A PHENOMENOLOGICAL STUDY OF HIGGS JETS AT A MUON COLLIDER

JAY DESAI

ADVISOR:

GEORGE STERMAN

Stony Brook University

C.N. YANG INSTITUTE for Theoretical Physics

OUTLINE

- Muon colliders
- Vector boson Fusion and collinear factorization
- Super-renormalizable splitting
- QCD di-jet events
- Comparison plots

CASE FOR A MUON COLLIDER

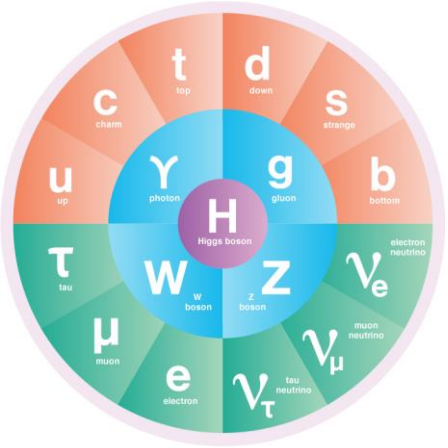
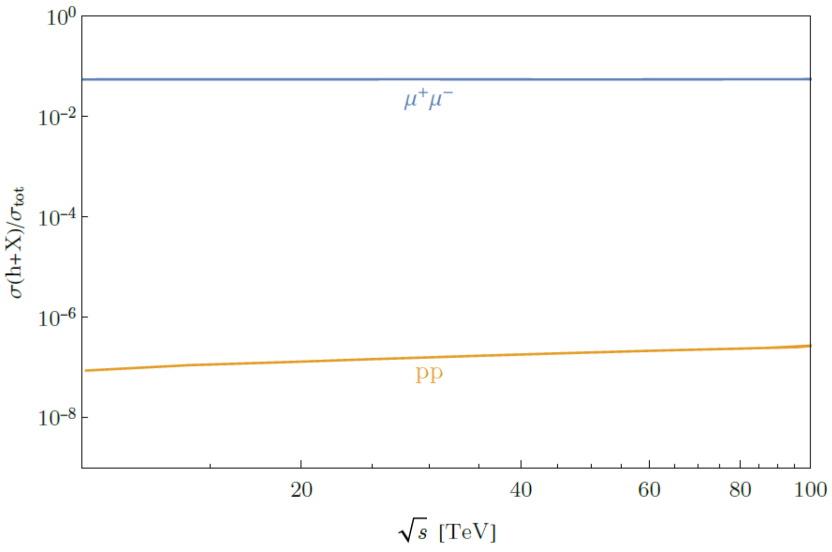


image ref: Symmetry Magazine

- Muon colliders can extend the precision frontier and the energy frontier in comparison to e^+e^- colliders and pp colliders.

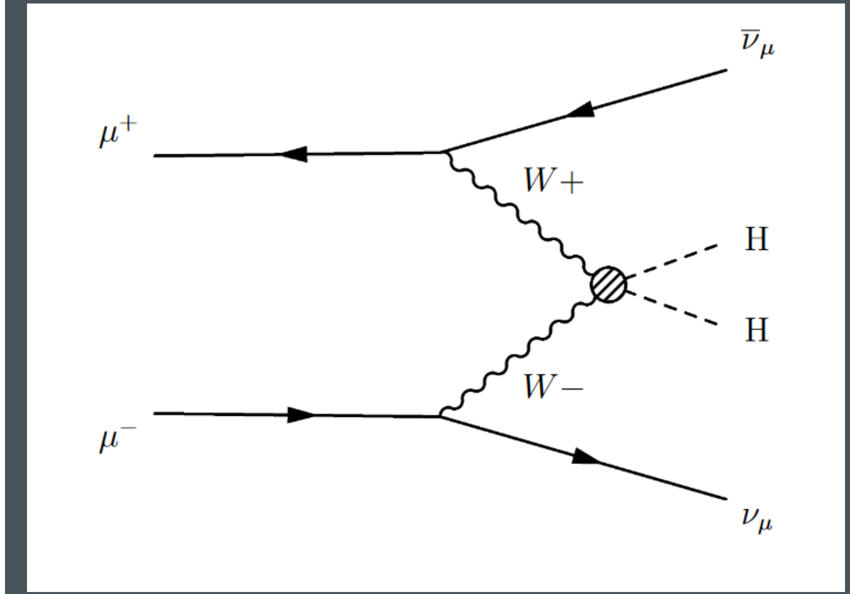
- An $\mathcal{O}(10)$ TeV muon collider with $\mathcal{O}(10/ab)$ luminosity could produce an order of magnitude more Higgs bosons compared to e^+e^- "Higgs factories". It will additionally produce $\mathcal{O}(10^4)$ di-Higgs events.

Higgs production as a fraction of "total" cross-section

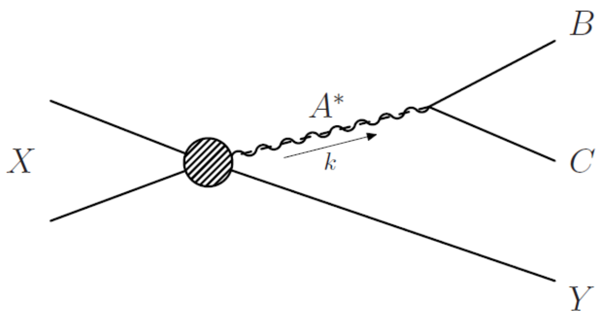


ref: The Muon Smasher's Guide

VECTOR-BOSON FUSION & COLLINEAR FACTORIZATION



- Vector boson fusion provides a dominant channel.
- We consider collinear factorization in final state splittings for High-energy electroweak processes.



- If the daughter particles B and C are approximately collinear to the offshell parent particle A*, we have

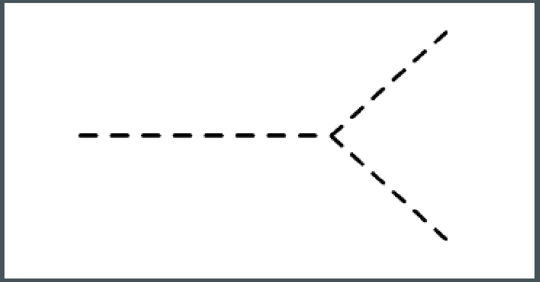
$$d\sigma_{Y,BC} \simeq d\sigma_{Y,A^*} \times dP_{A^* \to B+C}$$

- To compute the hard cross-section, we convolute the partonic cross-section with the W-boson PDFs.

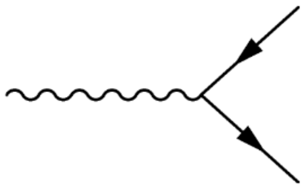
ref: T. Han et.al. arXiv:1611.00788v2
Cuomo et. al. arXiv:1911.12366v2

ref: T. Han et.al. arXiv:2007.14300v3

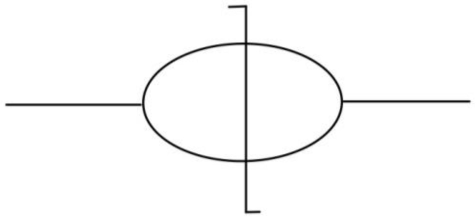
SUPER-RENORMALIZABLE SPLITTING



- All gauge and Yukawa splittings in the unbroken electroweak theory scale as dk_T^2/k_T^2, so typical splittings in the broken theory scale the same way.



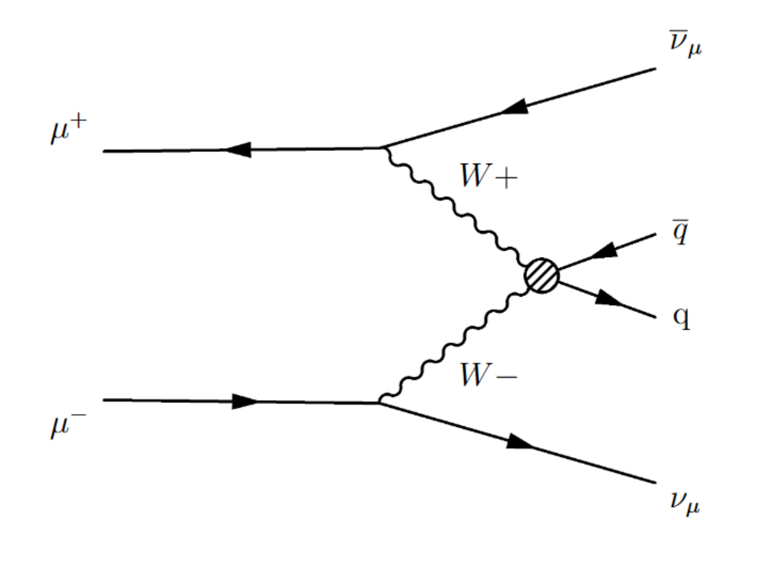
- After SSB, we also have 'super-renormalizable' splittings (or ultra-collinear) in the broken theory that scale as $m^2 dk_T^2/k_T^4$
- In particular, we look at $h \rightarrow hh$ splitting. We can calculate the jet function cross-section for the process with an offshell initial Higgs at an observed invariant jet mass m



$$\mathrm{J_H}(m^2) = \frac{\lambda^2 v^2}{16\pi} \frac{\sqrt{1-\frac{4m_h^2}{m^2}}}{\left(m^2-m_h^2\right)^2}$$

ref: T. Han et.al. arXiv:1611.00788v2

QCD BACKGROUND



PHENO '23

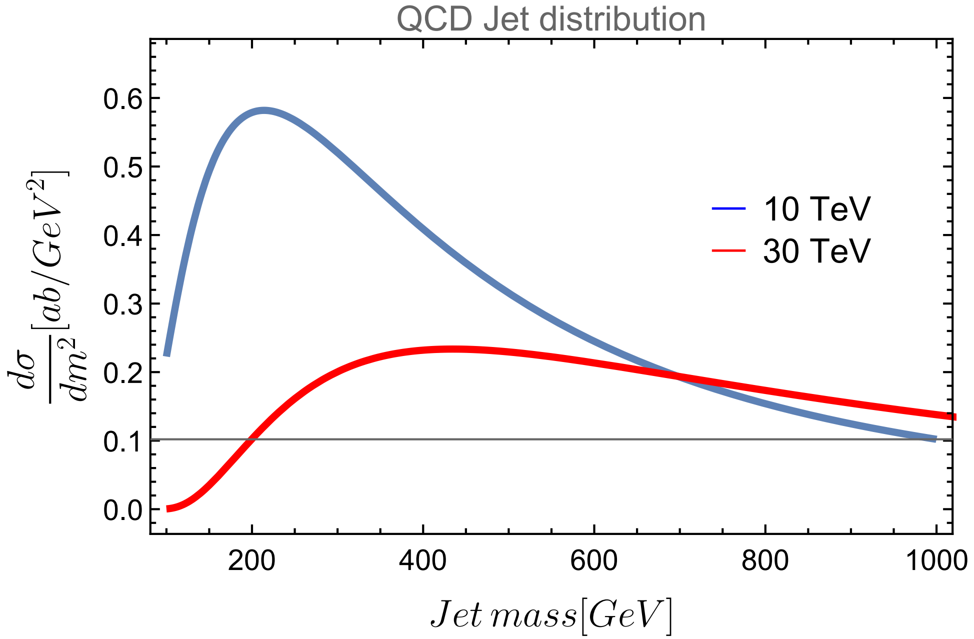
- The hard process that we study, at fixed jet mass m, for QCD backgrounds is

$$W^+W^- \to q\,\overline{q}$$

- The differential cross-section can be obtained by taking the inverse Laplace Transform of the NLL resummed cross-section

$$\frac{d\sigma}{dm^2} = \sigma_0 * \frac{d}{dm^2}\, R_{QCD}\left(\frac{m^2}{Q^2}, Q\right)$$

where, m^2 is the invariant mass squared of the final state jets.



ref: C. Berger, G. Sterman arXiv:hep-ph/0307394v2
S. Catani et.al Nuclear Physics B, Volume 407, Issue 1, 1993, Pages 3-42, ISSN 0550-3213

SUPER-RENORMALIZABLE HIGGS JET DISTRIBUTION

- Integrated cross-section for Higgs jets

$$R_H(m^2) = \frac{\int_{4m_h^2}^{m^2} J_H(m'^2)dm'^2}{\int_{4m_h^2}^{\infty} J_H(m'^2)dm'^2}$$

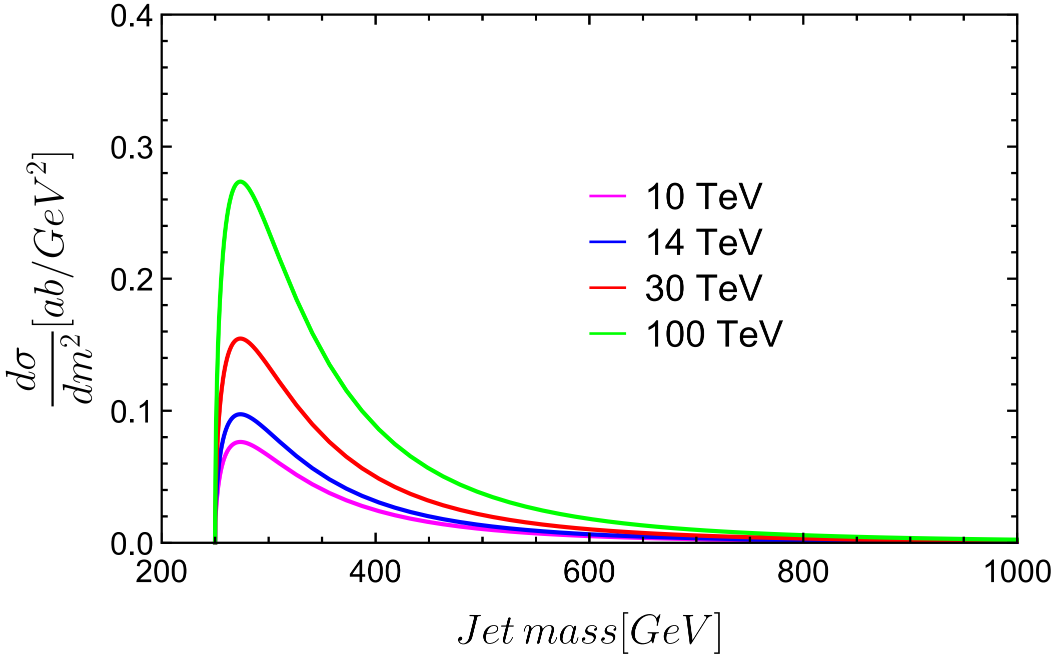
- The Higgs jet distribution is given by

$$\frac{1}{\sigma_{HH}}\frac{d\sigma}{dm^2} = \frac{d}{dm^2}R(m^2) = \frac{1}{\sigma_{tot}}J_H(m^2)$$

$$\frac{d\sigma}{dm^2} = \frac{\sigma_{HH}}{\sigma_{tot}}\,J_H(m^2)$$

- This is the lowest order in α_{EW}. What about higher-order corrections in R_H?

Jet distribution as a function of jet invariant mass

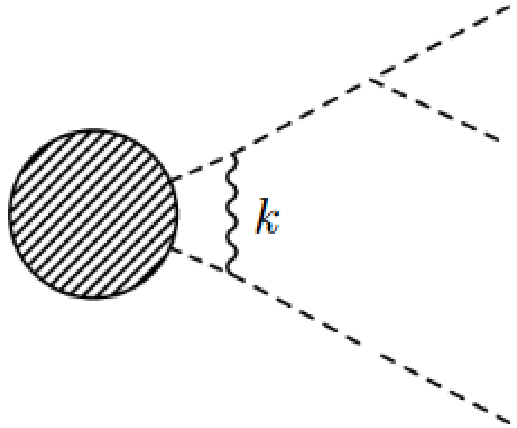


ELECTRO-WEAK CORRECTIONS

- Typical higher order Electroweak corrections that go as double log will look like ($\alpha_{EW} \simeq 0.033$)

$$C_{EW}^{(1)} = \frac{-2\alpha_{EW}}{\pi} \ln^2(Q^2/4m_H^2)$$

$$\simeq \quad -0.0866 * \ln^2(4 * Q[TeV])$$

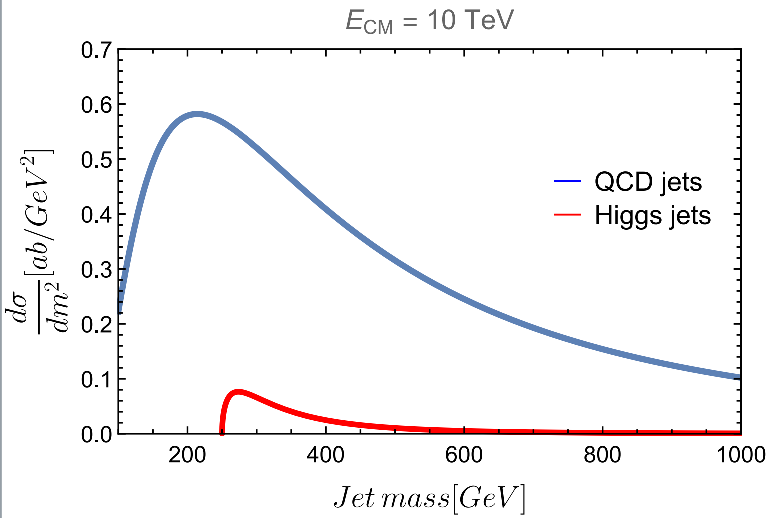


$$4m_H^2 \ll k_\perp^2 \ll Q^2$$

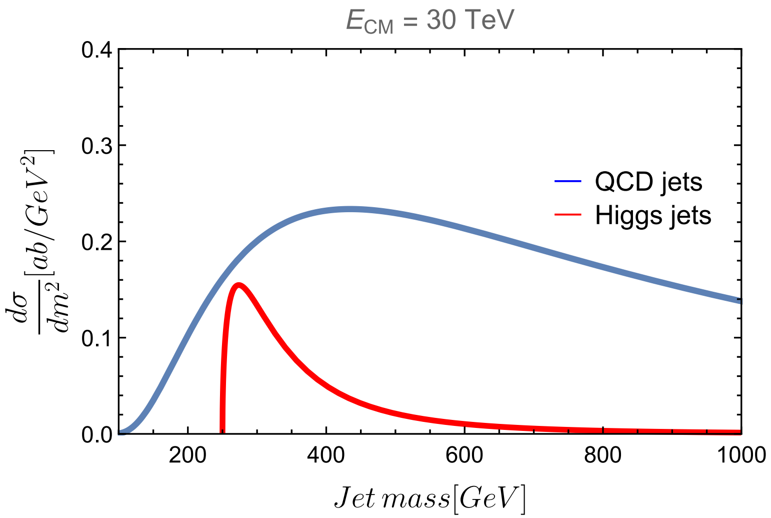
$C_{EW}^{(1)}(10\, TeV)$	$C_{EW}^{(1)}(30\, TeV)$	$C_{EW}^{(1)}(100\, TeV)$
-1.178	-1.984	-3.108

- While these corrections are not small, they can be resummed. This will be part of future work.

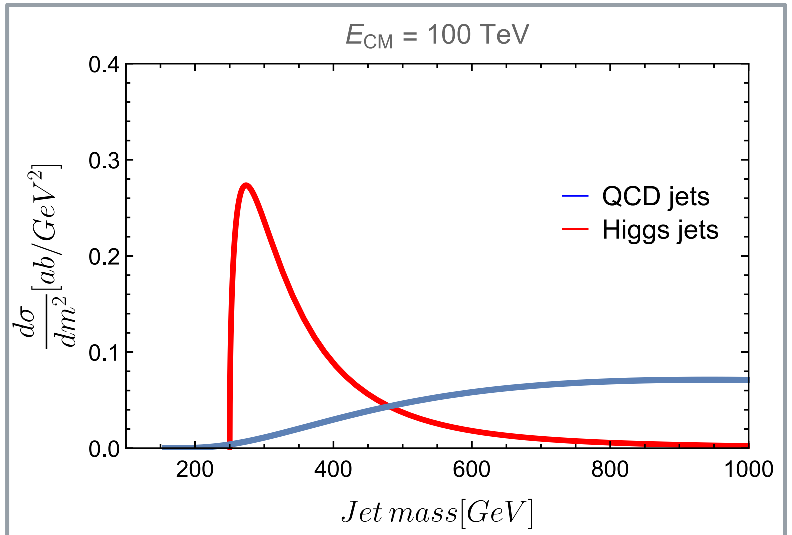
COMPARISON PLOTS



$$C_{EW}^{(1)}\,(10\;TeV) = -1.178$$



$$C_{EW}^{(1)}\,(30\;TeV) = -1.984$$



$$C_{EW}^{(1)}\,(100\;TeV) = -3.108$$

CONCLUSIONS

- We calculated the "Super-renormalizable" Higgs jet distribution at lowest order in the Jet function and the Hard cross section.

- We showed that at higher center of mass energies, the Higgs jet distribution shows a distinctive peak compared to QCD background jets.

- The higher order EW corrections, albeit not small, can be handled via resummation. They will give us Sudakov suppression but won't change the qualitative picture.

- Muon collider could provide an interesting opportunity to observe these jets with applications to test BSM physics.

WORKS CITED

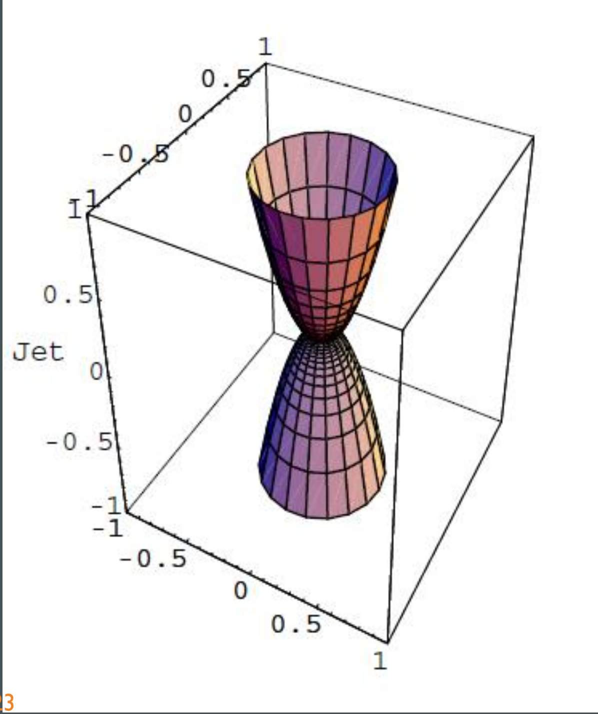
- Carola F. Berger and George Sterman JHEP09(2003)058, "Scaling rule for nonperturbative radiation in a class of event shapes"
- Tao Han, Yang Ma, and Keping Xie Phys. Rev. D 103, L031301, "High energy leptonic collisions and electroweak parton distribution functions"
- Chen, J., Han, T. & Tweedie, B. Electroweak splitting functions and high energy showering. *J. High Energ. Phys.* **2017**, 93 (2017). https://doi.org/10.1007/JHEP11(2017)093
- S. Catani, L. Trentadue, G. Turnock, B.R. Webber, "Resummation of large logarithms in e+e− event shape distributions", Nuclear Physics B, 1993, ISSN 0550-3213,
- https://arxiv.org/abs/2103.14043, "The Muon Smasher's Guide"
- G. Cuomo, L. Vecchi, A. Wulzer, Goldstone equivalence and high energy electroweak physics, SciPost Phys. 8 (5) (2020) 078, http://dx.doi.org/10.21468/SciPostPhys.8.5.078, arXiv:1911.12366

THANK YOU FOR LISTENING

Any Questions or Comments?

BACKUP SLIDES

QCD BACKGROUND



ALTERNATE

- For a fixed jet mass, m, we consider a well-known infrared safe event shape variable, Thrust.

$$1 - \frac{\mathrm{m}^2}{\mathrm{Q}^2} \simeq 1 - \tau \equiv T(N) = \max_{\hat{n}} \frac{\sum_i |\vec{p_i} . \hat{n}|}{\sum_j |\vec{p_j}|}$$

- The differential cross-section for such di-jet events at fixed values of τ is given by

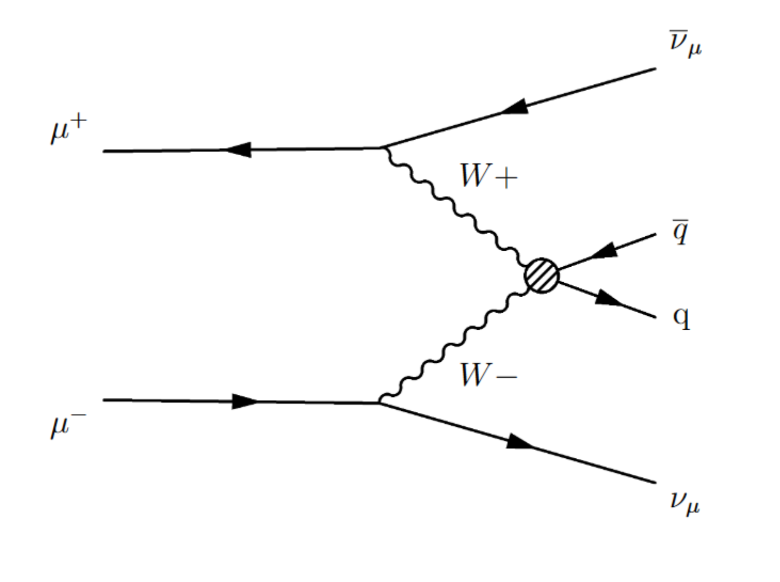
$$\frac{d\sigma(\tau, Q)}{d\tau} = \frac{1}{2Q^2} \sum_N |M(N)|^2 \, \delta(\tau - \tau(N))$$

- We work with the integrated cross-section or Radiator calculated for the e^+e^- annihilation

$$R(\tau, Q) = \frac{1}{\sigma_{tot}} \int_0^{\tau} d\tau' \, \frac{d\sigma(\tau', Q)}{d\tau'}$$

ref: https://arxiv.org/abs/hep-ph/0307394v2
ref: S. Catani et.al Nuclear Physics B, Volume 407, Issue 1, 1993, Pages 3-42, ISSN 0550-3213

QCD BACKGROUND

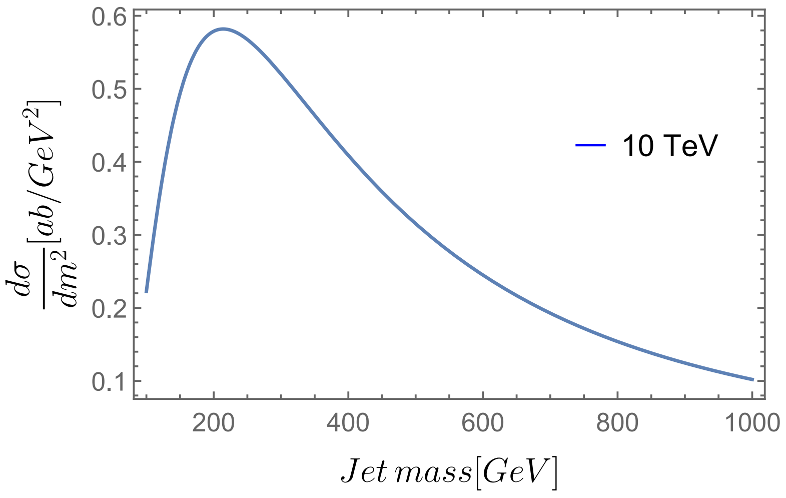


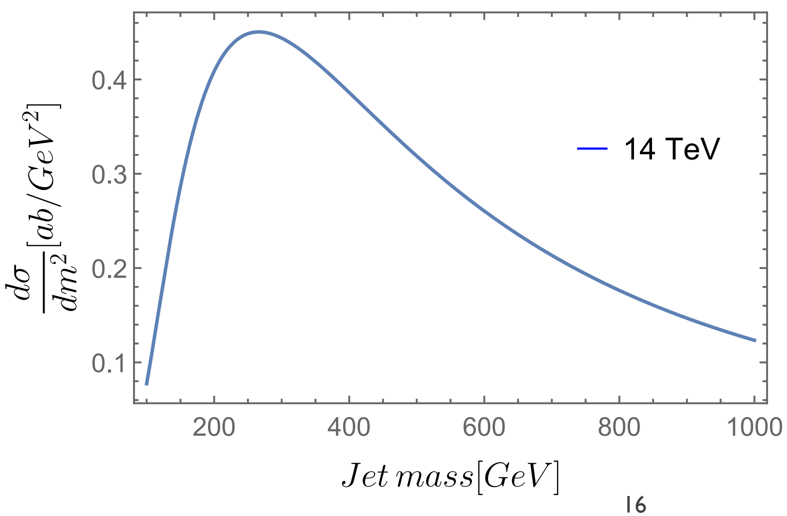
- The differential cross-section can be obtained by taking the inverse Laplace Transform of the NLL resummed exponent to get the Radiator.

$$\frac{1}{\sigma_{tot}} \frac{d\sigma(\tau, Q)}{d\tau} = \frac{1}{\tau} \frac{d}{d\ \ln\tau} R(\tau, Q)$$

- Using $\tau = m^2/Q^2$, we calculate $d\sigma/dm^2$
- The hard process that we study, at fixed jet mass m, for QCD backgrounds is

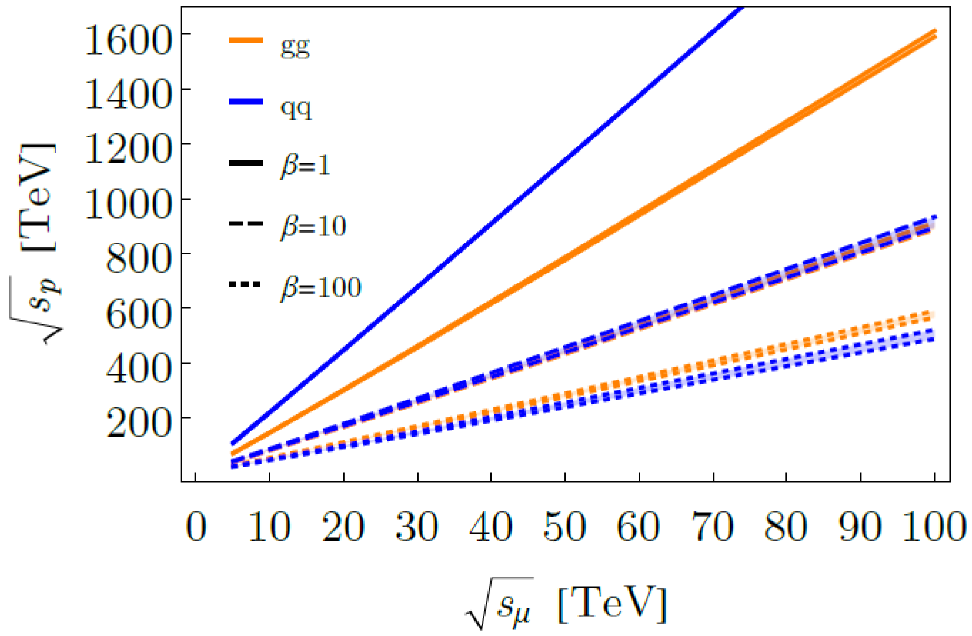
$$W^+W^- \rightarrow q\ \bar{q}$$



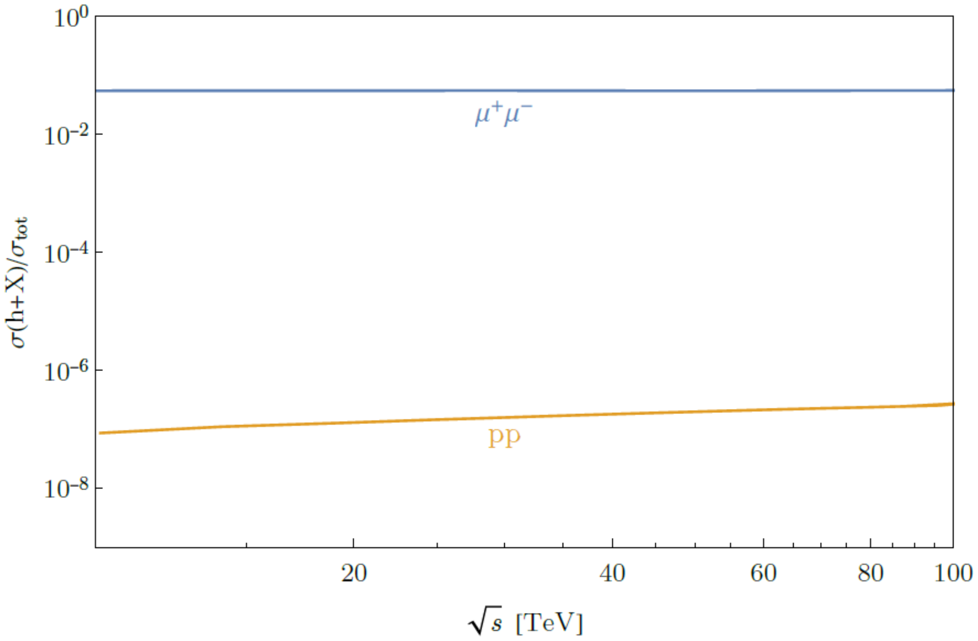


ref: https://arxiv.org/abs/hep-ph/0307394v2
ref: S. Catani et.al Nuclear Physics B, Volume 407, Issue 1, 1993, Pages 3-42, ISSN 0550-3213

MUON COLLIDER



Equivalent cross-section at pp collider v/s muon collider



Higgs production as a fraction of "total" cross-section

image ref: The Muon Smasher's Guide

DI-JET CROSS SECTION

$$e^+ + e^- \rightarrow J_1(N) + J_2(N)$$

- The differential cross section for such di-jet events at fixed values of τ_a is given by

$$\frac{d\sigma(\tau_a, Q)}{d\tau_a} = \frac{1}{2Q^2} \sum_N |M(N)|^2 \, \delta(\tau_a - \tau_a(N))$$

- For di-jet cross sections, we look at $\tau_a \ll 1$, and we take the laplace transform of the cross-section

$$\tilde{\sigma}(\nu, Q, a) = \int_0^1 d\tau_a e^{-\nu\tau_a} \frac{d\sigma(\tau_a, Q)}{d\tau_a}$$

- Large logarithms of ν need to be resummed.

RESUMMED CROSS-SECTION AT NLL

- The Next-to-leading-log (NLL) resummed cross-section for $a < 1$ in moment space, can be written as

$$\frac{1}{\sigma_{tot}}\tilde{\sigma}(\nu, Q, a) = \exp\{2\int_0^1 \frac{du}{u}[\int_{u^2Q^2}^{uQ^2} \frac{dp_T^2}{p_T^2} A\big(\alpha_s(p_T)\big)\big(e^{-u^{1-a}\nu(p_T/Q)^a} - 1\big) + \frac{1}{2}B(\alpha_s(Q\sqrt{u}))(e^{-u(\nu/2)^{\frac{2}{2-a}}} - 1)]\}$$
$$\equiv [\mathcal{J}(\nu, Q, a)]^2$$

RESUMMED CROSS-SECTION AT NLL

- The resummation is in terms of anomalous dimensions $A(\alpha_s)$ and $B(\alpha_s)$ which have finite expressions in the running coupling,

$$A(\alpha_s) = \sum_{n=1}^{\infty} A^{(n)} \left(\frac{\alpha_s}{\pi}\right)^n$$

- The coefficients of the perturbative expansion are well known at NLL,

$$A^{(1)} = C_F, \qquad B^{(1)} = -\frac{3}{2} C_F$$

$$A^{(2)} = \frac{1}{2} C_F [C_A \left(\frac{67}{18} - \frac{\pi^2}{6}\right) - \frac{10}{9} T_F N_f]$$

RADIATOR

- We work with integrated cross-section or the Radiator

$$R(\tau_a, Q) = \frac{1}{\sigma_{tot}} \int_0^{\tau_a} d\tau_a' \, \frac{d\sigma(\tau_a', Q)}{d\tau_a'}$$

- The Radiator can be directly calculated from the jet function $\mathcal{J}(\nu, Q, a)$ in transform space by

$$R(\tau_a, Q) = \frac{1}{2\pi i} \int_C \frac{d\nu}{\nu} e^{\nu \tau_a} \left[\mathcal{J}(\nu, Q, a)\right]^2$$

$$R(\tau_a, Q) = \frac{\exp\left\{2 \ln\left(\frac{1}{\tau_a}\right) g_1(x, a) + 2 g_2(x, a) + 2(2 - a) x^2 \ln\left(\frac{2\mu}{Q}\right) g_1'(x, a)\right\}}{\Gamma[1 - 2 g_1(x, a) - 2 x g_1'(x, a)]}$$

RADIATOR

$$g_1(x,a) = -\frac{4}{\beta_0}\frac{1}{1-a}\frac{1}{x}\,A^{(1)}\left[\left(\frac{1}{2-a}-x\right)\ln(1-(2-a)x)-(1-x)\ln(1-x)\right]$$

$$g_2(x,a) = \frac{2}{\beta_0}B^{(1)}\ln(1-x) \quad -\frac{8}{\beta_0^2}\frac{1}{1-a}A^{(1)}[\ln(1-x)-\ln(1-(2-a)x)]$$

$$+\frac{4}{\beta_0}\ln 2\,\frac{1}{1-a}\,A^{(1)}\left[\left(\frac{1}{2-a}-x\right)\ln(1-(2-a)x)-(1-x)\ln(1-x)\right]$$

$$-\frac{\beta_1}{\beta_0^3}\frac{1}{1-a}A^{(1)}[2\ln(1-(2-a)x)-2(2-a)\ln(1-x)$$

$$+\ln^2(1-(2-a)x)\; -(2-a)\ln^2(1-x)]$$

where,

$$x = \frac{\alpha_s(\mu)}{\pi}\,\frac{\beta_0}{2(2-a)}\ln(1/\tau_a)$$

COMPARISON PLOTS