RESUMMATION EFFECTS OF THE GAUGE BOSON PAIR PRODUCTION

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TESTING STANDARD MODEL
-----TRIPLE GAUGE BOSON COUPLINGS

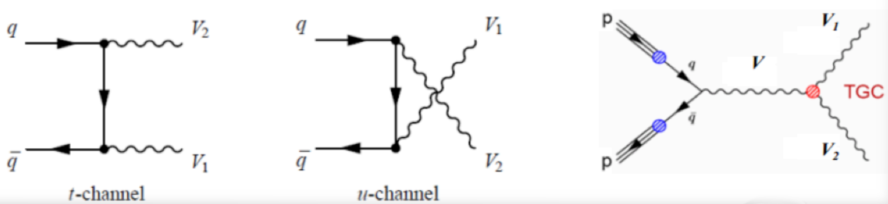
Probe **TGC** which are a fundamental prediction **o**f the non-Abelian SU(2)×U(1) gauge structure of electroweak theory.

$$\begin{aligned}\mathcal{L}_{WWV}/g_{WWV} &= ig_1^V\left(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\ &+ i\frac{\lambda_V}{m_W^2}W^\dagger_{\lambda\mu}W^\mu{}_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu\left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) \\ &+ g_5^V\epsilon^{\mu\nu\lambda\rho}\left(W^\dagger_\mu\partial_\lambda W_\nu - \partial_\lambda W^\dagger_\mu W_\nu\right)V_\rho \\ &+ i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + i\frac{\tilde{\lambda}_V}{m_W^2}W^\dagger_{\lambda\mu}W^\mu{}_\nu\tilde{V}^{\nu\lambda},\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{Z\gamma V} &= -ie\left[\left(h_1^V F^{\mu\nu} + h_3^V \tilde{F}^{\mu\nu}\right)Z_\mu\frac{(\Box + m_V^2)}{m_Z^2}V_\nu\right. \\ &\left.+\left(h_2^V F^{\mu\nu} + h_4^V\tilde{F}^{\mu\nu}\right)Z^\alpha\frac{(\Box + m_V^2)}{m_Z^4}\partial_\alpha\partial_\mu V_\nu\right],\end{aligned}$$

coupling	parameters	channel
$WW\gamma$	λ_γ, $\Delta\kappa_\gamma$	WW, $W\gamma$
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
$Z\gamma Z$	f_{40}^Z, f_{50}^Z	ZZ
ZZZ	f_{40}^γ, f_{50}^γ	ZZ

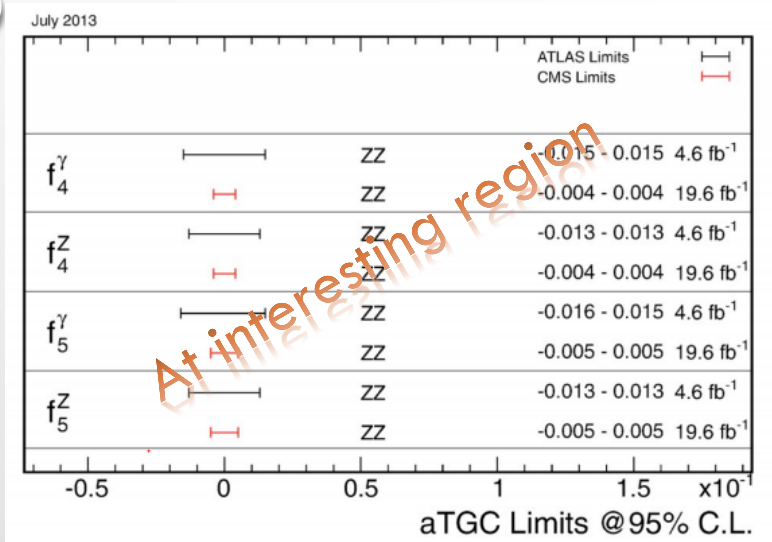
LO production diagram

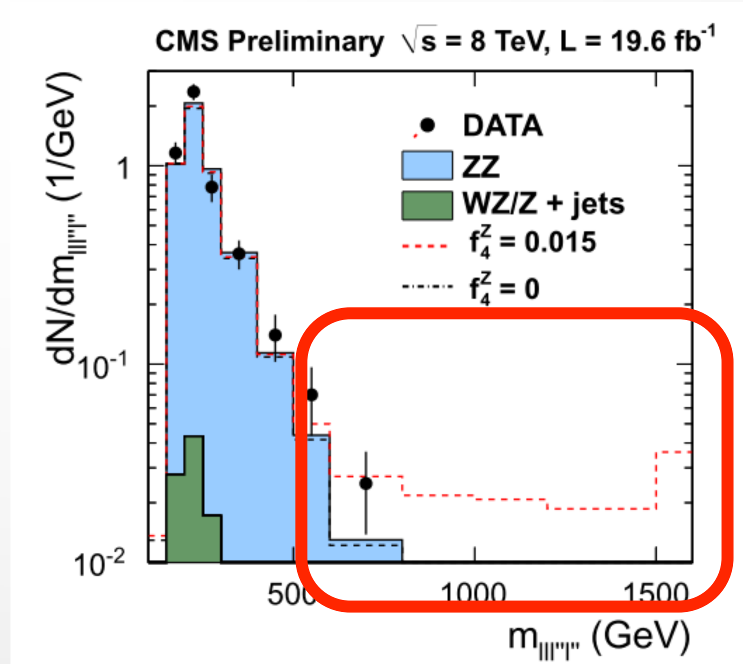


In SM, $SU(2)\times U(1)_Y$ gauge symmetry,

- no neutral TGC vertex at LO.
- Charged TGC vertex at LO are only $\lambda_\gamma=\lambda_Z=0$, $g_1^Z=\kappa_\gamma=\kappa_Z=1$.

TESTING STANDARD MODEL
-----TRIPLE GAUGE BOSON COUPLINGS





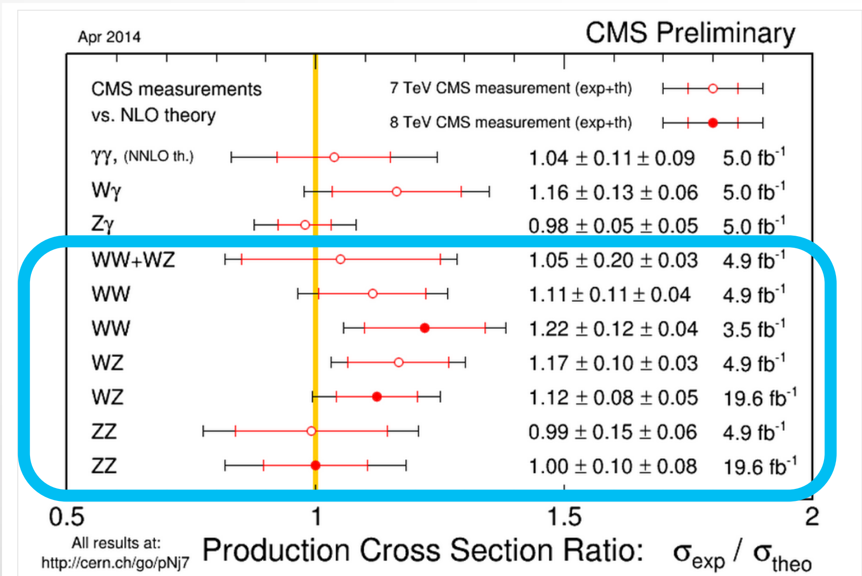
At the one-loop level,
fermion triangles generate nTGCs : 10^{-4} ,
G. J. Gounaris, et. al. Phys. Rev. D 62, 073013 (2000).

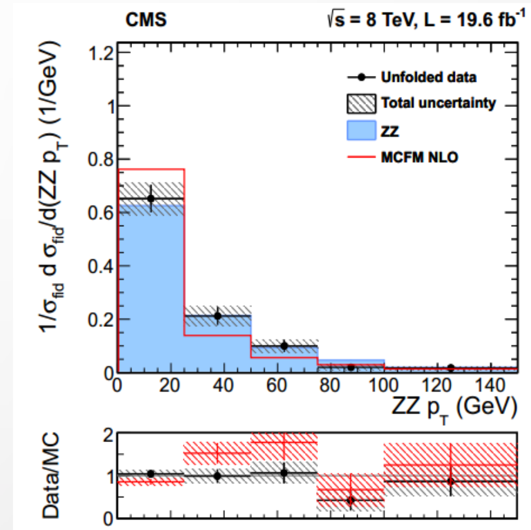
Many new physics models
predict values of nTGCs :10^{-4} ~ 10^{-3} .
J. Ellison and J.Wudka, Annu. Rev. Nucl. Part. Sci. 48,33 (1998).

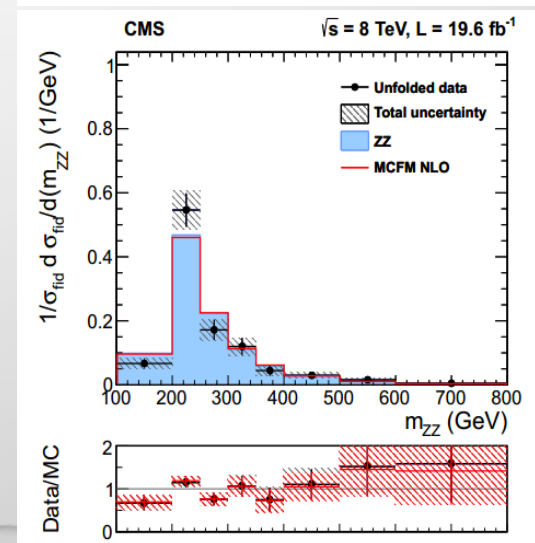
aTGC effects: often increase cross sections at high invariant mass (M_{VV}) and its proxies (q_T)

EXPERIMENTS

The SM has been tested at a new energy frontier by the LHC **at 7 and 8 TeV.**







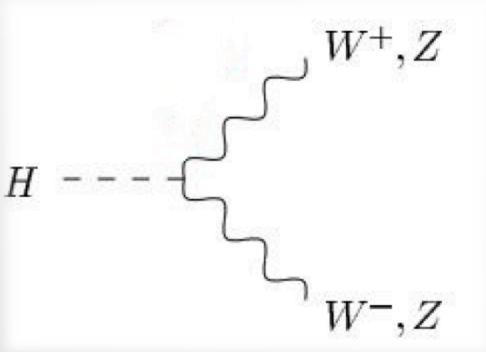
For the total cross section, the discrepancies in $W^{+} W^{-}$ channel between the measured data and the SM NLO calculation are about 20%.
For $W^{\pm} Z$ channel, they are about 10%.

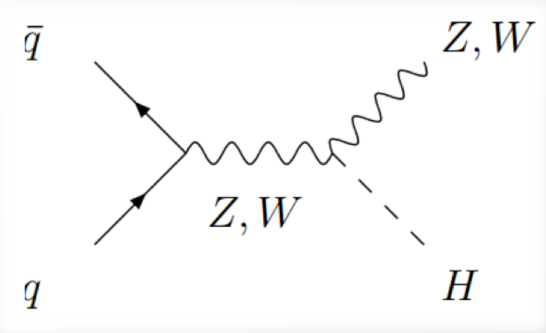
Differential measurements are also different to some extent.

arXiv:1406.0113

IRREDUCIBLE BACKGROUND

Diboson production is a significant and irreducible background to Higgs production





It is sensitive to the production and decay of new particles predicted in models with extended Higgs sectors, extra vector bosons, extra dimensions or models such as Supersymmetry and Technicolor.

GAUGE BOSON PAIR PRODUCTION

- The efforts of obtaining accurate theoretical prediction for this process has been for a long times.

- **BEYOND NLO QCD**
- G. Chachamis, M. Czakon, and D. Eiras, JHEP 12 (2008) 003.
- F. Campanario and S. Sapeta, Phys. Lett. B 718, 100 (2012).
- M. Grazzini, JHEP 01, 15 (2006)
- R. Frederix, M. Grazzini, PLB 662, 353 (2008)
- S. Dawson, I.M. Lewis, and M. Zeng, Phys. Rev. D 88, 054028 (2013).
- P. Meade, H. Ramani, and M. Zeng, Arxiv: 1407.4481

- **NNLO QCD**
- T. Gehrmann, L. Tancredi and E. Weihs, JHEP 1308 (2013) 070
- J. M. Henn, K. Melnikov and V. A. Smirnov, JHEP 05 (2014) 090
- T. Gehrmann, A. Von Manteuffel, L. Tancredi and E. Weihs, JHEP 06 (2014) 032.
- F. Caola, J. M. Henn, K. Melnikov and V. A. Smirnov, JHEP 1409 (2014) 043
- F. Cascioli, T. Gehrmann, M. Grazzini, and S. Kallweit, et al, PLB 735 (2014) 311

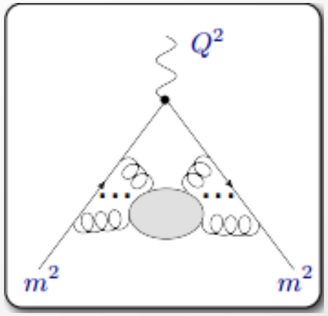
WHY RESUMMATION

Generally, there will be large logarithms $L = \ln Q/m$, arising from hierarchy between small variable m and large scale Q, where $Q \gg m$.

So, the convergence is poor, and the fixed order predictions are unreliable.

Thus, these logarithms should be resumed to all order.

a short-distance scale Q



a long-distance scale **m**

	LO	NLO	NNLO	NNNLO		
σ_0 [	1	$+ \alpha_s L^2$	$+ \alpha_s^2 L^4$	$+ \alpha_s^3 L^6 + \ldots$	**LL**	
		$+ \alpha_s L$	$+ \alpha_s^2 L^3$	$+ \alpha_s^3 L^5 + \ldots$	**NLL**	
		$+ \alpha_s$	$+ \alpha_s^2 L^2$	$+ \alpha_s^3 L^4 + \ldots$	**NNLL**	**Resummation**
			$+ \alpha_s^2 L$	$+ \alpha_s^3 L^3 + \ldots$	**NNNLL**	
			$+ \alpha_s^2$	$+ \alpha_s^3 L^2 + \ldots$	…	
				$+ \alpha_s^3 L + \ldots$]		

Fixed order

THRESHOLD RESUMMATION : WHY RESUMMATION

Generic observable in hadron collisions at energy $\sqrt{s}$:

$$\sigma(\tau, M^2) = \sigma_0 \int_\tau^1 \frac{dz}{z} \mathcal{L}(\tau/z) C(z, \alpha_s(M^2)); \quad \tau = M^2/s$$

Parton luminosity.

$$\mathcal{L}(y, \mu_f) = \sum_{qq'} \int_y^1 \frac{dx}{x} \left[f_q(x, \mu_f) f_{q'}(y/x, \mu_f) \right]$$

For the parton cross section $C(z, \alpha_s)$, it can be expanded as

$$C(z, \alpha_s) = \delta(1-z) + \sum_n^\infty C_n(z) \alpha_s^n \; ; \; z = M^2/s$$

When s is close to M^2, $\tau \to 1$, since $z \geq \tau$ is also close to 1.

$$C_n(z) \sim \left[\frac{\log^{2n-1}(1-z)}{1-z} \right]_+$$

The perturbative expansion is unreliable in this region.

The effect of soft-gluon resummation can be relevant even relatively far from the hadronic threshold.

T. Becher, M. Neubert and G. Xu, JHEP 0807 (2008) 030

THRESHOLD RESUMMATION : FACTORIZATION FORMULAS IN SCET

YW, Chong Sheng Li, Ze Long Liu, Ding Yu Shao, Phys. Rev. D 90, 034008 (2014)

We can factorize the resummed cross section as

$$d\sigma/dM_{VZ}^2 \sim H(\mu_h)\cdot S(\mu_s)\otimes\phi(\mu_f)$$

The renormalization-group equation for the hard function is

$$\frac{d}{d\ln\mu}\mathcal{H}_{VZ}(M_{VZ},\mu) = 2\left[\Gamma^F_{\rm cusp}(\alpha_s)\ln\frac{-M_{VZ}^2}{\mu^2} + 2\gamma^q(\alpha_s)\right]\mathcal{H}_{VZ}(M_{VZ},\mu)\,,$$

defining

$$\mathcal{H}_{V_lZ} = \mathcal{H}^{(0)}_{V_lZ} + \frac{\alpha_s}{4\pi}\mathcal{H}^{(1)}_{V_lZ} + \cdots\,.$$

The exact solution to

$$\mathrm{H}\,(-M^2,\mu_f) = \exp(4S(\mu_h,\mu_f) - 4a_\gamma(\mu_h,\mu_f))\,(-M^2/\mu_h^2)^{-a_\Gamma(\mu}$$

THRESHOLD RESUMMATION : FACTORIZATION FORMULAS IN SCET

We choose $\mu_h^2 \sim -M_{VZ}^2$ **to eliminate** π^2 terms arising from $Log[-\mu_h^2/M^2]$.

Meantime we need evaluated $\alpha_s(-\mu_h^2)$ **to** $\alpha_s(\mu_h^2)$ by the equation

$$\frac{\alpha_s(\mu^2)}{\alpha_s(-\mu^2)} = 1 - ia(\mu^2) + \frac{\alpha_s(\mu^2)}{4\pi}\left[\frac{\beta_1}{\beta_0}\ln[1 - ia(\mu^2)]\right] + \mathcal{O}(\alpha_s^2),$$

The soft function is defined as

$$\mathcal{S}(s(1-z)^2,\mu) = \sqrt{s}W(s(1-z)^2,\mu),$$

The momentum-space Wilson loop obeys the integro-differential evolution equation

$$\frac{dW(\omega,\mu)}{d\ln\mu} = -\left(4\Gamma_{cusp}(\alpha_s)\ln\frac{\omega}{\mu} + 2\gamma(\alpha_s)\right)W(\omega,\mu)$$

$$-4\Gamma_{cusp}(\alpha_s)\int_0^\omega d\omega' \frac{W(\omega',\mu) - W(\omega,\mu)}{\omega - \omega'}$$

THRESHOLD RESUMMATION : FACTORIZATION FORMULAS IN SCET

the exact solution can be written in the form

$$\omega W(\omega^2, \mu_f) = \exp\left(-4S(\mu_s, \mu_f) + 2a_{\gamma^W}(\mu_s, \mu_f)\right) \tilde{s}(\partial_\eta, \mu_s) \left(\frac{\omega^2}{\mu_s^2}\right)^\eta \frac{e^{-2\gamma\eta}}{\Gamma(2\eta)},$$

After combining the soft and hard function, the differential cross section can be factorized as

$$\frac{d\sigma}{dM_{VZ}^2} = \frac{\sigma_0}{S} \int_\tau^1 \frac{dz}{z} \mathcal{L}\left(\frac{\tau}{z}, \mu_f\right) \mathcal{H}_{VZ}(M_{VZ}, \mu_h) C(M_{VZ}, \mu_h, \mu_s, \mu_f),$$

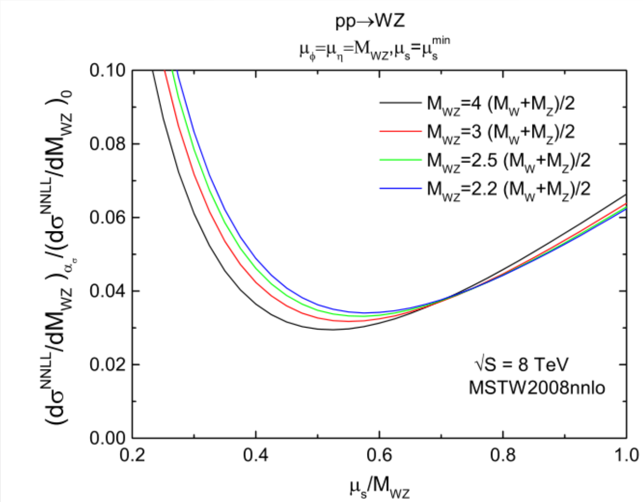
where

$$C\left(M, \mu_h^2, \mu_s^2, \mu_f^2\right) = \exp\left[4S(\mu_h, \mu_s) - 2a_{\gamma^V}(\mu_h, \mu_s) + 4a_{\gamma^\phi}(\mu_s, \mu_f)\right] \left(\frac{M^2}{\mu_h^2}\right)^{-2a_\Gamma(\mu_s, \mu_h)} \frac{(1-z)^{2\eta-1}}{z^\eta} \tilde{s}\left[\log\left(\frac{(1-z)^2 M^2}{z\mu_s^2}\right) + \partial_\eta, \mu_s\right] \frac{e^{-2\gamma\eta}}{\Gamma(2\eta)}$$

THRESHOLD RESUMMATION : THE SCALE SETTINGS

--- $W^{\pm}Z$ FOR EXAMPLE

In the following, we take $W^{\pm}Z$ production as an example.
The behavior of ZZ is very similar.

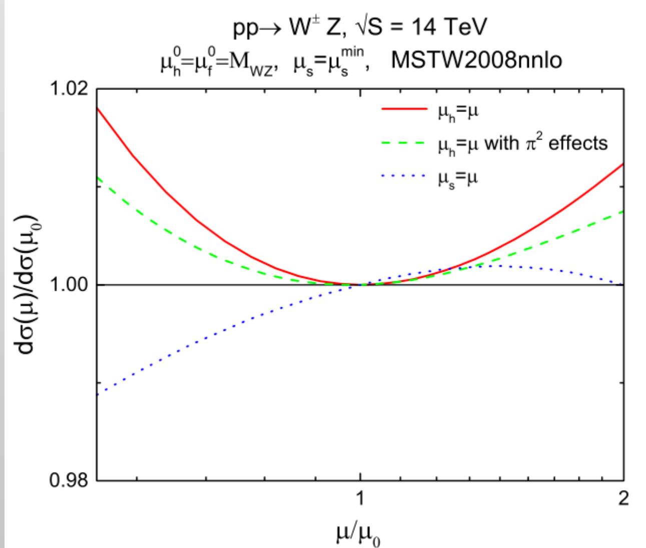


The contribution of the one-loop corrections of the soft functions as a function of $\mu_s/M_{V_1V_2}$.

The requirement: have a well-behaved stability.

$$\mu^{min}_{s,W^\pm Z} = M_{W^\pm Z}\frac{1-\tau}{(3.004\sqrt{\tau}+1.339)^{2.134}},$$

$$\mu^{min}_{s,ZZ} = M_{ZZ}\frac{1-\tau}{(3.013\sqrt{\tau}+1.323)^{2.356}}.$$



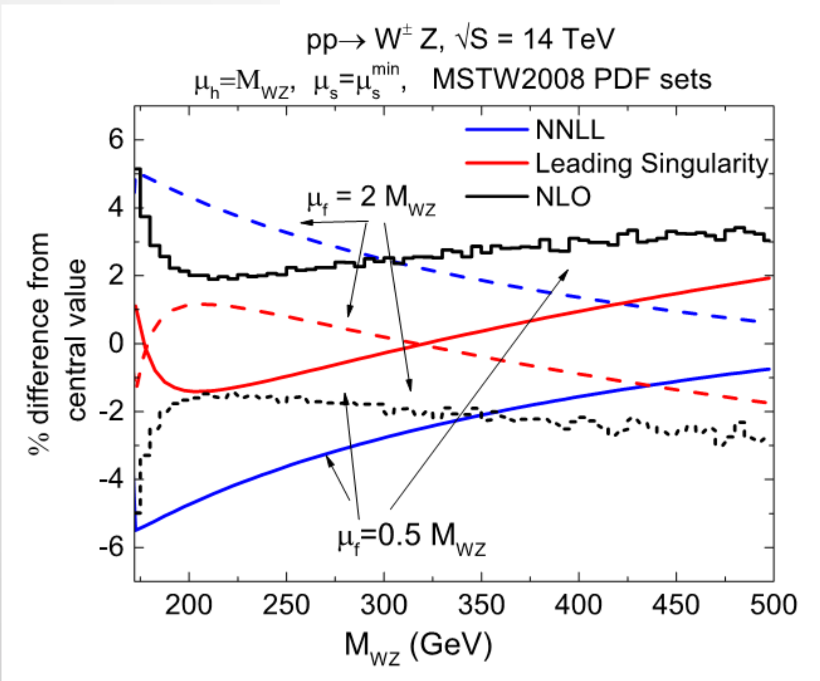
Scale dependence of the resummed cross section on μ_s **and** μ_h

THRESHOLD RESUMMATION : FACTORIZATION SCALE DEPENDENCE

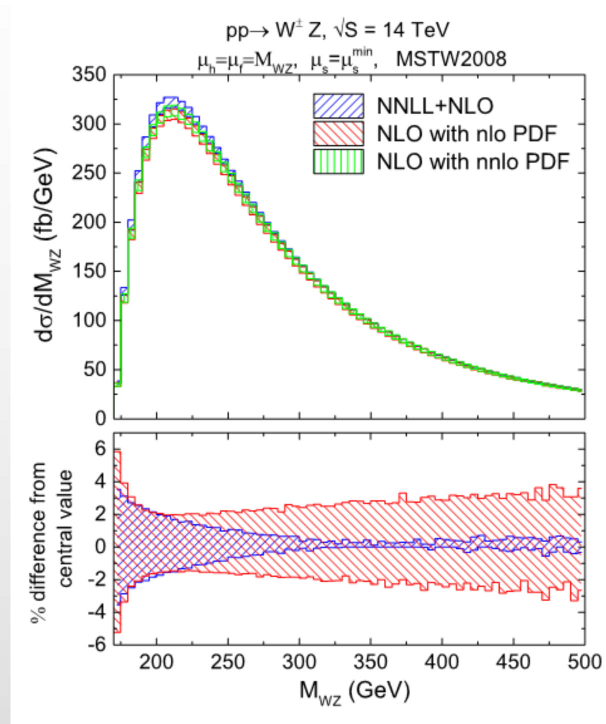
---$W^{\pm} Z$ FOR EXAMPLE

In order to get the total cross section, we should including the nonsingular terms :

$$\frac{d\sigma^{\text{NNLL+NLO}}}{dq_T} = \frac{d\sigma^{\text{NNLL}}}{dq_T} + \left[\frac{d\sigma^{\text{NLO}}}{dq_T} - \frac{d\sigma^{\text{NNLL}}}{dq_T}\right]_{\text{expanded to NLO}}.$$

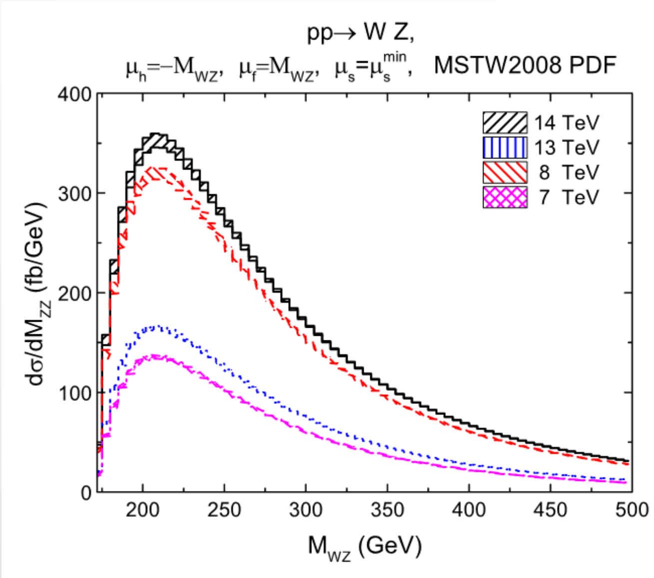


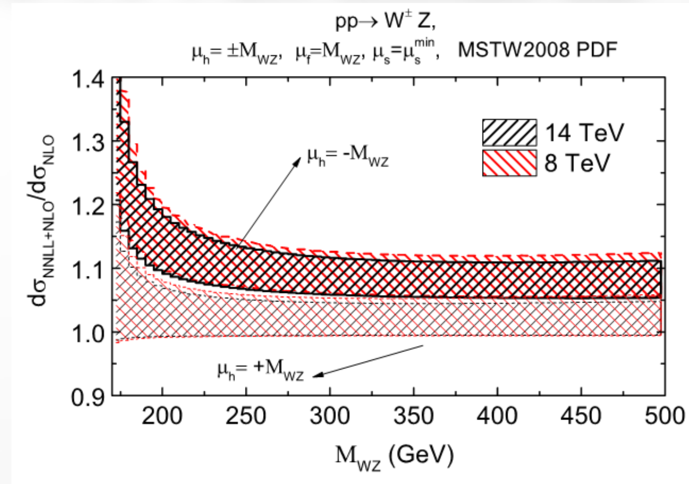
The factorization scale dependences of the three part cancle each other



The final NNLL+NLO results have a factorization scale dependence.

THE INVARIANT MASS DISTRIBUTION
---$W^{\pm} Z$ FOR EXAMPLE





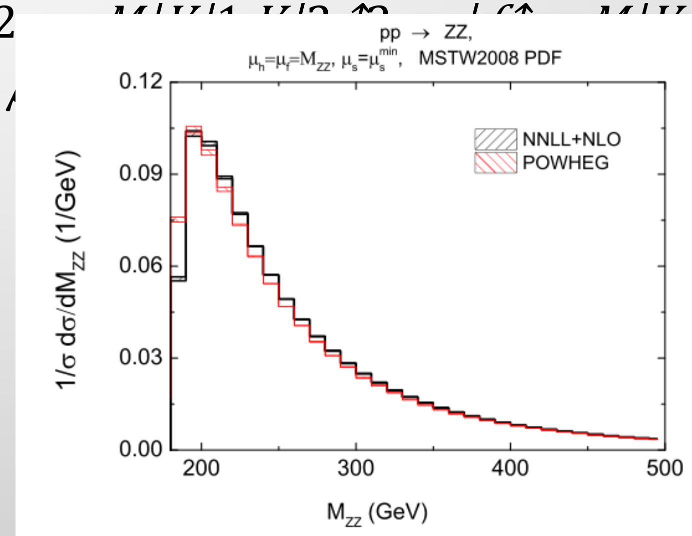
The invariant mass distributions with

$\mu\downarrow h\uparrow 2$ … 1

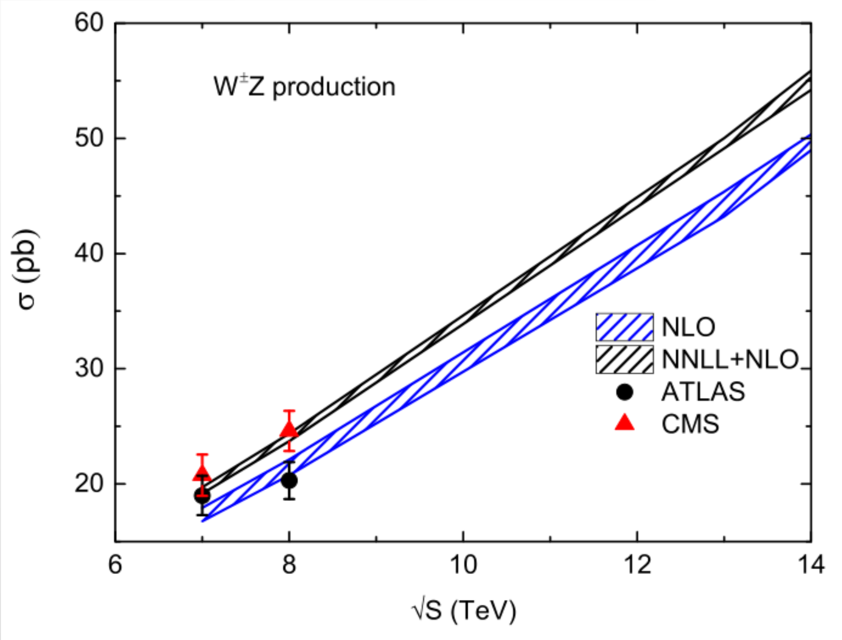
$V\downarrow 2$, …

We compare the normalized invariant mass distribution with the predictions by POWHEG

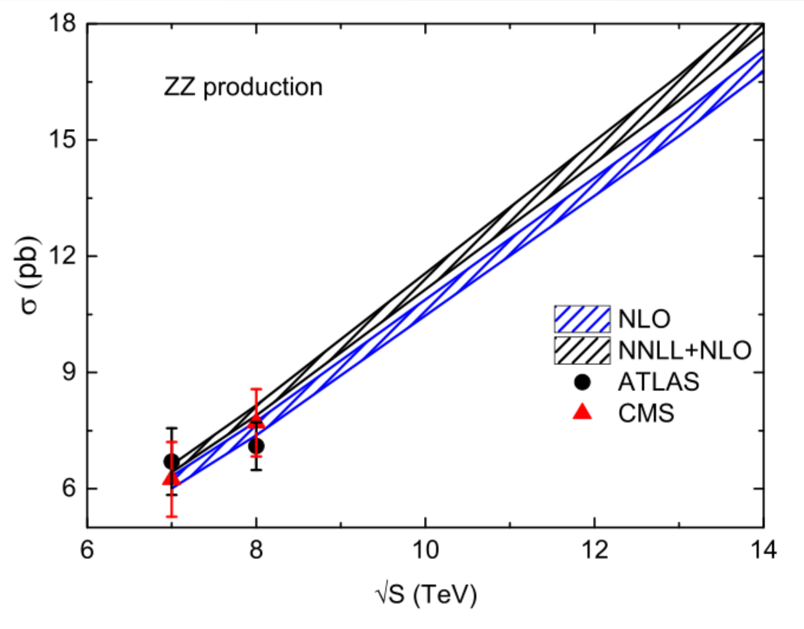
They agree with each other very well.



RESUMMED PREDICTION: THE TOTAL CROSS SECTION



The total cross sectiones with different center-of-mass energies for gauge boson pair production at the LHC.



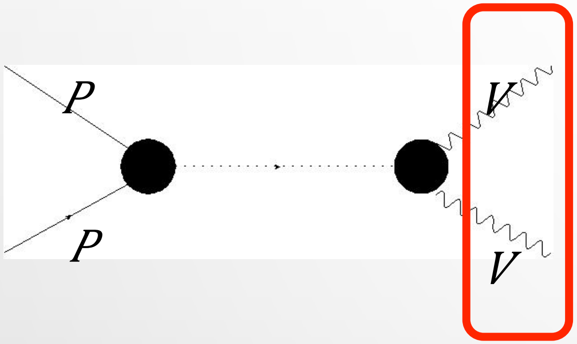
They agree to the experiment data very well.

CONCLUSION

- **Presenting NLO + NNLL thershold resummations for $W^{\pm}Z$ and ZZ productions, with π^2 enhancement effects**
- **The results decrease the scale dependences, especially for the $W^{\pm}Z$ production .**
- **Resummation results increase the NLO cross section by about 8% for ZZ and 12% for WZ.**
- **Results agree with powheg and experimental data very well.**

q_T DISTRIBUTION : WHY RESUMMATION

bind together $\rightarrow q_T$



The large logarithms $L=\ln \mu_h / q_T$ arise from the hierarchy of the small transvers momentum of the gauge boson pair and hard scattering scale.

- **No resummation predictions for the $W^{\pm}Z$ production before.**
- **The resummation for $W^{+}W^{-}$ and ZZ are calculated to NLO + NLL in the CSS framework.**
- **We performed the NLO + NNLL resummation for $W^{+}W^{-}$, $W^{\pm}Z$ and ZZ production at the LHC.**

q_T RESUMMATION : FACTORIZATION FORMULAS IN SCET

YW, Chong Sheng Li, Ze Long Liu, Ding Yu Shao and Hai Tao Li, Phys. Rev. D 88, 114017 (2013)

We can factorize the total cross section as :

$d\sigma = \phi_{i,j} \times I_{i,j} \times H$

Λ_{QCD} μ_B

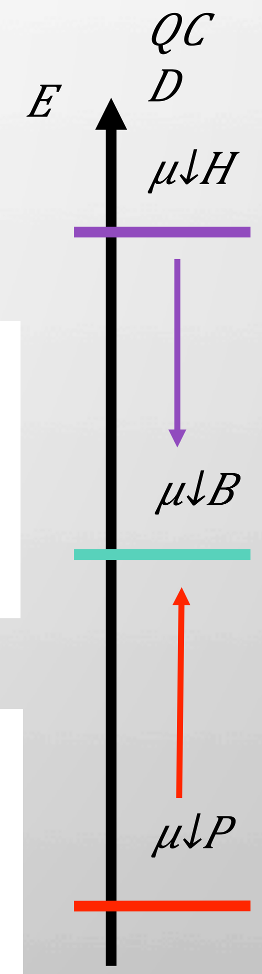
μ_H

Combining the evolution effects of the hard function and beam function, we get

$$\frac{d^2\sigma}{dq_T^2 dy} = \frac{1}{S} \sum_{i,j=q,q',g} \mathcal{H}_{VV}(M,\mu_f) \int_{\xi_1}^1 \frac{dz_1}{z_1} \int_{\xi_2}^1 \frac{dz_2}{z_2} \bar{C}_{qq'\to ij}\left(z_1, z_2, q_T^2, \mu_f\right) \times \phi_{i/N_1}(\xi_1/z_1,\mu_f)\phi_{j/N_2}(\xi_2/z_2,\mu_f) + (q, i \leftrightarrow q', j)].$$

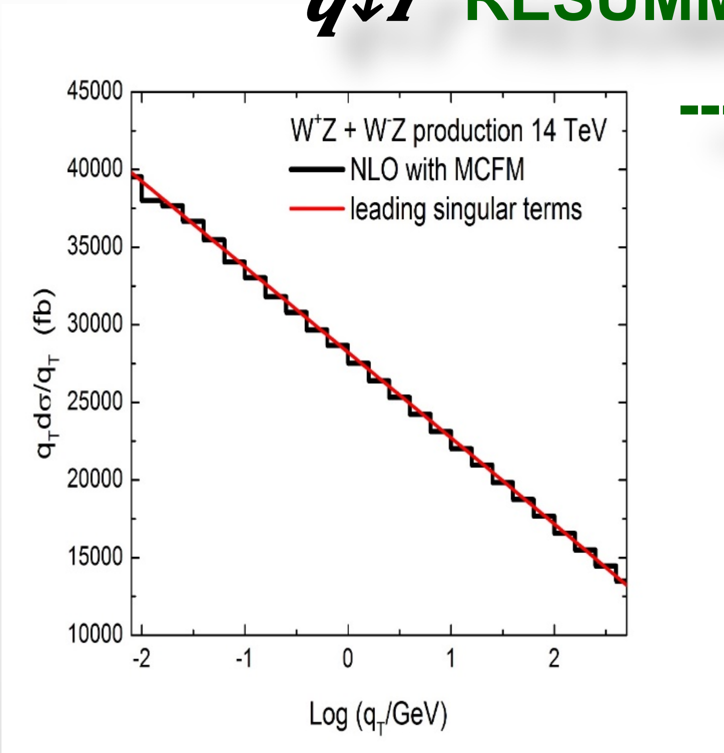
where

$$\bar{C}_{qq'\to ij}\left(z_1, z_2, q_T^2, \mu_f\right) = \frac{1}{2}\int_0^\infty dx_T x_T J_0(x_T q_T)\ \exp\left[g_F(\eta, L_\perp, \alpha_s)\right] \times \left[\bar{I}_{q\leftarrow i}(z_1, L_\perp, \alpha_s)\bar{I}_{q'\leftarrow j}(z_2, L_\perp, \alpha_s)\right],$$



q_T RESUMMATION : PREDICTION

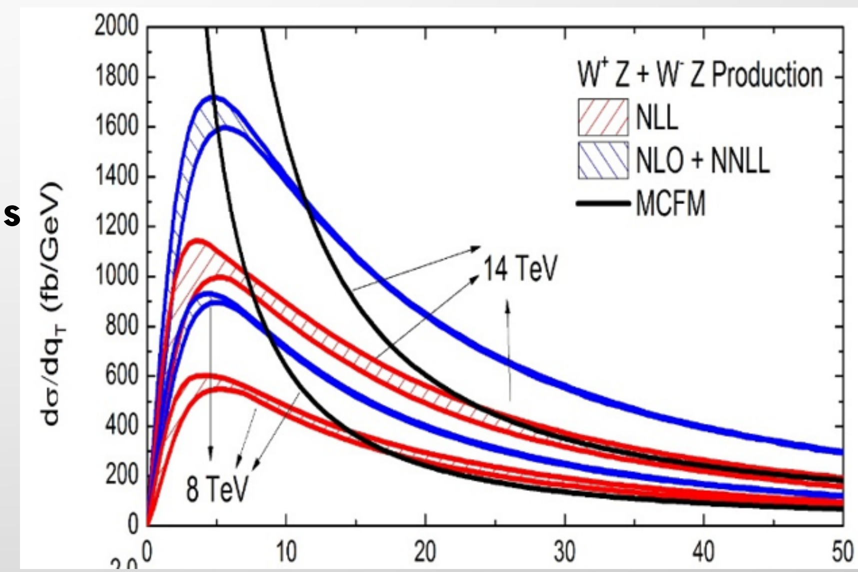
--- $W^{\pm} Z$ FOR EXAMPLE



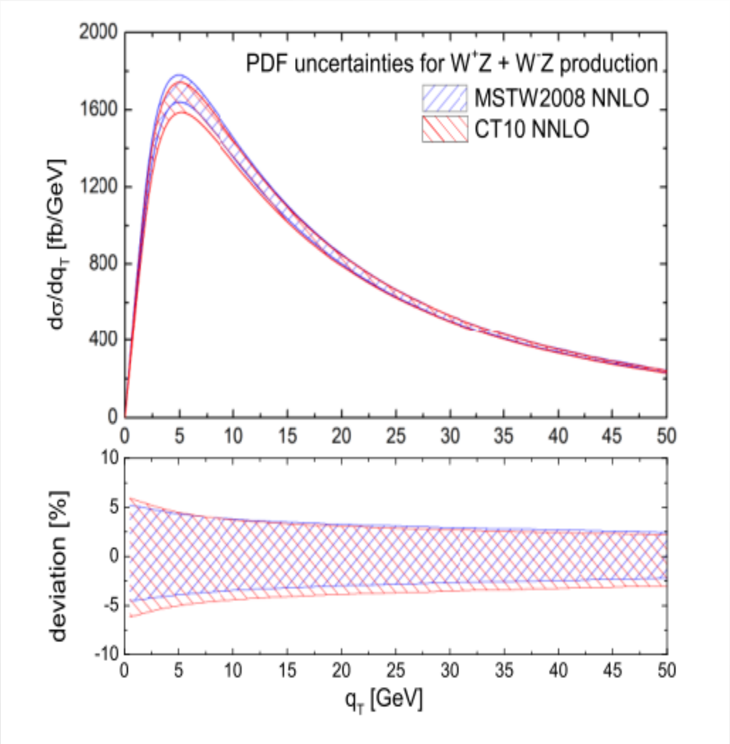
Comparison of leading singular terms and exact NLO cross section in the small q_T region.

Compare the NNLL q_T distribution predictions with the NLL and NLO results.

The uncertainties of the NNLL prediction are much smaller than those of the NLL.
Scale uncertainties $\Delta\sigma \leq$ 1%, when $q_T > 10$ GeV. $\Delta\sigma \leq$ 4%, at peak position.



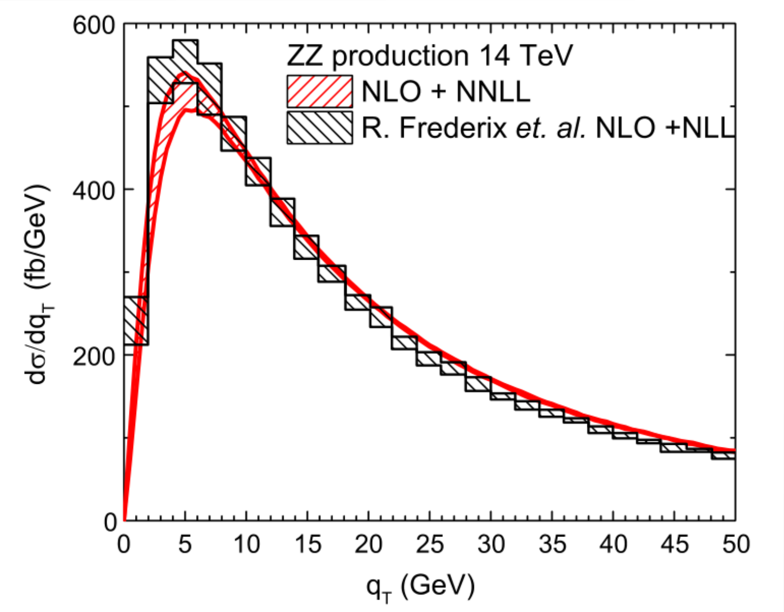
q_T RESUMMATION : PREDICTION
--- $W^{\pm} Z$ FOR EXAMPLE

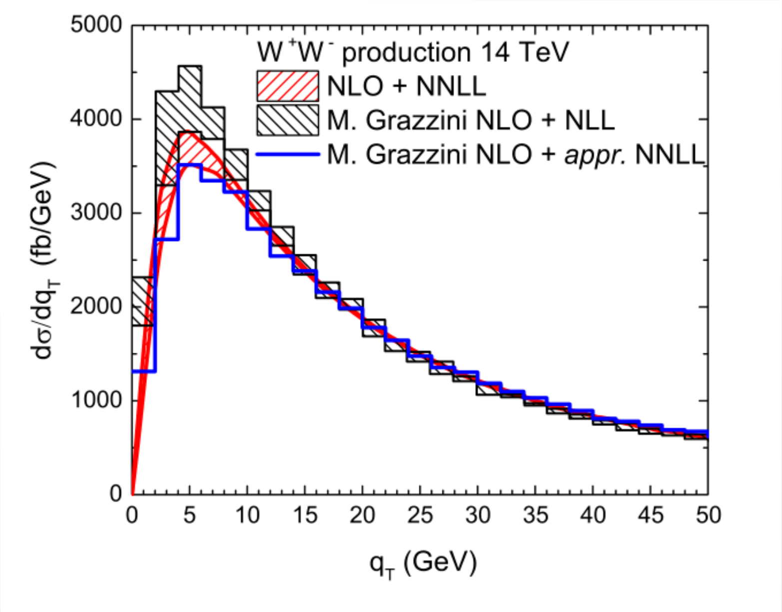


PDF uncertainties with MSTW2008 NNLO 90cl and CT10 NNLO 90cl.

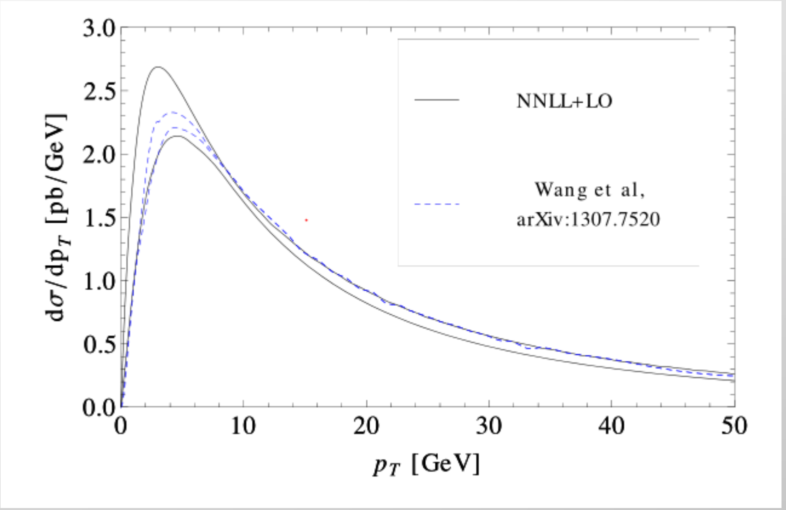
In the large q_T region: <2.5%
In the peak position: <4%,
which are comparable with the scale uncertainties.

q_T RESUMMATION : COMPARE OTHER'S WORK



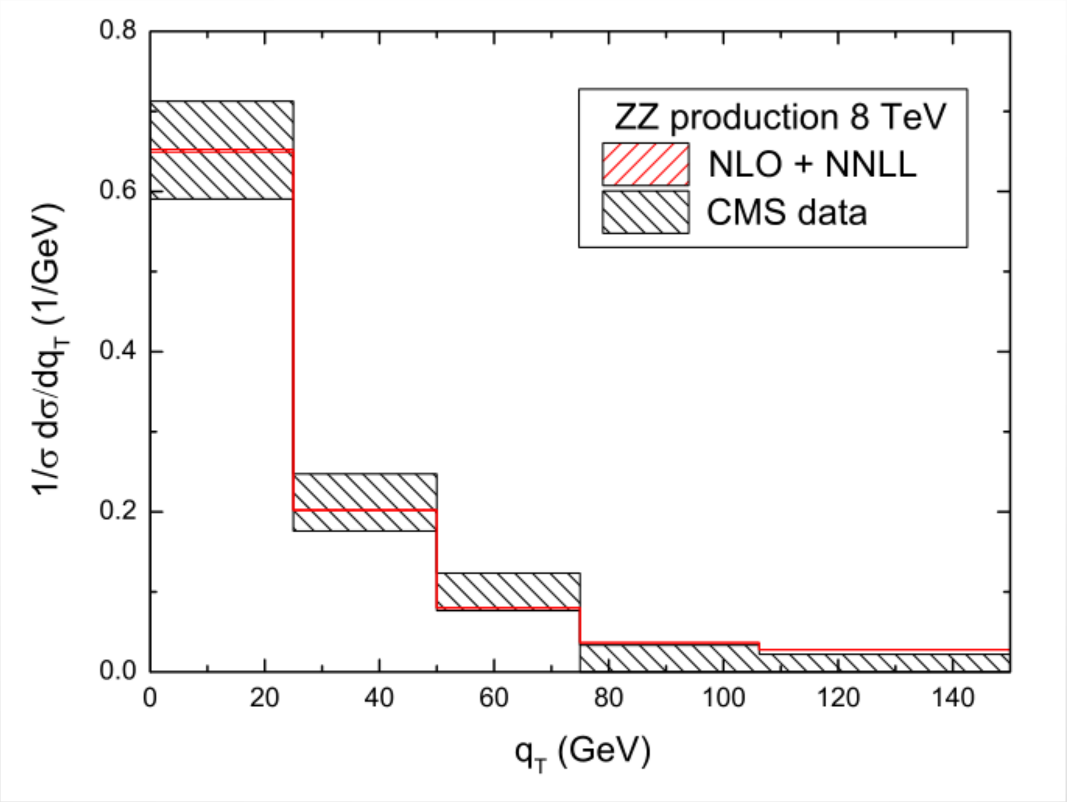


Compare the results in the SCET framework with the prediction in CSS framework. They agree with each other



Patrick Meade, Harikrishnan Ramani, Mao Zeng, **arXiv:1407.4481**

q_T RESUMMATION : COMPARE WITH EXPERIMENT



Compare with the data with $19.6\ fb^{-1}$ **at** $\sqrt{s} = 8$ **TeV at the LHC by the CMS collaboration (CMS PAS SMP-13-005).**

CONCLUSION

- Presenting NLO + NNLL transverse momentum resummations for W^+W^-, $W^\pm Z$ and ZZ productions, including π^2 enhancement effects.
- Scale dependences are decreased obviously.
- Results agree with the experimental data, as well as the the prediction in the tranditional method very well .