Jet Veto at Hadron Colliders

In collaboration with Chong Sheng Li and Hai Tao Li

JHEP07(2013)169;   arXiv:1406.XXXX

Speaker: Ding Yu Shao

2014/05/16, The 9th Workshop of TeV Physics, Sun Yat-sen University

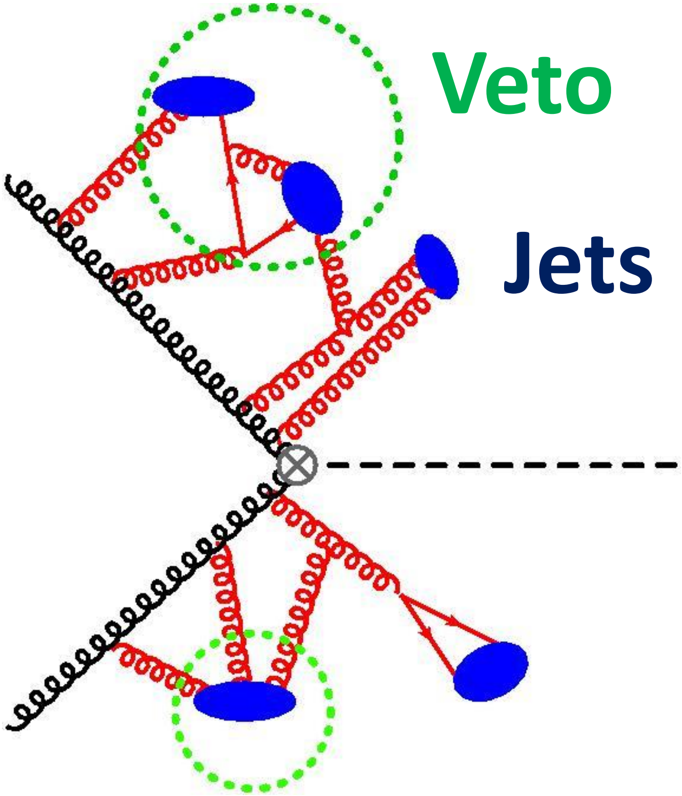
What is Jet Veto?

eg. $pp \to H$ @LHC

$$P_{T,i}^{Jet} < P_T^{Veto}$$

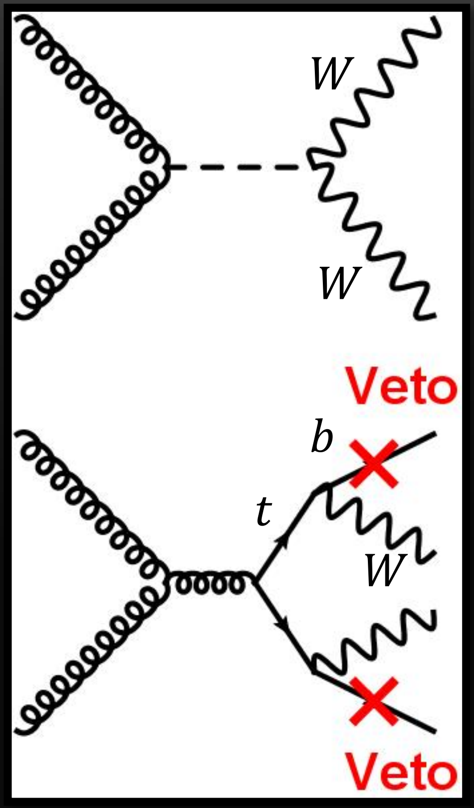
$$i = 1, \dots, n$$

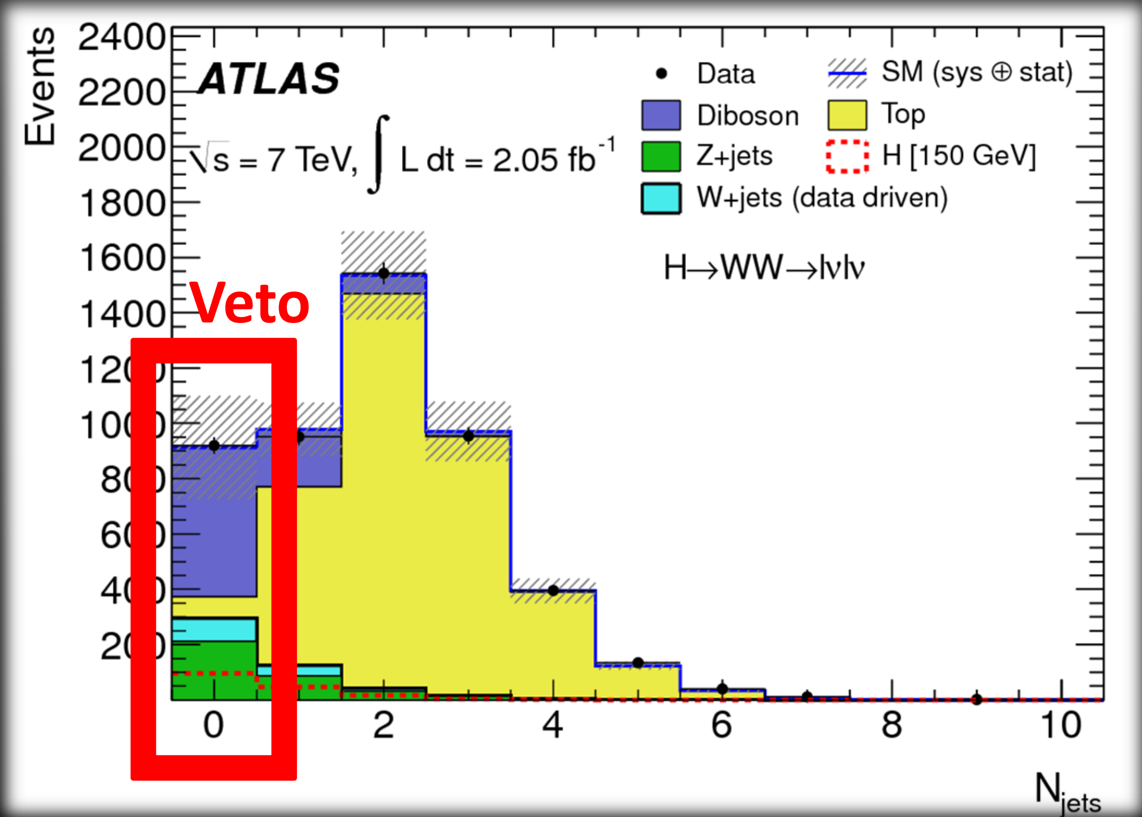
$$P_T^{Veto} \sim 20 - 30\ GeV$$



Why Jet Veto?

In order to suppress the SM background (e.g. $t\,\bar{t}$ process) which can produce more energetic jets, the jet veto is always applied by experimentalists.





How to calculate $\sigma(p_T^{veto})$?

Due to the existence of a small scale p_T^{veto}, perturbative convergence is poor, and the fixed order predictions are unreliable.

Thus, the QCD resummation is necessary and the large logarithmic terms $\alpha_s^n \log^m(p_T^{veto}/Q)$ should be resummed to all order.

Resummation for Jet Veto

Perturbative QCD
Soft-Collinear Effective Theory

- Veto on other kinematic variables (Stewart, *et.al*.,2010, …)
  - beam thrust, N–jettiness…
- NLL efficiency by CAESAR : (Salam,*et.al*.,1203)
  - $\epsilon(p_T^{veto}) = \frac{\sigma(p_T^{veto})}{\sigma_{tot}}$, Full Numerically
- NNLL “collinear anomaly” (Becher, Neubert,1205)
- Updated NNLL efficiency (Salam,*et.al*.,1206)
- NNNLL’ “collinear anomaly” (Becher, Neubert, *et.al*.,1307)
- NNNLL’ “rapidity renormalization group” (Stewart, *et.al*.,1308)

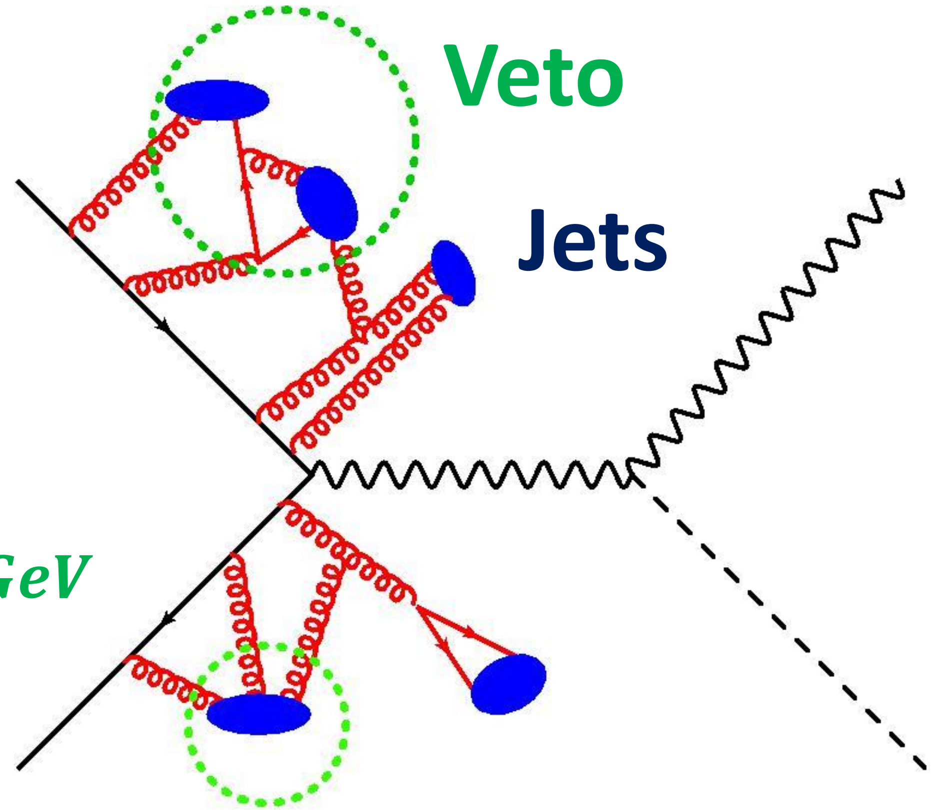
Resummation Prediction on Higgs and Vector Boson Associated Production with a Jet Veto “$HV + 0j$” at the LHC

JHEP 1402 (2014) 117 DYS, Chong Sheng Li and Hai Tao Li

$$P_{T,i}^{Jet} < P_T^{Veto}$$

$$i = 1, \dots, n$$

$$P_T^{Veto} \sim 20 - 30\ GeV$$



Scale in $HV + 0j$ (SCET)

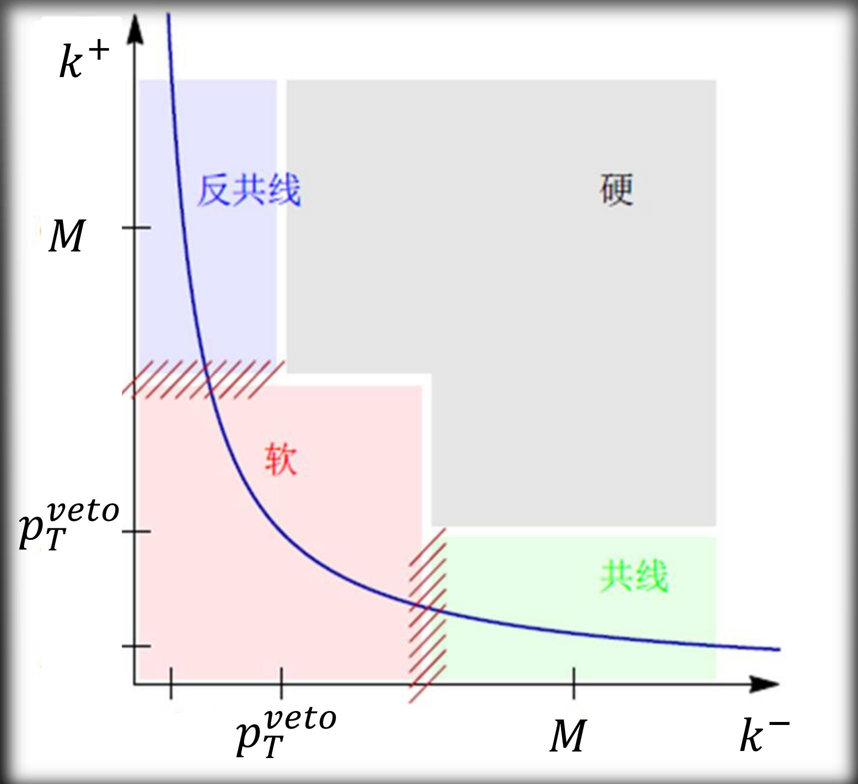
$$k^\mu = k^+ \frac{\bar{n}^\mu}{2} + k^- \frac{n^\mu}{2} + k_\perp^\mu$$

Expanding parameter:

$\lambda \sim p_T^{veto}/M$

M: Invariant Mass of HV

Momentum modes	$(k^+, k^-, k_\perp)$	Virtuality
Hard	$(1,1,1)M$	M
Collinear	$(1, \lambda^2, \lambda)M$	$\lambda M \sim p_T^{veto}$
Anti-Collinear	$(\lambda^2, 1, \lambda)M$	$\lambda M \sim p_T^{veto}$
Soft	$(\lambda, \lambda, \lambda)M$	$\lambda M \sim p_T^{veto}$



$$k^2 = k^+ k^- + k_\perp^2$$

Rapidity Divergence

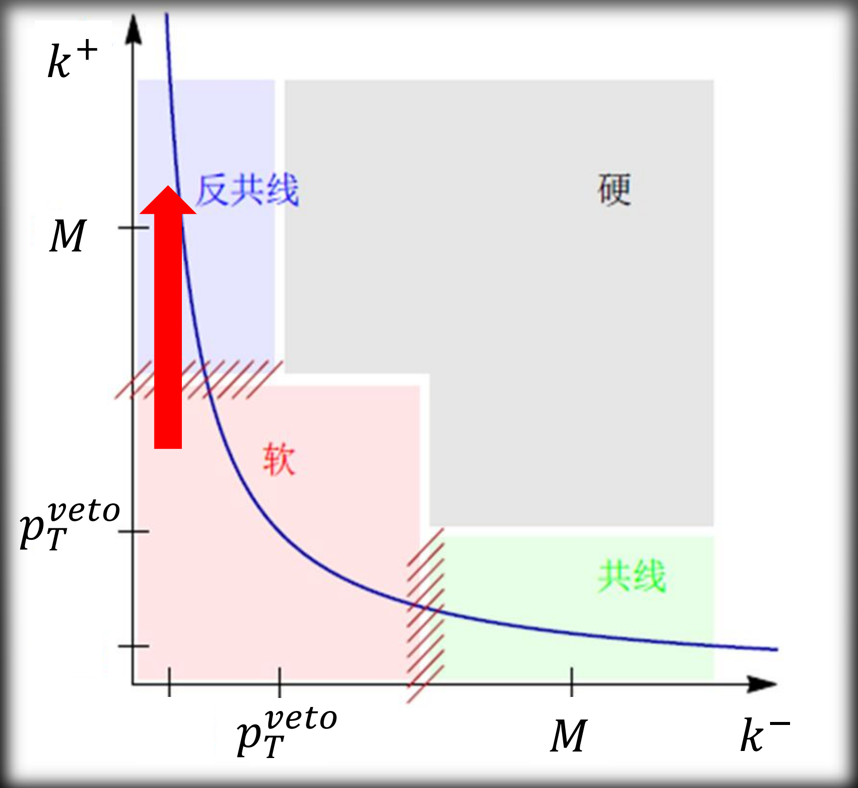
$$I = \int_{p_T^{veto}}^{M} \frac{dk^+}{k^+}$$

Sector Decomposition

$$I = \int_{p_T^{veto}}^{\Lambda} \frac{dk^+}{k^+} + \int_{\Lambda}^{M} \frac{dk^+}{k^+}$$

Effective Theory

$$I = \int_{p_T^{veto}}^{\infty} \frac{dk^+}{k^+} + \int_{0}^{M} \frac{dk^+}{k^+}$$



Regularization of the Rapidity Divergences

- Go off the light cone $n^2 \neq 0$; Collins and Soper 1981, Collins 1989
- Analytic regulator; Smirnov 1990
- "delta" regulator; Chiu *et.al.* 2009
- Rapidity Renormalization Group; *Chiu et.al. 2012*
- Collinear Anomaly; Becher *et.al. 2012*

Regularization of the Rapidity Divergences

Collinear Anomaly

- Phase Space integration
  - $\int d^D k \ \rightarrow \int d^D k \ \left(\frac{\nu}{k^+}\right)^\alpha$
  - New divergences as $\frac{1}{\alpha}$

Rapidity Renormalization Group

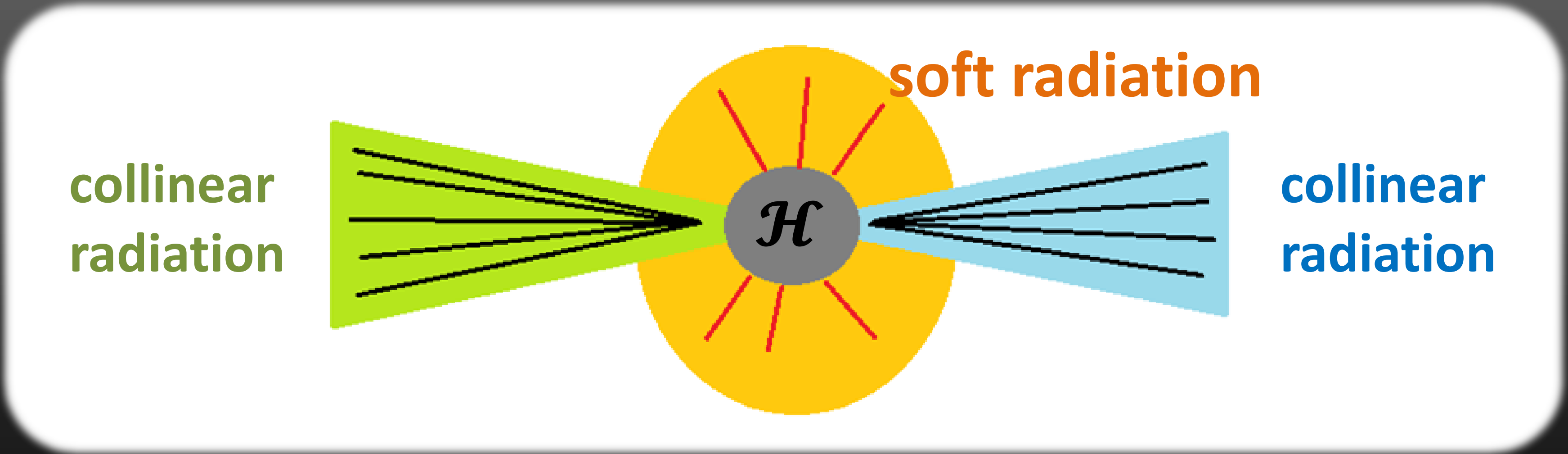
- Lagrangian
  - Modify the definition of Wilson Line

$$W_n = \sum_{perms} \exp\left[\frac{g_s \omega^2}{\bar{n}\cdot\mathcal{P}} \frac{\left|\bar{n}\cdot\mathcal{P}_g\right|^{-\eta}}{\nu^{-\eta}} \bar{n}\cdot A_n\right]$$

$$S_n = \sum_{perms} \exp\left[\frac{g_s \omega}{n\cdot\mathcal{P}} \frac{\left|2\mathcal{P}_{g,3}\right|^{-\eta/2}}{\nu^{-\eta/2}} \bar{n}\cdot A_s\right]$$

  - New divergences as $\frac{1}{\eta}$
  - New RGE about scale ν

Factorization in SCET

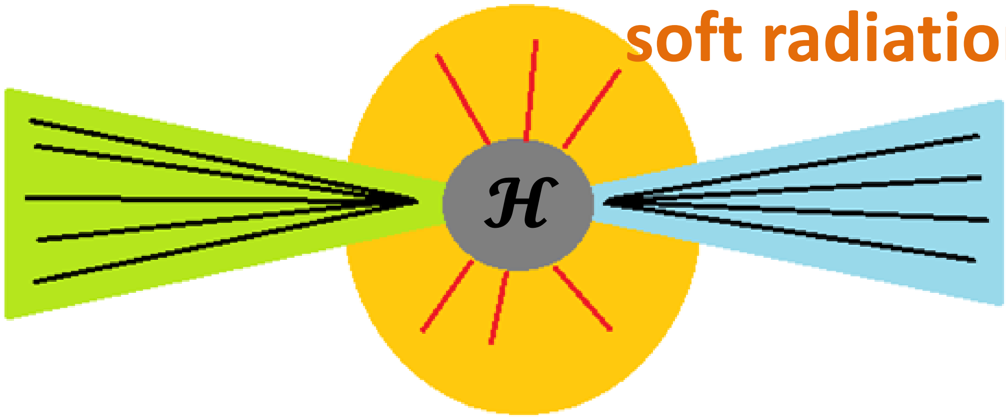


- Work in sequential jet algorithms

$$d_{ij} = \min(p_{T,i}^{n}, p_{T,j}^{n}) \frac{\sqrt{\Delta y^2 + \Delta\phi^2}}{R}, \qquad d_{iB} = p_{T,i}^{n}$$

- Cluster soft and collinear radiation separately as long as $R < \ln M / p_T^{veto} \sim 2$

Factorization in SCET

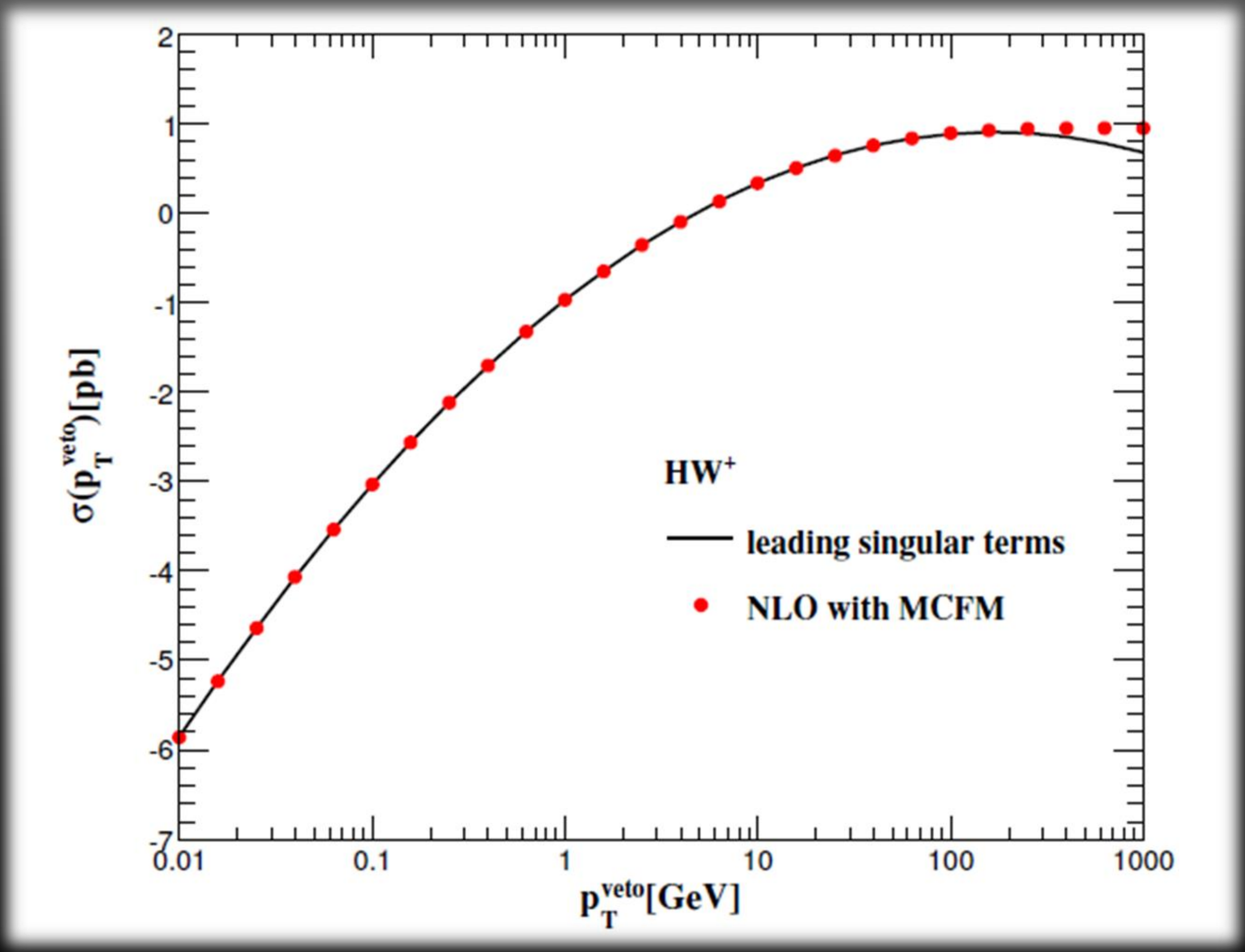


$$\frac{d\sigma(p_T^{veto})}{dM^2dY} = \frac{\sigma_0}{s}\mathcal{H}(M^2,\mu^2)\mathcal{B}^{n}{}_{q\leftarrow N_1}(\zeta_1, p_T^{veto},\mu)\,\mathcal{B}^{\bar{n}}{}_{\bar{q}\leftarrow N_2}(\zeta_2, p_T^{veto},\mu)\mathcal{S}(p_T^{veto},\mu)$$

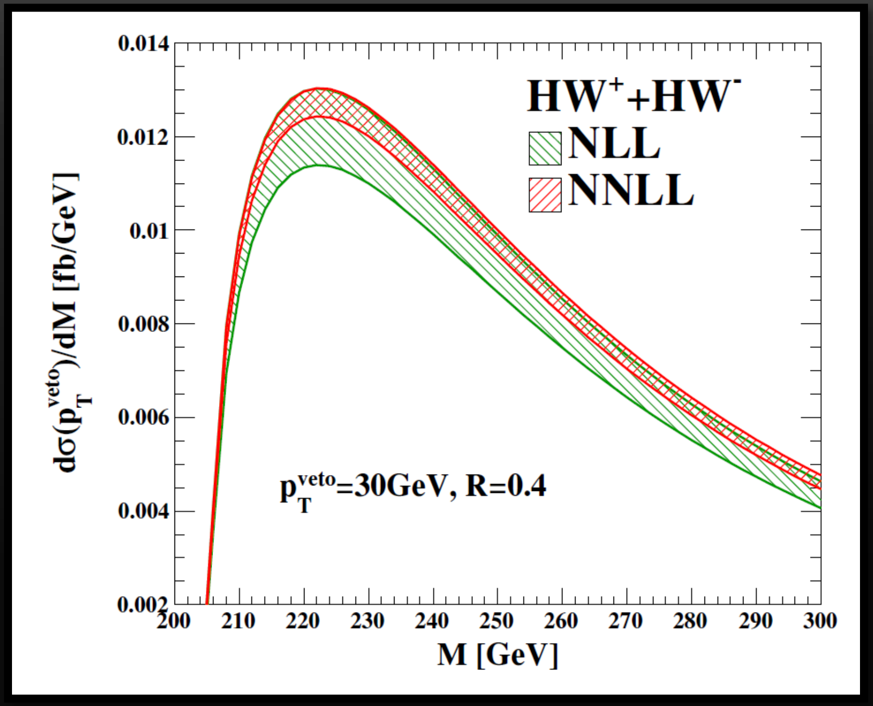
$$\mathcal{B}^n_{q/N}(z, p_T^{\rm veto},\mu) = \int \frac{dt}{2\pi} e^{-izt\bar{n}\cdot p} \sum_{X_n,{\rm reg}} \mathcal{M}_{\rm veto}(p_T^{\rm veto}, R, \{\underline{p_n}\}) \times \langle N(p)|\bar{\chi}_n(t\bar{n})|X_n\rangle\langle X_n|\chi_n(0)|N(p)\rangle$$

Jet Algorithms

Leading Singular terms

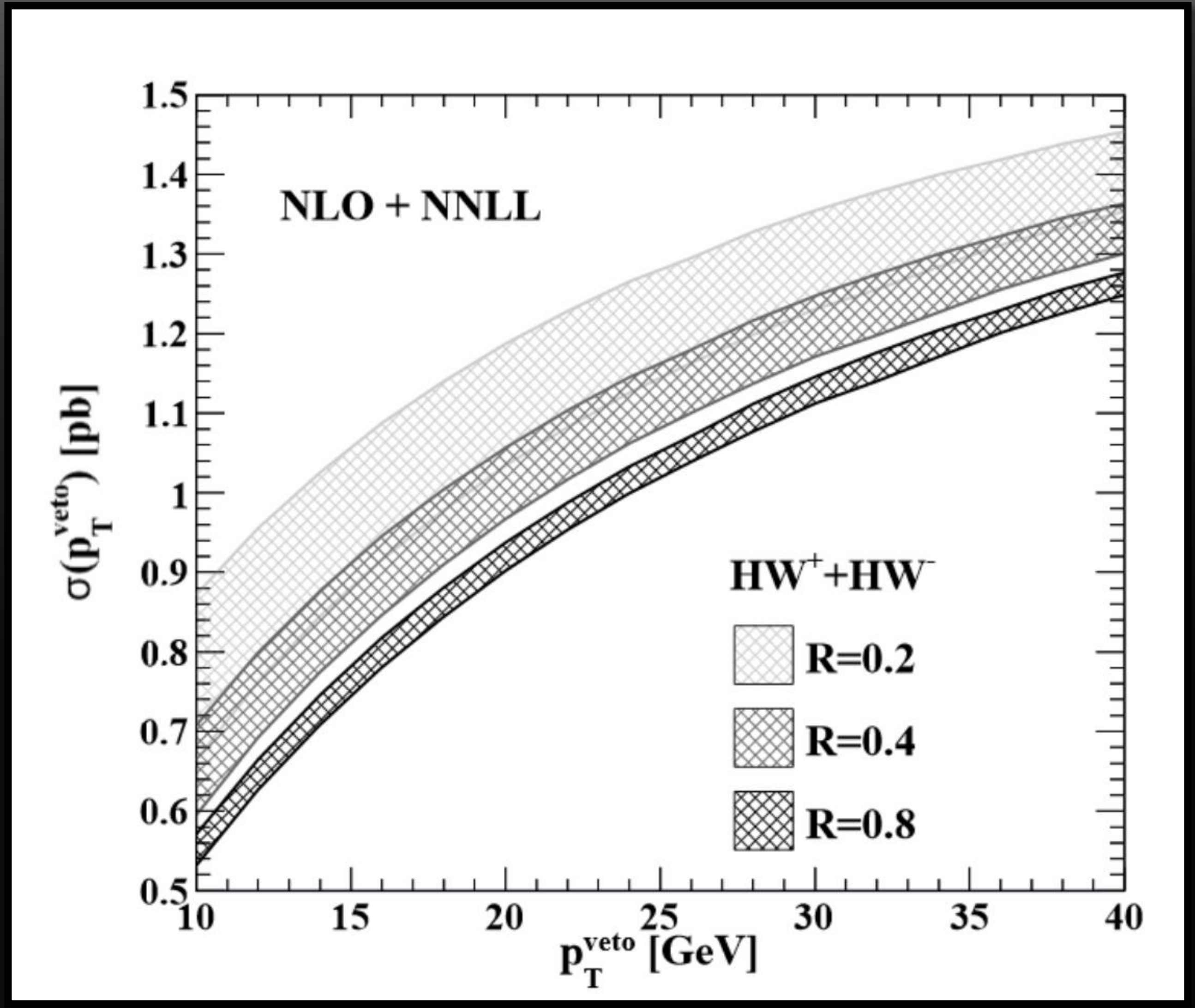


Resummation Predictions

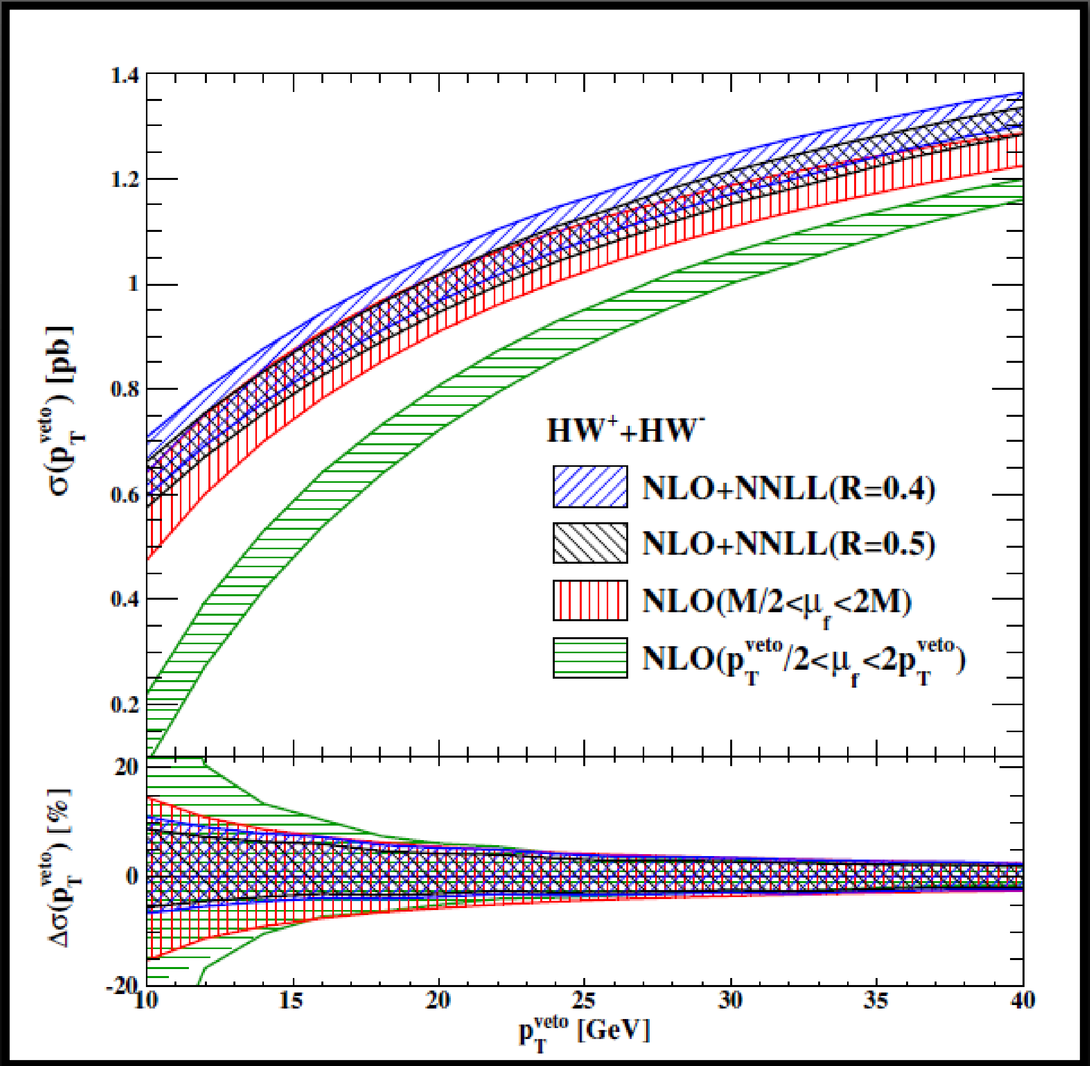


- Scale reduce from NLL to NNLL !
- Perturbative convergence are well behaved in all the invariant mass region!

jet vetoed cross section



NLO+NNLL v.s. NLO

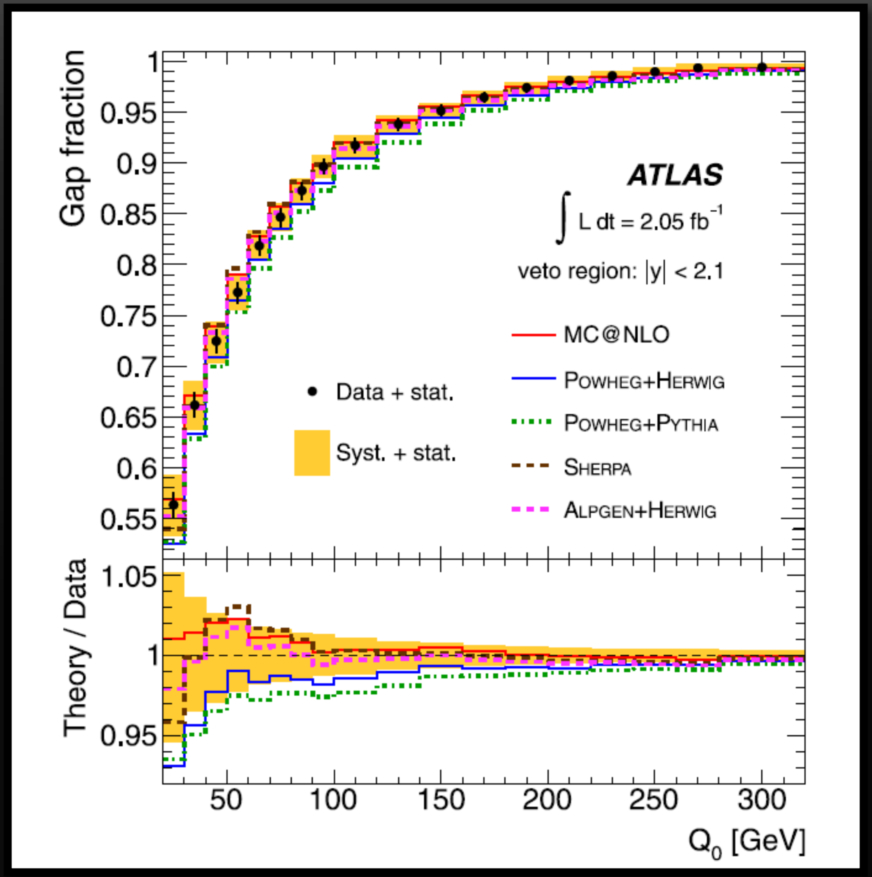


Factorization and NLO+NNLL predictions on the $t\bar{t}+0j$ process at hadron colliders

arXiv:1406.XXXX, DYS, Chong Sheng Li and Hai Tao Li

Why $t\bar{t} + 0j$?

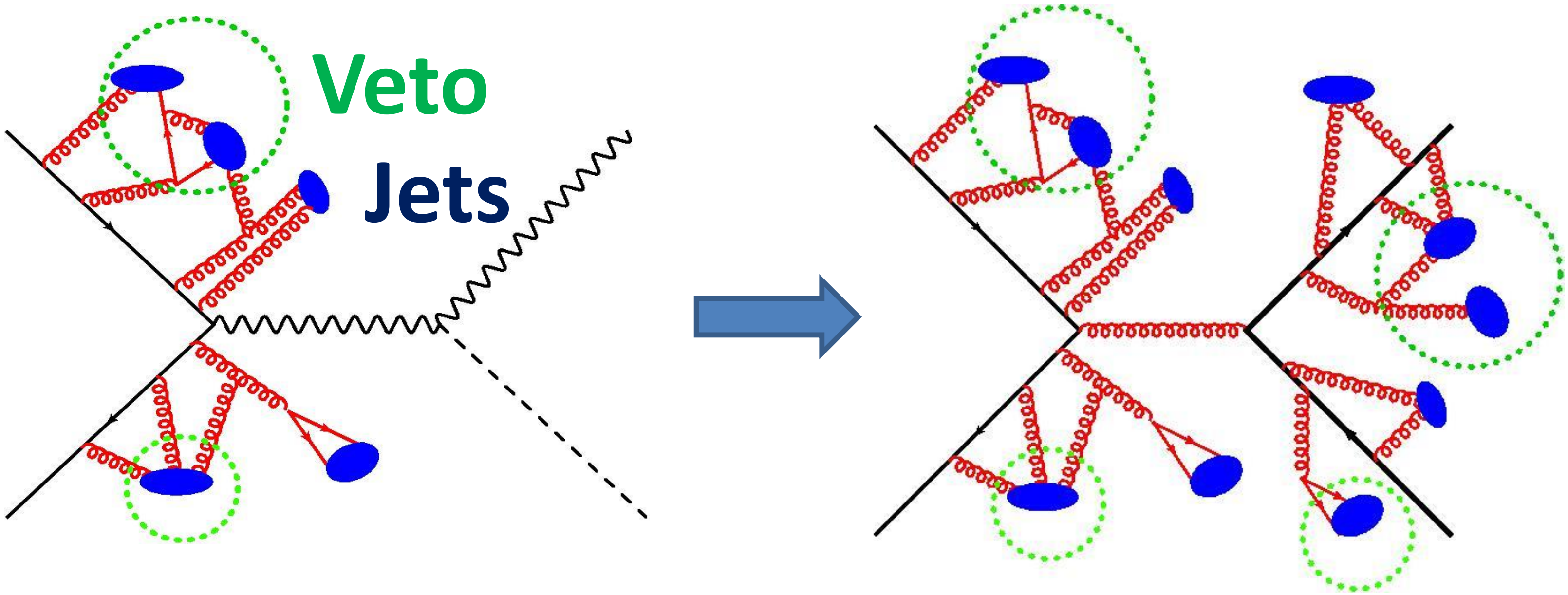
$\sigma(t\bar{t} + 0j)/\sigma(t\bar{t}X)$



Eur. Phys. J. C72 (2012) 2043]

- Test pQCD at top quark scale
- Constrain modeling uncertainties in Monte Carlo generator
- Enhance New Physics signals
  - Sung, Phys. Rev. D **80**, 094020 (2009).
  - S. Ask et al., JHEP,**1201**, 018 (2012).
  - …

Difference with $HV + 0j$ process



Factorization for $t\bar{t} + 0j$ at hadron colliders

$$N_1\, N_2 \to t\, \bar{t}\, X$$

$$d\sigma = \frac{1}{2s}\frac{d^3\vec{p}_3}{(2\pi)^3 2E_3}\frac{d^3\vec{p}_4}{(2\pi)^3 2E_4}\sum_X{}' \int d^4x \langle \mathcal{M}(x)|\mathcal{M}(0)\rangle$$

$$|\mathcal{M}(x)\rangle = \langle t\, \bar{t}\, X|\mathcal{H}_{eff}(x)|\, N_1 N_2\rangle$$

Factorization in SCET+HQET

$$\sum_X{}' \langle \mathcal{M}(x)|\mathcal{M}(0)\rangle = \sum_{mm'} \int dt_1 dt_2 dt_1' dt_2' e^{-i(p_3+p_4)\cdot x} \langle 0| \left[\mathcal{O}'^h_m(0)\right]^{\rho\sigma} |t\bar{t}\rangle\langle t\bar{t}| \left[\mathcal{O}^h_m(0)\right]^{\mu\nu} |0\rangle$$

Hard

$$\times \sum\!\!\!\!\!\!\!\int_{X_n,\mathrm{reg}} \mathcal{M}_{\mathrm{veto}}(p_T^{\mathrm{veto}}, R, \{\underline{p_n}\}) \langle N_1|\mathcal{A}_{n\rho\perp}(x^+ + x_\perp + t_1'\bar{n})|X_c\rangle\langle X_c|\mathcal{A}_{n\mu\perp}(t_1\bar{n})|N_1\rangle$$

Collinear

$$\times \sum\!\!\!\!\!\!\!\int_{X_{\bar{n}},\mathrm{reg}} \mathcal{M}_{\mathrm{veto}}(p_T^{\mathrm{veto}}, R, \{\underline{p_{\bar{n}}}\}) \langle N_2|\mathcal{A}_{\bar{n}\sigma\perp}(x^+ + x_\perp + t_2'\bar{n})|X_{\bar{c}}\rangle\langle X_{\bar{c}}|\mathcal{A}_{n\nu\perp}(t_2\bar{n})|N_2\rangle$$

Anti-Collinear

$$\times \sum\!\!\!\!\!\!\!\int_{X_s,\mathrm{reg}} \mathcal{M}_{\mathrm{veto}}(p_T^{\mathrm{veto}}, R, \{\underline{p_s}\}) \left\langle \widetilde{C}'_m(t_1',t_2')\right| \langle 0|\mathcal{O}^{s\dagger}(x_\perp)|X_s\rangle\langle X_s|\mathcal{O}^s(0)|0\rangle \left|\widetilde{C}_m(t_1,t_2)\right\rangle$$

Soft

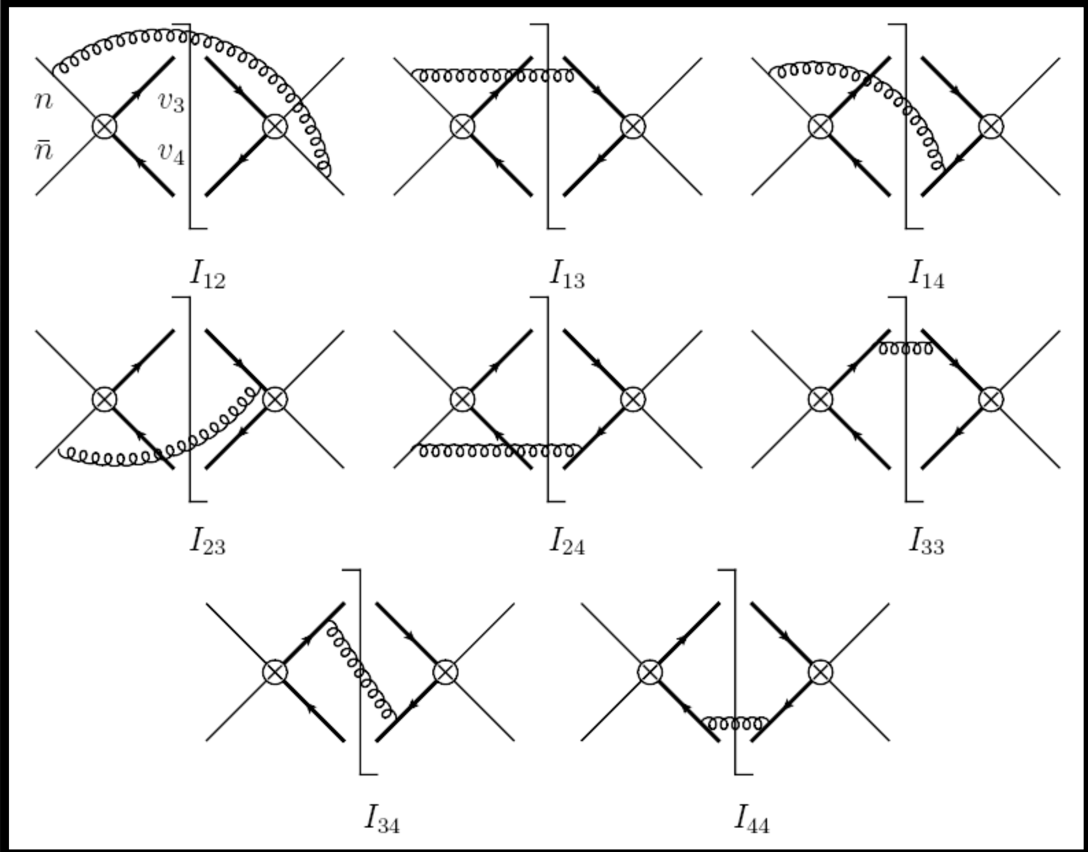
$$d\sigma \sim Tr[\overline{H}\ \bar{S}]\ \overline{I I} \otimes \overline{f f}$$

Soft Function in HQET

In HQET top quark fields are labeled by their velocity:

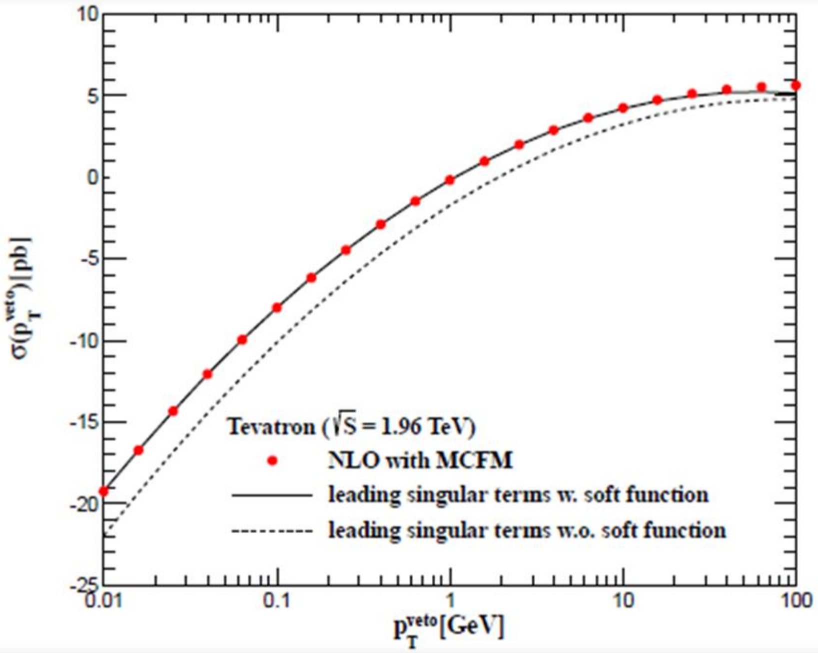
$p \sim m_t \, v + k,$

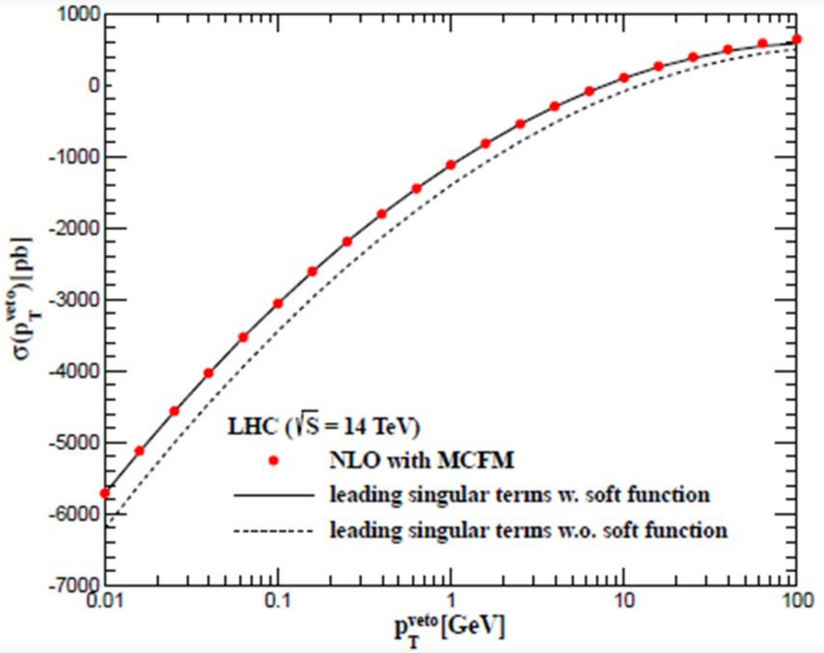
k is the soft mode.



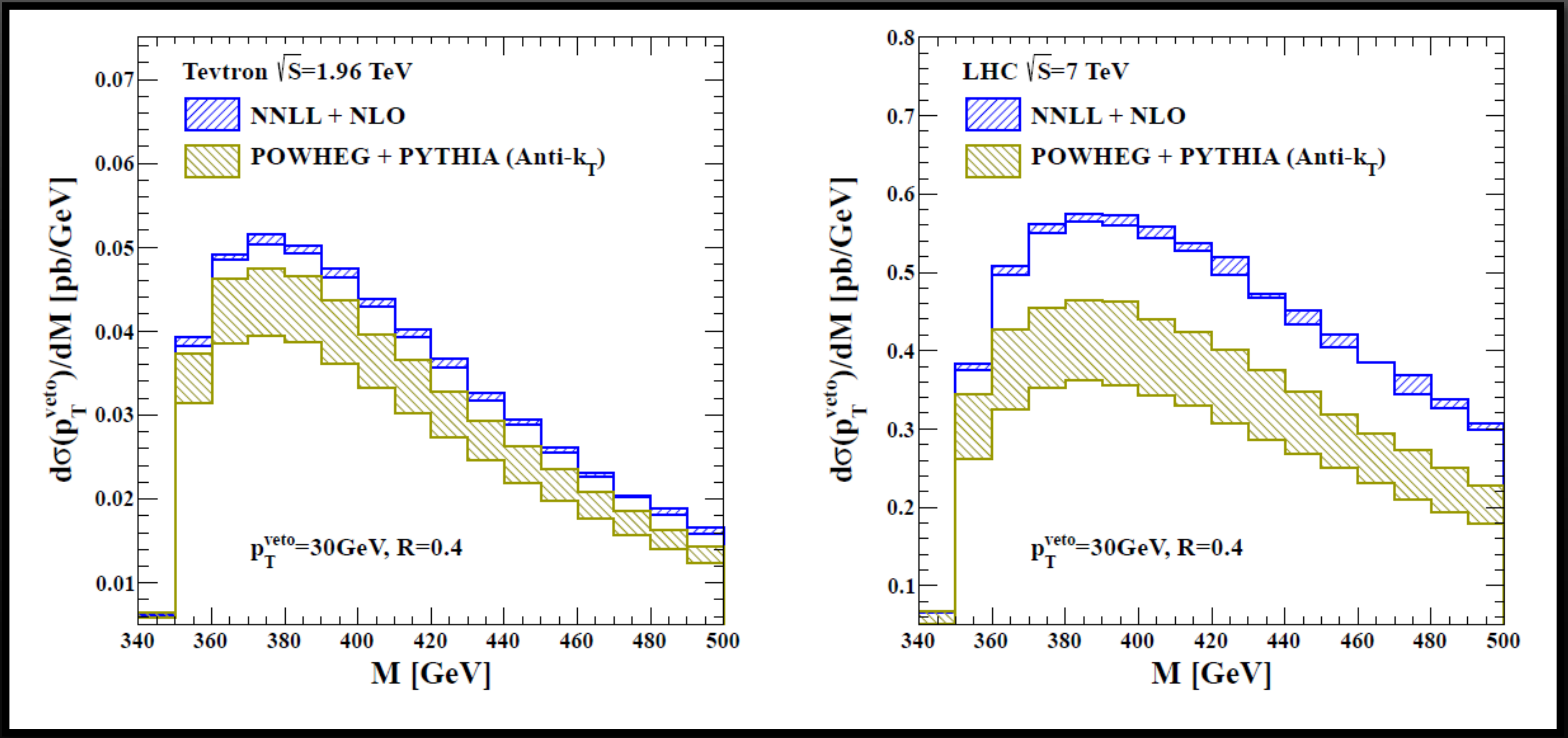
$$\mathcal{S}(p_T^{veto}) \sim \int d^D k \left(\frac{\nu}{k^+}\right)^{\alpha} \delta(k^2)\, \theta(p_T^{veto} - k_T)\, \frac{v_i \cdot v_j}{v_i \cdot k \; v_j \cdot k}$$

Leading Singular Terms





NNLL+NLO v.s. POWHRG+PYTHIA



Conclusions

- We derive the factorization expressions and study the resummation effects for the $HV + 0j$ process at the LHC. Our results can help to precisely study the physical property of the SM Higgs boson through HV production at the LHC in the future;

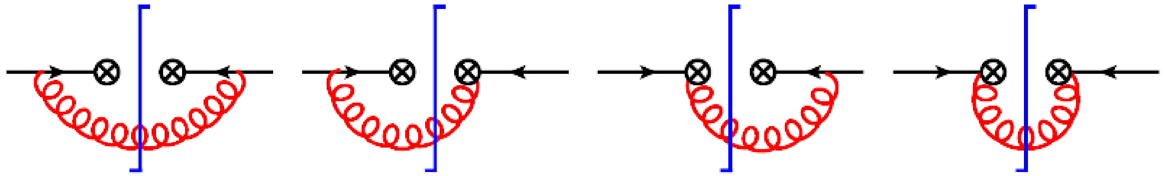
- We propose a soft function to describe the jet vetoed soft radiation from massive color states and develop a framework to calculate the resummation effects for $t\bar{t} + 0j$ process at hadron colliders based on SCET and HQET.

Thank You!!!

Backup Slides

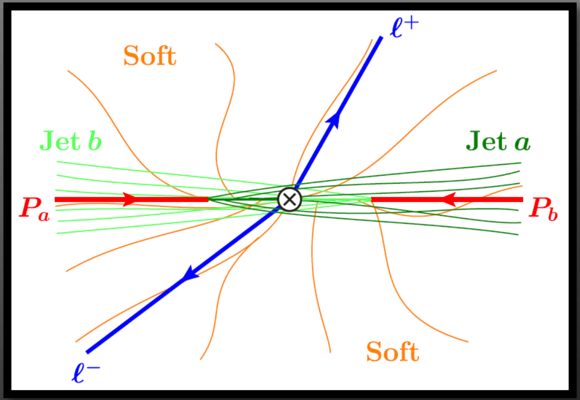
Beam Function

$$\mathcal{B}^{n}_{q/N}(\zeta, p_T^{\rm veto}, \mu) = \sum_{i=g,q,\bar{q}} \int_\zeta^1 \frac{dz}{z} \mathcal{I}_{q\leftarrow i}(z, p_T^{\rm veto}, \mu) f_{i/N}(\zeta/z, \mu).$$



$$\mathcal{I}^{(1),\rm bare}_{q\leftarrow q}(z, p_T^{\rm veto}, \mu) = g_s^2 C_F \mu^{2\epsilon} \int \frac{d^D k}{(2\pi)^{D-1}} \left(\frac{\nu}{k^+}\right)^\alpha \delta(k^2)\theta(k^0)\delta(k^- - (1-z)p^-)$$
$$\times\, \theta(p_T^{\rm veto} - k_T) \frac{k^-}{k_T^2} \left[(D-2)(1-z) + \frac{4z}{1-z}\right]$$

BUT!!!



$$\sigma \sim \sigma_0 \mathcal{H}(Q^2, \mu^2) \otimes \mathcal{B}^n{}_{q \leftarrow N_1}(\zeta_1, p_T^{veto}, \mu) \otimes \mathcal{B}^{\bar{n}}{}_{\bar{q} \leftarrow N_2}(\zeta_2, p_T^{veto}, \mu) \otimes \mathcal{S}(p_T^{veto}, \mu)$$

1. **Scale independent:**

$$\frac{d\mathcal{H}}{dln\mu} \sim \left(\Gamma_{cusp} \ln \frac{Q^2}{\mu^2} + \gamma\right)\mathcal{H}, \qquad \frac{d\sigma}{dln\mu} = 0 \Rightarrow \frac{d\mathcal{B}}{d\ln\mu} \sim F(Q)\mathcal{B} \;\; or \;\; \frac{d\mathcal{S}}{d\ln\mu} \sim F(Q)\mathcal{S}$$

Hard Scale!

2. **Extra divergence:**

When matching $\mathcal{B} \sim f \otimes I$,
traditional dimensional regularization is not enough!

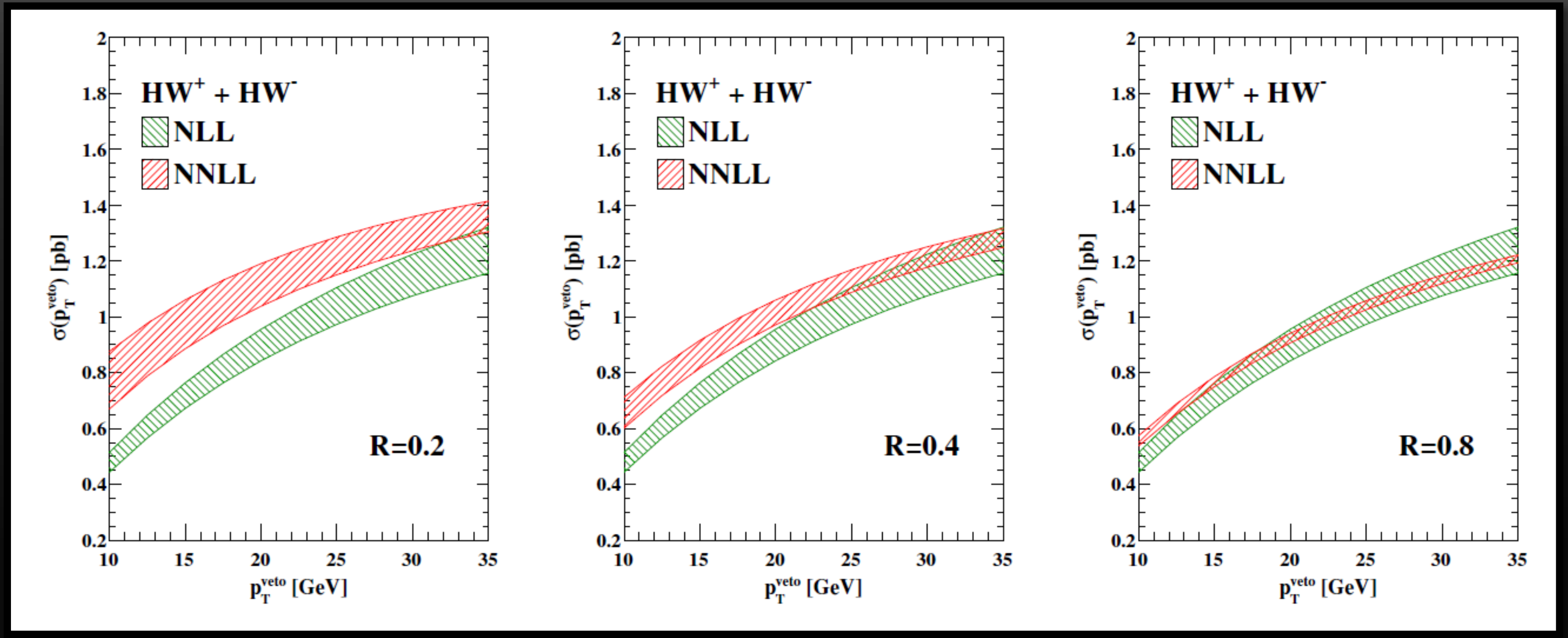
Factorization in SCET

$$\mathcal{B}^{n}_{q/N}(\zeta, p_T^{\text{veto}}, \mu) = \sum_{i=g,q,\bar{q}} \int_{\zeta}^{1} \frac{dz}{z} \mathcal{I}_{q\leftarrow i}(z, p_T^{\text{veto}}, \mu) f_{i/N}(\zeta/z, \mu).$$

$$\left[\mathcal{I}_{q\leftarrow i}(z_1, p_T^{\text{veto}}, \mu_f)\mathcal{I}_{\bar{q}\leftarrow j}(z_2, p_T^{\text{veto}}, \mu_f)\right]_{q^2=M^2} = \left(\frac{M}{p_T^{\text{veto}}}\right)^{-2F_{q\bar{q}}(p_T^{\text{veto}}, \mu_f)} I_{q\leftarrow i}(z_1, p_T^{\text{veto}}, \mu_f) I_{\bar{q}\leftarrow j}(z_2, p_T^{\text{veto}}, \mu_f)$$

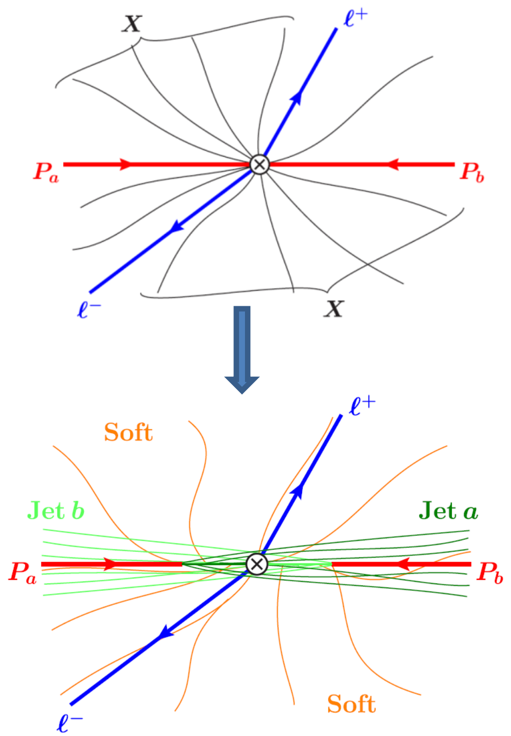
$$\frac{d\sigma(p_T^{\text{veto}})}{dM^2} = \frac{\sigma_0}{s}\overline{H}(M, p_T^{\text{veto}}) \int_{\tau}^{1} \frac{dz}{z} \bar{I\!I}_{ij}(z, p_T^{\text{veto}}, \mu_f) f\!f_{ij}\left(\frac{\tau}{z}, \mu_f\right)$$

Resummed Cross Section with different jet radius R



How to resum $\ln(p_T^{veto}/Q)$?

The measurement restricting the hadronic final state introduces a new scale $p_T^{veto} \ll Q$.



Beam Function: **Stewart, *et.al.* , 2010**

Below p_T^{veto}, the initial-state evolution is described by the usual PDF evolution which changes x, while above p_T^{veto} it is governed by a different renormalization group evolution that sums double logarithms of p_T^{veto}/Q and leaves x fixed.