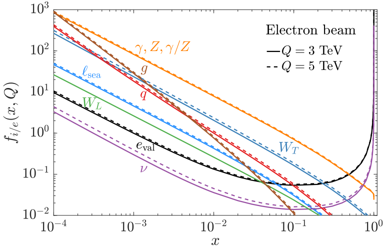
    $\nu = \sum_i (\nu_i + \bar{\nu}_i)$,

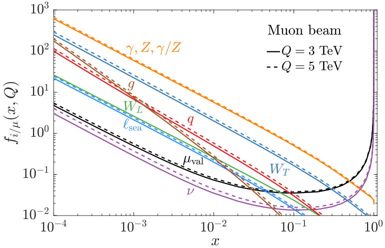
    $\ell\text{sea} = \bar{\mu} + \sum_{i\neq\mu}(\ell_i + \bar{\ell}_i)$,

    $q = \sum_{i=d}^{t}(q_i + \bar{q}_i)$

    There is even neutrino due to the EW sector

- W_L does not evolve at the leading order.
- The EW correction is not small: $\sim 50\%$ (100%) for $f_{d/e}$ $(f_{d/\mu})$ due to the relatively **large SU(2) gauge coupling**. [T. Han, Y. Ma, K.Xie 2103.09844]
- Scale uncertainty: $\sim 15\%$ (20%) between $Q = 3$ TeV and $Q = 5$ TeV





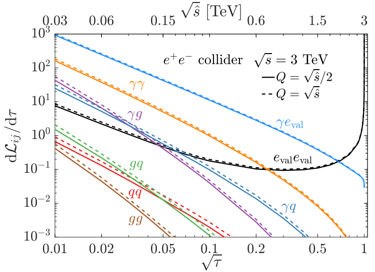
Parton luminosities at high-energy lepton colliders

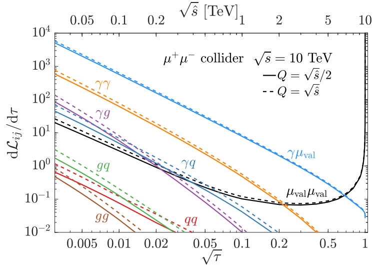
A 3 TeV e^+e^- machine and a 10 TeV $\mu^+\mu^-$ machine

- Partonic luminosities for

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

- $\gamma\gamma$ gives the largest partonic luminosity
- The luminosity of $\gamma g + \gamma q$ is $\sim 50\%$ (20%) of $\gamma\gamma$
- The luminosities of qq, gq, and gg are $\sim 2\%$ (0.5%) of $\gamma\gamma$
- Given the stronger QCD coupling, **sizable QCD cross sections are expected**.
- Scale uncertainty is $\sim 20\%$ (50%) for photon (gluon) initiated processes.



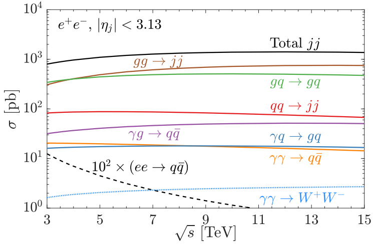


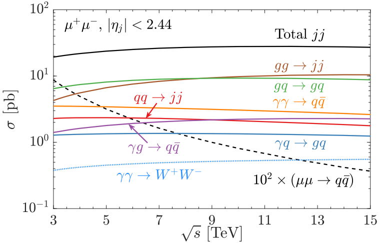
Jet production at possible lepton colliders

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

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

- Large $\alpha_s \ln(Q^2)$ brings a $6\% \sim 15\%$ $(30\% \sim 40\%)$ enhancement if $Q = 2Q$
- The QCD contributions result in total cross section.
- gg initiated cross sections are large for the **multiplicity**
- gq initiated cross sections are large for the **luminosity**.
- $\gamma\gamma$ gives smaller cross sections than the EPA does.

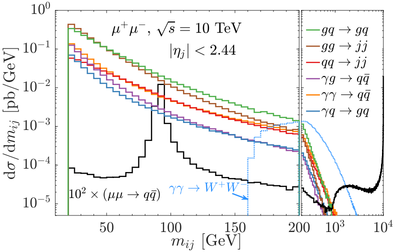


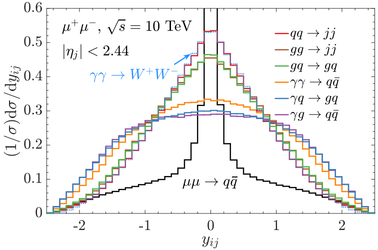


Di-jet distributions at a muon collider

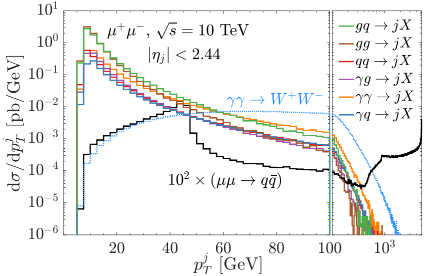
Rather a conservative set up: $\theta = 10^\circ$

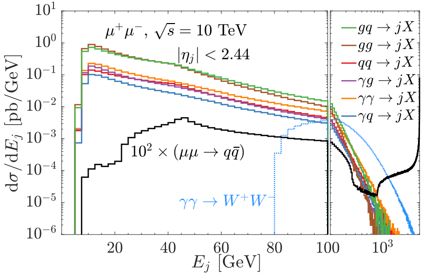
- Some physics:
  Two different mechanisms: $\mu^+\mu^-$ **annihilation** VS **Fusion processes**
  - Annihilation is more than 2 orders of magnitude smaller than fusion process.
  - Annihilation peaks at $m_{ij} \sim \sqrt{s}$;
  - Fusion processes peak near m_{ij} threshold.
  - Annihilation is very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





Inclusive jet distributions at a muon collider





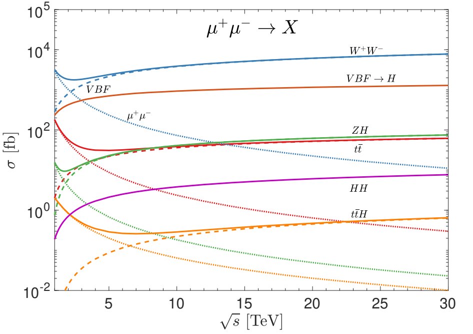
We expect

- Jet production dominates over WW production until $p_T > 60$ GeV;
- WW production takes over around energy ~ 200 GeV.

The full picture: Semi-inclusive processes

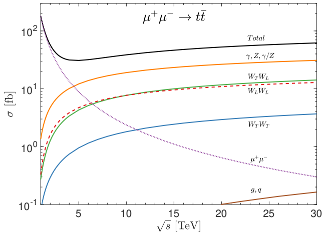
Just like in hadronic collisions:

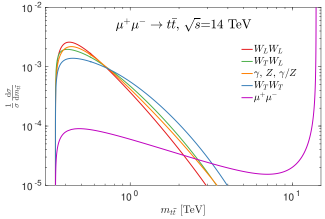
$$\mu^+\mu^- \to \text{exclusive particles} + \text{remnants}$$



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

One example: $\mu^+\mu^- \to t\bar{t} + X$

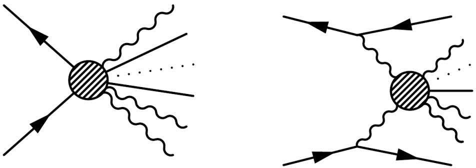




Multi-boson physics

New phenomenology at a multi-TeV lepton collider:

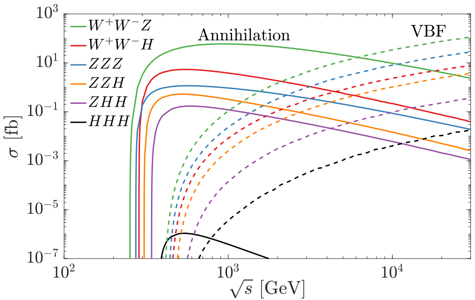
1. Multi-boson production (annihilation)
2. …and vector boson fusion (**VBF**) to multi-bosons, leading to multi-fermion final states with resonance structure.

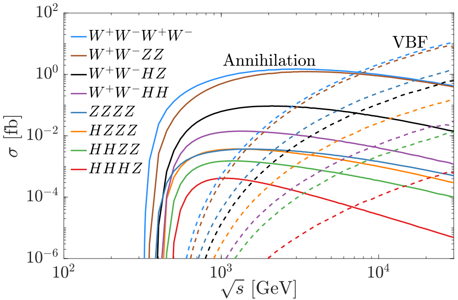


[Barger, Cheung, Han, Phillips 1995] [Boos, He, Kilian, Pukhov, Yuan, Zerwas 1998]

Task:
Measure all interactions of multiple SM particles exclusively and with precision, from threshold to up to 2 orders of magnitude above EW scale.

Annihilation vs VBF: Properties (SM)





VBF:

- Increases rapidly
- Most events are at the threshold
- Highly boosted final state (forward/backward)

Annihilation:

- Decreases slowly
- Most events are at the machine energy
- One Boson highly off-shell
- Final state in rest frame (central)

Annihilation processes are important for analysis at all energies

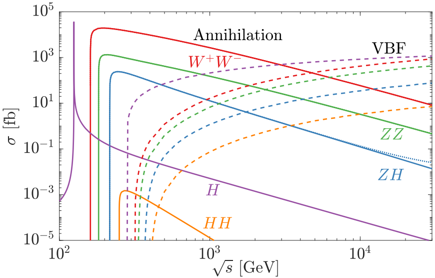
Muon-Higgs Coupling

- Physics: We actually do not know whether the SM mass-generation mechanism applies just to the heavy particles, or also to the 1st/2nd generations.
- Logical possibility: Muon mass not (only) generated by SM Higgs.
  $\Rightarrow$ **Why not have an arbitrary Yukawa coupling?**

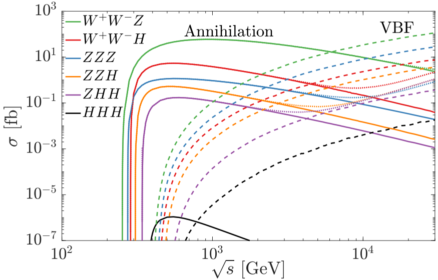
Multi-boson final states and the Muon-Higgs coupling

- **SM**: $\lambda(\text{Muon}-\text{Higgs}) \sim y_\mu^{\text{SM}} = \sqrt{2} m_\mu^{\text{SM}}/v$
- **Possible BSM physics**: $m_\mu = m_\mu^{\text{SM}}$, $\lambda(\text{Muon}-\text{Higgs}) \sim \kappa_\mu y_\mu^{\text{SM}}$, e.g. $\kappa_\mu = 0$

Two-boson final states

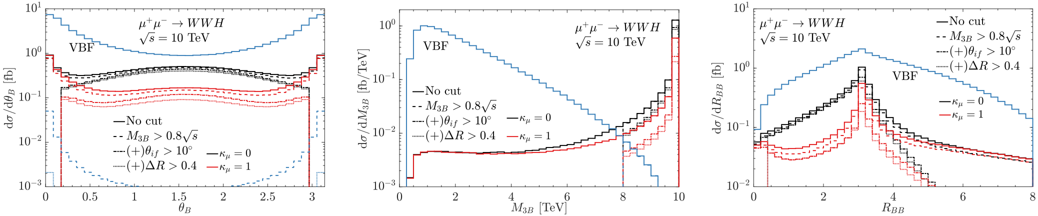


Three-boson final states



New physics signal shows up in the high energy region

WWH at a 10 TeV muon collider: Kinematics



- Background (VBF) is much larger than signal (annihilation)
- VBF events accumulate around threshold, and mostly forward
- Annihilation in the rest frame (central, and $M \sim \sqrt{s}$ spread by ISR)
- Annihilation also has forward dominance, due to the gauge splitting $W \to WH$

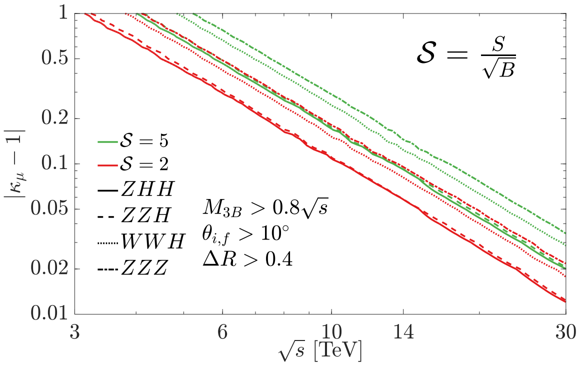
WWH at a 10 TeV muon collider: Cuts

Cut flow	$\kappa_\mu = 1$	w/o ISR	$\kappa_\mu = 0$ (2)	CVBF	NVBF
σ [fb]	WWH				
No cut	0.24	0.21	0.47	2.3	7.2
$M_{3B} > 0.8\sqrt{s}$	0.20	0.21	0.42	$5.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-2}$
$10^\circ < \theta_B < 170^\circ$	0.092	0.096	0.30	$2.5 \cdot 10^{-4}$	$2.7 \cdot 10^{-4}$
$\Delta R_{BB} > 0.4$	0.074	0.077	0.28	$2.1 \cdot 10^{-4}$	$2.4 \cdot 10^{-4}$
# of events	740	770	2800	2.1	2.4
S/B	2.8				

- Integrated luminosity $\mathcal{L} = (\sqrt{s}/10\ \text{TeV})^2 \cdot 10\,\text{ab}^{-1}$ [1901.06150]
- $S = N_{\kappa_\mu} - N_{\kappa_\mu=1},\ B = N_{\kappa_\mu=1} + N_{\text{VBF}}.$
- VBF and ISR are mostly excluded by invariant mass cut.
- Angular cut also weaken VBF further.

Test the muon Yukawa: statistical sensitivity

- The most sensitive channels are ZHH and ZZH, similar probes due to GBET.
- Taking $\mathcal{S} = 2$ criterion, we can test the muon-Higgs coupling up to 10% (1%) precision at a 10 (30) TeV muon collider, corresponding to new physics scale $\Lambda_{\rm NP} \sim 30 - 100$ TeV.



Charm-Higgs Coupling

The same question is asked again

- Physics: We actually do not know whether the SM mass-generation mechanism applies just to the heavy particles, or also to the 1st/2nd generations.
- Logical possibility: Muon mass not (only) generated by SM Higgs.
  $\Rightarrow$ **What if the Charm-Higgs coupling is not related to m_c ?**

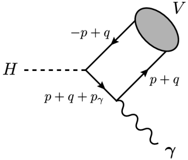
Current status of charm Yukawa coupling testing

Measuring $Hc\bar{c}$ coupling is not easy

- Branching fraction ($H \to c\bar{c}$): 2.9%
- Large QCD background at hadron colliders
- c-tagging is challenging

Current experimental searching

- κ framework: For $y_c^{\rm SM} = \sqrt{2}m_c/v$, set $y_c = \kappa_c y_c^{\rm SM}$
- $pp \to VH(c\bar{c})$
  - Need c-tagging.
  - LHC Run 2: ATLAS $\kappa_c \leq 8.5$ [ATLAS-CONF-2021-021], CMS $1.1 < |\kappa_c| < 5.5$ [CMS-PAS-HIG-21-008]
  - Future HL-LHC: $\kappa_c \leq 3$. [2201.11428, ATL-PHYS-PUB-2021-039]
- Production of $c\bar{c}$ bound states via Higgs decay: $H \to J/\psi + \gamma$
  - Clean final states $J/\psi \to \mu^+\mu^-$, avoid c-tagging
  - The rate is too low: $BR \sim 10^{-6}$. [1306.5770, 1407.6695]
  - Result is less sensitive: $\kappa_c \leq 100$. [1807.00802, 1810.10056]



Our idea: Higgs decay to charmonium in NRQCD

$$H \to c + \bar{c} + J/\psi \,(\mathrm{or}\, \eta_c)$$

Nonrelativistic QCD framework

$$\Gamma = \sum_{\mathbb{N}} \hat{\Gamma}_{\mathbb{N}}(H \to (Q\bar{Q})[\mathbb{N}] + X) \times \langle \mathcal{O}^h[\mathbb{N}] \rangle,$$

$$\mathrm{d}\hat{\Gamma}_{\mathbb{N}} = \frac{1}{2m_H} \frac{|\mathcal{M}|^2}{\langle \mathcal{O}^{Q\bar{Q}} \rangle} \mathrm{d}\Phi_3$$

Long distance matrix element (LDME)

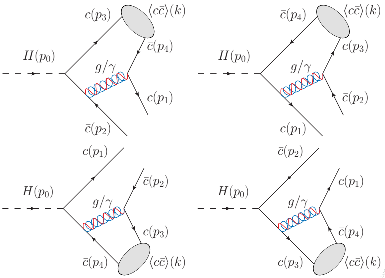
Related to the wave function at origin

$$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{[1]}] \rangle = \frac{3N_c}{2\pi}|R(0)|^2, \; \langle \mathcal{O}^{\eta_c}[{}^1S_0^{[1]}] \rangle = \frac{N_c}{2\pi}|R(0)|^2,$$

$$\langle \mathcal{O}^{Q\bar{Q}} \rangle = 6N_c, \text{ for } {}^3S_1^{[1]}, \; \langle \mathcal{O}^{Q\bar{Q}} \rangle = 2N_c, \text{ for } {}^1S_0^{[1]}$$

Color-singlet:

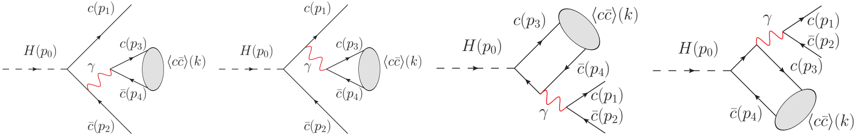
Charm quark fragmentation to ${}^3S_1^{[1]}(J/\psi)$ and ${}^1S_0^{[1]}(\eta_c)$



More corrections from QED and EW sector

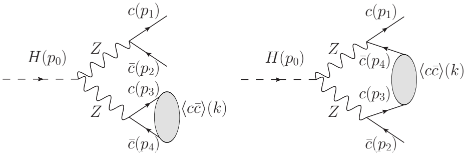
Pure QED diagrams: sizable correction to ${}^3S_1^{[1]}(J/\psi)$ production

Single photon fragmentation (SPF) $\Rightarrow$ **logarithmic enhancement**



Electroweak correction from the HZZ diagrams

One of the Z can be on shell $\Rightarrow$ **resonance enhancement**



- Sizable for ${}^1S_0^{[1]}(\eta_c)$ due to the larger axial $Zc\bar{c}$ coupling.

Charmonium productiuon via color octet states

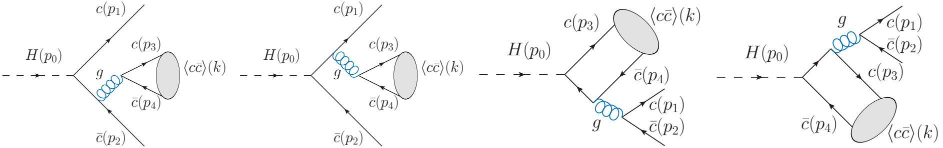
A key property of NRQCD

- A quarkonium can also be produced through **color-octet** $Q\bar{Q}$ Fork states
- New states involved: ${}^3S_1^{[8]}$, ${}^1S_0^{[8]}$, ${}^3P_J^{[8]}$, and ${}^1P_1^{[8]}$
- The LDMEs $\langle\mathcal{O}^h[{}^{2S+1}L_J^{[\mathrm{color}]}]\rangle$ need to be fitted from experimental data

Reference	$\langle\mathcal{O}^{J/\psi}[{}^1S_0^{[8]}]\rangle$	$\langle\mathcal{O}^{J/\psi}[{}^3S_1^{[8]}]\rangle$	$\langle\mathcal{O}^{J/\psi}[{}^3P_0^{[8]}]\rangle/m_c^2$
G. Bodwin,	$(9.9 \pm 2.2) \times 10^{-2}$	$(1.1 \pm 1.0) \times 10^{-2}$	$(4.89 \pm 4.44) \times 10^{-3}$
K.T. Chao,	$(8.9 \pm 0.98) \times 10^{-2}$	$(3.0 \pm 1.2) \times 10^{-3}$	$(5.6 \pm 2.1) \times 10^{-3}$
Y. Feng,	$(5.66 \pm 4.7) \times 10^{-2}$	$(1.77 \pm 0.58) \times 10^{-3}$	$(3.42 \pm 1.02) \times 10^{-3}$

New diagrams for ${}^3S_1^{[8]}$

Single gluon fragmentation (SGF) $\Rightarrow$ **logarithmic enhancement**



Standard Model results (I)

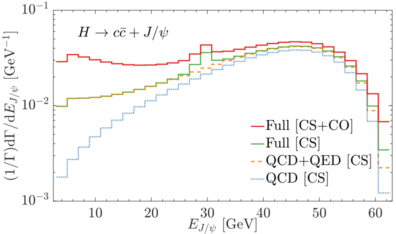
Numerical parameters

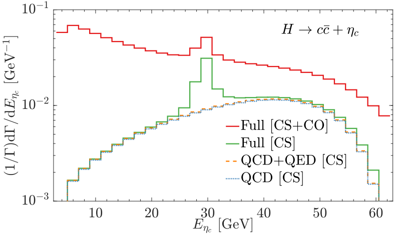
$$\alpha = 1/132.5,\ \alpha_s(2m_c) = 0.235,\ m_c^{\text{pole}} = 1.5\,\text{GeV},\ m_c(m_H) = 0.694\,\text{GeV},\ m_H = 125\,\text{GeV},$$
$$m_W = 80.419\,\text{GeV},\ m_Z = 91.188\,\text{GeV},\ v = 246.22\,\text{GeV},\ y_c^{\text{SM}} = \frac{\sqrt{2}m_c(m_H)}{v} \approx 3.986 \times 10^{-3}.$$

Decay width and branching fraction

	QCD [CS]	QCD+QED [CS]	Full [CS]	Full [CO]	Full [CS+CO]
$\Gamma(H \to c\bar{c} + J/\psi)$ (GeV)	4.8×10^{-8}	5.8×10^{-8}	6.1×10^{-8}	2.2×10^{-8}	8.3×10^{-8}
$\text{BR}(H \to c\bar{c} + J/\psi)$	1.2×10^{-5}	1.4×10^{-5}	1.5×10^{-5}	5.3×10^{-6}	2.0×10^{-5}
$\Gamma(H \to c\bar{c} + \eta_c)$ (GeV)	4.9×10^{-8}	5.1×10^{-8}	6.3×10^{-8}	1.8×10^{-7}	2.4×10^{-7}
$\text{BR}(H \to c\bar{c} + \eta_c)$	1.2×10^{-5}	1.2×10^{-5}	1.5×10^{-5}	4.5×10^{-5}	6.0×10^{-5}

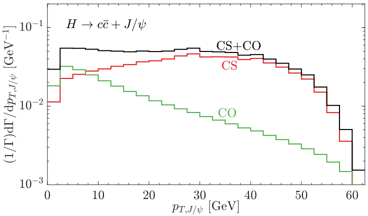
Charmonium energy distributions

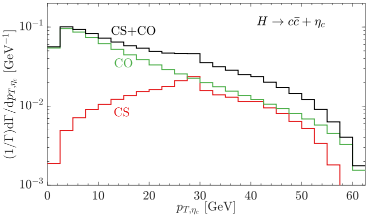




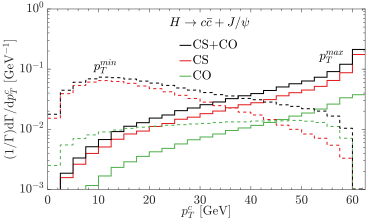
Standard Model results (II): Transverse momentum (p_T) distributions

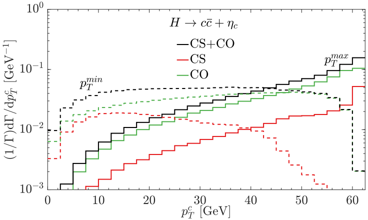
Charmonium p_T distributions





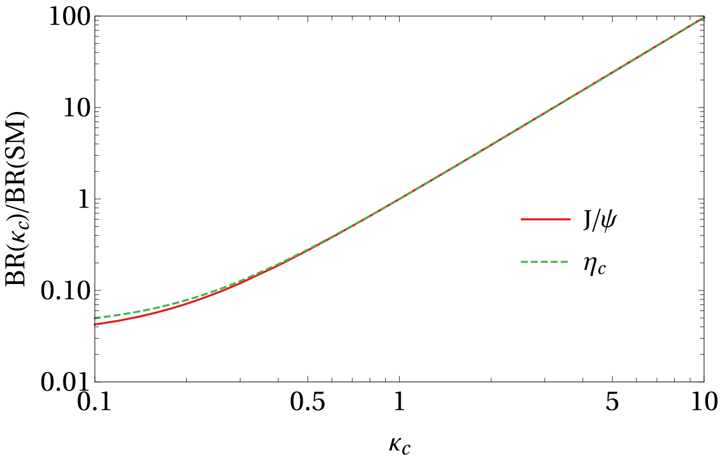
Free charm quark p_T distributions





Probe the $Hc\bar{c}$ coupling (I)

Use the κ framework $y_c = \kappa_c y_c^{\rm SM}$, $\mathrm{BR} \approx \kappa_c^2\,\mathrm{BR}^{\rm SM}$



Probe the $Hc\bar{c}$ coupling (II)

Some rough analysis:

- Higgs production cross section at LHC $\sigma_H \sim 50$ pb
- Expect HL-LHC $L \sim 3\,\mathrm{ab}^{-1}$ at ATLAS and CMS and $L \sim 0.3\,\mathrm{ab}^{-1}$ at LHCb
- Detection efficiency ϵ for the final state $c\bar{c} + \ell^+\ell^-$
- $\mathrm{BR}(J/\psi \to \ell^+\ell^-) \sim 12\%, \mathrm{BR}(H \to J/\psi + c\bar{c}) \sim 2 \times 10^{-5}$
- Event number

$$N = L\sigma_H\,\epsilon\,\mathrm{BR}(H \to J/\psi + c\bar{c})\mathrm{BR}(J/\psi \to \ell^+\ell^-) \approx 24\,\kappa_c^2 \times \frac{L}{\mathrm{ab}^{-1}} \times \frac{\epsilon}{20\%}$$

- Considering the statistical error only $\delta N \sim \sqrt{N}$ gives

$$\Delta\kappa_c \approx 10\% \times (\frac{L}{\mathrm{ab}^{-1}} \times \frac{\epsilon}{20\%})^{-1/2}$$

- **With $\epsilon \sim 20\%$, we see $\Delta\kappa_c \sim 6\%$ at ATLAS and CMS.**
- **For a smaller luminosity, $\Delta\kappa_c \sim 18\%$ at LHCb.**

Conclusion

- 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 lepton collider is an EW version of HE LHC. We have laid out the EW PDFs framework and provide the SM expectation for future leoton colliders.
- Higgs is believed to be a portal to the new physics beyond the SM.
  - By using multi-boson production processes, we claim that it is possible to measure Muon-Higgs coupling to 10% level at future 10-TeV level muon collider.
  - We also suggest to test the charm-Higgs coupling using Higgs decay to charmonia process at the HL-LHC.

Acknowledgement

Thanks !

- To the committee members:
  Tao Han, Brian Batell, Vittorio Paolone, Manfred Paulini, Andrew Zentner
- To those who were teaching me in the past 6 years:
  Tao Han, Brian Batell, Daniel Boyanovsky, Ayres Freitas, Kaoru Hagiwara, Jeremy Levy, Roger Mong, Manfred Paulini, Andrew Zentner
- To my collaborators:
  Tao Han, Adam Leibovich, Keping Xie, Wolfgang Kilian, Nils Kreher, Jürgen Reuter,...
- To my colleagues and classmates:
  Rudrajit Banerjee, Hongbo Cai, Lisong Chen, Yilun Guan, Sze Ching Leung, Chi Wing Ng, Qian Song, Barmak Shams Es Haghi, Yongcheng Wu, Zhite Yu, Bomin Zhang, ...
- To Prof. Stanley Brodsky for "Yang, you should work hard"

I will continue working hard at INFN Bologna

INFN BOLOGNA
Istituto Nazionale di Fisica Nucleare
Sezione di Bologna

Solving the DGLAP: Singlet and Non-singlet PDFs

The singlets

$$f_L = \sum_{i=e,\mu,\tau} (f_{\ell_i} + f_{\bar{\ell}_i}),\ f_U = \sum_{i=u,c} (f_{u_i} + f_{\bar{u}_i}),\ f_D = \sum_{i=d,s,b} (f_{d_i} + f_{\bar{d}_i})$$

The non-singlets

- The only non-trivial singlet $f_{e,NS} = f_e - f_{\bar{e}}$
- the leptons $f_{\ell_i,NS} = f_{\ell_i} - f_{\bar{\ell}_i} (i = 2, 3),\ f_{\ell,12} = f_{\bar{e}} - f_{\bar{\mu}},\ f_{\ell,13} = f_{\bar{e}} - f_{\bar{\tau}};$
- the up-type quarks $f_{u_i,NS} = f_{u_i} - f_{\bar{u}_i},\ f_{u,12} = f_u - f_c;$
- and the down-type quarks $f_{d_i,NS} = f_{d_i} - f_{\bar{d}_i},\ f_{d,12} = f_d - f_s,\ f_{d,13} = f_d - f_b.$

Reconstruction:

$$f_e = \frac{f_L + (2N_\ell - 1) f_{e,NS}}{2N_\ell},\ f_{\bar{e}} = f_\mu = f_{\bar{\mu}} = f_\tau = f_{\bar{\tau}} = \frac{f_L - f_{e,NS}}{2N_\ell}.$$

$$f_u = f_{\bar{u}} = f_c = f_{\bar{c}} = \frac{f_U}{2N_u},\ f_d = f_{\bar{d}} = f_s = f_{\bar{s}} = f_b = f_{\bar{b}} = \frac{f_D}{2N_d}.$$

The QED⊗QCD case

- The singlets and gauge bosons

$$\frac{\mathrm{d}}{\mathrm{d}\log Q^2}\begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix} = \begin{pmatrix} P_{\ell\ell} & 0 & 0 & 2N_\ell P_{\ell\gamma} & 0 \\ 0 & P_{uu} & 0 & 2N_u P_{u\gamma} & 2N_u P_{ug} \\ 0 & 0 & P_{dd} & 2N_d P_{d\gamma} & 2N_d P_{dg} \\ P_{\gamma\ell} & P_{\gamma u} & P_{\gamma d} & P_{\gamma\gamma} & 0 \\ 0 & P_{gu} & P_{gd} & 0 & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} f_L \\ f_U \\ f_D \\ f_\gamma \\ f_g \end{pmatrix}$$

- The non-singlets

$$\frac{\mathrm{d}}{\mathrm{d}\log Q^2} f_{NS} = P_{ff} \otimes f_{NS}.$$

- The averaged momentum fractions of the PDFs: $f_{\ell_{\mathrm{val}}},\ f_\gamma,\ f_{\ell_{\mathrm{sea}}},\ f_q,\ f_g$

$$\langle x_i \rangle = \int x f_i(x)\mathrm{d}x,\ \sum_i \langle x_i \rangle = 1$$

$$\frac{\langle x_q \rangle}{\langle x_{\ell\mathrm{sea}} \rangle} \lesssim \frac{N_c\left[\sum_i (e_{u_i}^2 + e_{\bar{u}_i}^2) + \sum_i (e_{d_i}^2 + e_{\bar{d}_i}^2)\right]}{e_{\bar{\ell}_{\mathrm{val}}}^2 + \sum_{i\neq\ell\mathrm{val}} (e_{\ell_i}^2 + e_{\bar{\ell}_i}^2)} = \frac{22/3}{5}$$

The DGLAP for the full SM

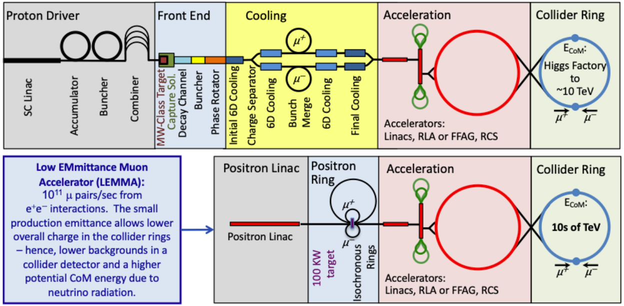
$$\frac{\mathrm{d}}{\mathrm{d}L}\begin{pmatrix} f_L^{0\pm} \\ f_Q^{0\pm} \\ f_E^{0\pm} \\ f_U^{0\pm} \\ f_D^{0\pm} \\ f_B^{0\pm} \\ f_W^{0\pm} \\ f_g^{0\pm} \end{pmatrix} = \begin{pmatrix} P_{LL}^{0\pm} & 0 & 0 & 0 & 0 & P_{LB}^{0\pm} & P_{LW}^{0\pm} & 0 \\ 0 & P_{QQ}^{0\pm} & 0 & 0 & 0 & P_{QB}^{0\pm} & P_{QW}^{0\pm} & P_{Qg}^{0\pm} \\ 0 & 0 & P_{EE}^{0\pm} & 0 & 0 & P_{EB}^{0\pm} & 0 & 0 \\ 0 & 0 & 0 & P_{UU}^{0\pm} & 0 & P_{UB}^{0\pm} & 0 & P_{Ug}^{0\pm} \\ 0 & 0 & 0 & 0 & P_{DD}^{0\pm} & P_{DB}^{0\pm} & 0 & P_{Dg}^{0\pm} \\ P_{BL}^{0\pm} & P_{BQ}^{0\pm} & P_{BE}^{0\pm} & P_{BU}^{0\pm} & P_{BD}^{0\pm} & P_{BB}^{0\pm} & 0 & 0 \\ P_{WL}^{0\pm} & P_{WQ}^{0\pm} & 0 & 0 & 0 & 0 & P_{WW}^{0\pm} & 0 \\ 0 & P_{gQ}^{0\pm} & 0 & P_{gU}^{0\pm} & P_{gD}^{0\pm} & 0 & 0 & P_{gg}^{0\pm} \end{pmatrix} \otimes \begin{pmatrix} f_L^{0\pm} \\ f_Q^{0\pm} \\ f_E^{0\pm} \\ f_U^{0\pm} \\ f_D^{0\pm} \\ f_B^{0\pm} \\ f_W^{0\pm} \\ f_g^{0\pm} \end{pmatrix}$$

$$\frac{\mathrm{d}}{\mathrm{d}L}\begin{pmatrix} f_L^{1\pm} \\ f_Q^{1\pm} \\ f_W^{1\pm} \\ f_{BW}^{1\pm} \end{pmatrix} = \begin{pmatrix} P_{LL}^{1\pm} & 0 & P_{LW}^{1\pm} & P_{LM}^{1\pm} \\ 0 & P_{QQ}^{1\pm} & P_{QW}^{1\pm} & P_{QM}^{1\pm} \\ P_{WL}^{1\pm} & P_{WQ}^{1\pm} & P_{WW}^{1\pm} & 0 \\ P_{ML}^{1\pm} & P_{MQ}^{1\pm} & 0 & P_{MM}^{1\pm} \end{pmatrix} \otimes \begin{pmatrix} f_L^{1\pm} \\ f_Q^{1\pm} \\ f_W^{1\pm} \\ f_{BW}^{1\pm} \end{pmatrix}$$

$$\frac{\mathrm{d}}{\mathrm{d}L} f_W^{2\pm} = P_{WW}^{2\pm} \otimes f_{WW}^{2\pm}$$

The splitting functions can be found in [Chen et al. 1611.00788, Bauer et al. 1703.08562,1808.08831]

Muon collider implementations



Muon Accelerator Program

map.fnal.gov [1901.06150,1907.08562]

- Protons $\to$ pions $\to$ muons
- 6D cooling is needed

Low EMittance Muon Accelerator

web.infn.it/LEMMA [1901.06150]

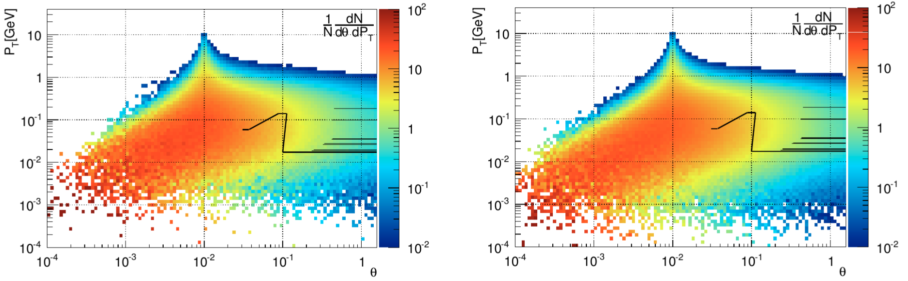
- $e^+e^- \to \mu^+\mu^-$:
  45 GeV e^+ to rest e^-
- Cooling is not a problem
- High luminosity is challenging

Photon induced hadronic production at high-energy lepton colliders

- 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.

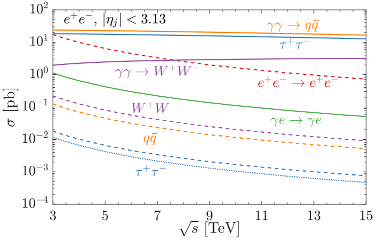


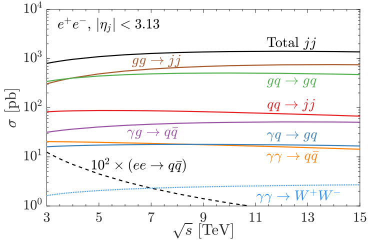
(a) Pythia sample (b) SLAC sample

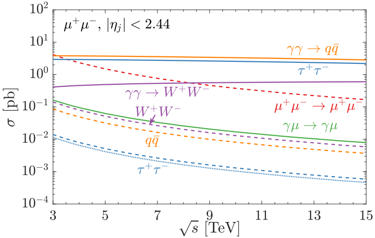
[T. Barklow, D. Dannheim, M. O. Sahin, and D. Schulte, LCD-2011-020]

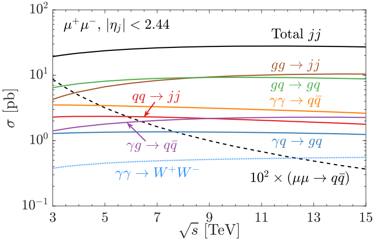
What is the dominant process at a high-energy muon collider (in the high p_T range)?

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









Muon Yukawa coupling: running

- In SM $m_\mu(Q) = y_\mu(Q)v(Q)/\sqrt{2}$

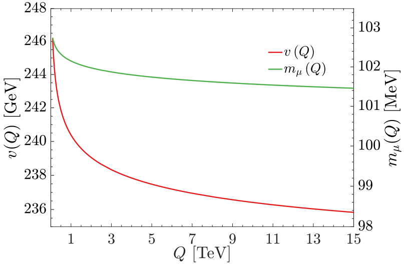
$$\begin{aligned}
\beta_{y_t} &= \frac{\mathrm{d}y_t}{\mathrm{d}t} = \frac{y_t}{16\pi^2}\left(\frac{9}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right), \\
\beta_{y_\mu} &= \frac{\mathrm{d}y_\mu}{\mathrm{d}t} = \frac{y_\mu}{16\pi^2}\left(3y_t^2 - \frac{9}{4}(g_2^2 + g_1^2)\right), \\
\beta_v &= \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{v}{16\pi^2}\left(\frac{9}{4}g_2^2 + \frac{9}{20}g_1^2 - 3y_t^2\right), \\
\beta_{g_i} &= \frac{\mathrm{d}g_i}{\mathrm{d}t} = \frac{b_i g_i^3}{16\pi^2},
\end{aligned}$$

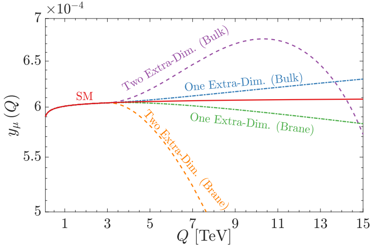
- In potential new physics (NP)

$$\beta_\lambda = \beta_\lambda^{\mathrm{SM}} + \sum_{s\in\mathrm{NP}} \Theta\left(Q - M_s\right) \times N_s \beta_{s,\lambda}^{\mathrm{NP}}$$

Example: the Bulk and Brane extra-dimensional scenarios

Choose $1/R = 3$ TeV for illustration [Cornell et al. 1110.1942, 1209.6239, 1306.4852]





EFT parameterizations

- Nonlinear HEFT [Coleman et al., PR1969, Weinberg, PLB1980, $\cdots$]

$$\begin{aligned}\mathcal{L}_{UH} =& \frac{v^2}{4}\,\mathrm{Tr}\left[D_\mu U^\dagger D^\mu U\right] F_U(H) + \frac{1}{2}\partial_\mu H \partial^\mu H - V(H) \\ & - \frac{v}{2\sqrt{2}}\left[\bar{\ell}^i_L \tilde{Y}^{ij}_\ell(H) U \left(1-\tau_3\right)\ell^j_R + \text{ h.c.}\right]\end{aligned}$$

with $F_U, V, \tilde{Y}$ expanded as

$$F_U(H) = 1 + \sum_{n\geq 1} f_{U,n}\left(\frac{H}{v}\right)^n, V(H) = v^4 \sum_{n\geq 2} f_{V,n}\left(\frac{H}{v}\right)^n, \tilde{Y}^{ij}_\ell(H) = \sum_{n\geq 0} \tilde{Y}^{ij}_{\ell,n}\left(\frac{H}{v}\right)^n$$

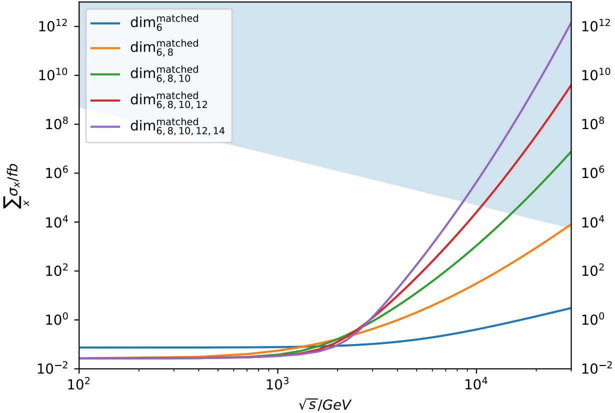
which gives muon-Higgs effective coupling $\kappa_\mu = \frac{v}{\sqrt{2}m_\mu} y_1$.

- Linear SMEFT [Weinberg PRL1979, Abbott & Wise PRD1980, $\cdots$]

$$\mathcal{L} = \mathcal{L}_{\mathrm{EW}} + \left[\sum_{n=1}^{N} \frac{\tilde{C}^{(n)ij}_{\ell\varphi}}{\Lambda^{2n}}\left(\varphi^\dagger\varphi\right)^n \bar{\ell}^i_L \varphi e^j_R + \text{ h.c.}\right] \quad \Rightarrow \kappa^{(6)}_\mu = 1 - \frac{v^3}{\sqrt{2}m_\mu} c^{(1)}_{\ell\varphi}$$

Unitarity bounds on a nonstandard Yukawa sector

Inclusive inelastic cross section $\mu^+\mu^- \to X$ for multiple Goldstone and Higgs-boson production in the GBET approximation



Standard Model results: Contributions from different states

Color-octet contributions

	$^3S_1^{[8]}$	$^1S_0^{[8]}$	$^1P_1^{[8]}$	$^3P_J^{[8]}$	Total
$\Gamma(H \to c\bar{c} + J/\psi)$ (GeV)	2.0×10^{-8}	9.8×10^{-10}	-	2.2×10^{-10}	2.2×10^{-8}
$\mathrm{BR}(H \to c\bar{c} + J/\psi)$	5.0×10^{-6}	2.4×10^{-7}	-	5.3×10^{-8}	5.3×10^{-6}
$\Gamma(H \to c\bar{c} + \eta_c)$ (GeV)	1.8×10^{-7}	3.6×10^{-11}	1.0×10^{-10}	-	1.8×10^{-7}
$\mathrm{BR}(H \to c\bar{c} + \eta_c)$	4.5×10^{-5}	8.9×10^{-9}	2.5×10^{-8}	-	4.5×10^{-5}

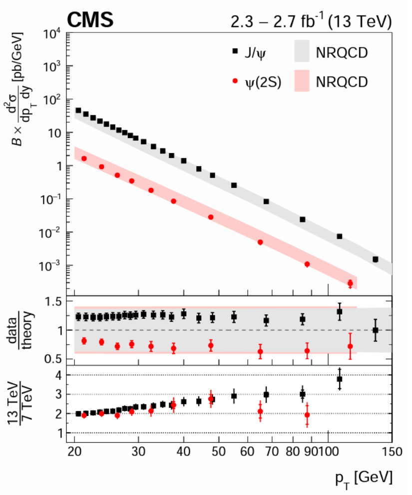
Contributions with respect to QCD

$\hat{\Gamma}_{\mathbb{N}}/\hat{\Gamma}_{\mathbb{N}}^{\mathrm{QCD}}$	$^1S_0^{[1]}$	$^3S_1^{[1]}$	$^1S_0^{[8]}$	$^3S_1^{[8]}$	$^1P_1^{[8]}$	$^3P_0^{[8]}$	$^3P_1^{[8]}$	$^3P_2^{[8]}$
QCD	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
QED	1.1×10^{-4}	0.077	0.0073	1.1×10^{-5}	0.0068	0.0073	0.0073	0.0073
QCD×QED	0.021	0.14	-0.17	0.0012	-0.15	-0.17	-0.17	-0.17
EW	0.24	0.051	0.28	2.6×10^{-4}	1.4	0.29	0.33	1.5

Some observations

- QCD is dominant in most of the Fock states
- SPF brings sizable QED correction to $^3S_1^{[1]}$, but it is forbidden for $^1S_0^{[1]}$
- SGF makes $^3S_1^{[8]}$ super large
- For $^1S_0^{[8]}$ and $^3P_J^{[8]}$, QED and QCD differ by a universal factor
- EW correction is large since Z is closed to its mass shell

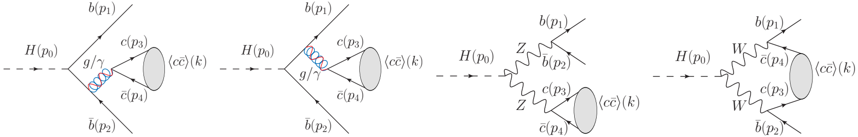
Probe the $Hc\bar{c}$ coupling: Background from $pp \to J/\psi + X$



- Prompt J/ψ production $\mathrm{BR}(J/\psi \to \mu^+\mu^-) \times \sigma(pp \to J/\psi) \simeq 860$ pb
  Charm-tagging is needed.
- Estimate 75000 events for $pp \to J/\psi + c\bar{c}$ at a $3\ \mathrm{ab}^{-1}$ HL-LHC
  Corresponding to a $25\ \mathrm{fb}$ cross section
  Some kinematic cut may help.

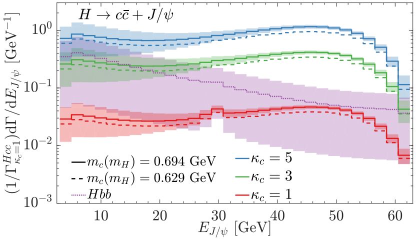
Probe the $Hc\bar{c}$ coupling: Background from $H \to J/\psi + b\bar{b}$

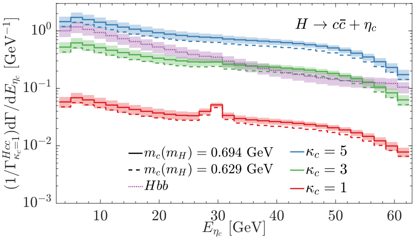
Color-octet contribution dominates



Charmonium energy distributions

Take the color-octet LDME uncertainty for error estimation





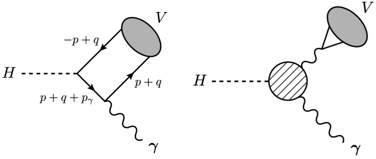
$H \to J/\psi + \gamma$

- Small decay rate

$$\mathrm{BR}(H \to J/\psi + \gamma) \simeq 2.8 \times 10^{-6}$$

- Insensitive to $Hc\bar{c}$ coupling
  $\Rightarrow \kappa_c \lesssim 100$

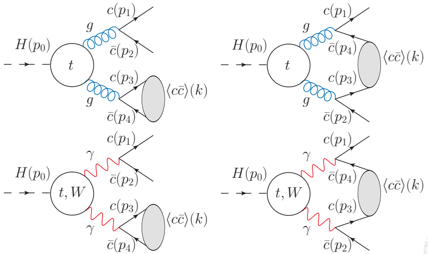
"Vector meson dominance" (VMD)



- $\gamma^* \to J/\psi$ dominates over $Hc\bar{c}$

$H \to J/\psi + c\bar{c}$

- Larger decay rate
  $$\mathrm{BR}(H \to J/\psi + c\bar{c}) \simeq 2 \times 10^{-5}$$
- Sensitive to $Hc\bar{c}$ coupling
  QCD and QED dominates
- Other diagrams
  $$H \to g^*g^*/\gamma^*\gamma^* \to J/\psi + c\bar{c}$$



$$\mathrm{BR}(g^*g^*) \sim 2.5 \times 10^{-6}, \mathrm{BR}(\gamma^*\gamma^*) < 2 \times 10^{-7}$$

- **No need to worry about VMD**