Precision Test of Standard Model and Searching for New Physics

Chong Sheng Li

ITP，Peking University

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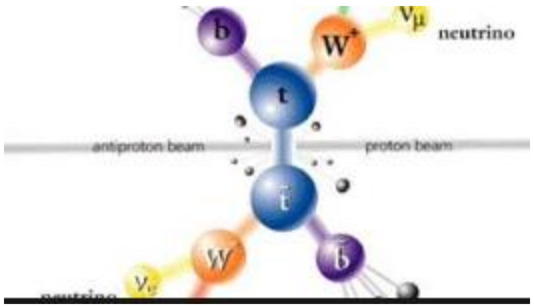
OUTLINE

- SM and QCD corrections at the LHC
- Electroweak Gauge Boson Pair production
  - Threshold resummation
  - q_T resummation
  - Jet-veto resummation
- Vhh production at NNLO
- Conclusion

Part 1

SM and QCD corrections at the LHC

Standard Model (SM)



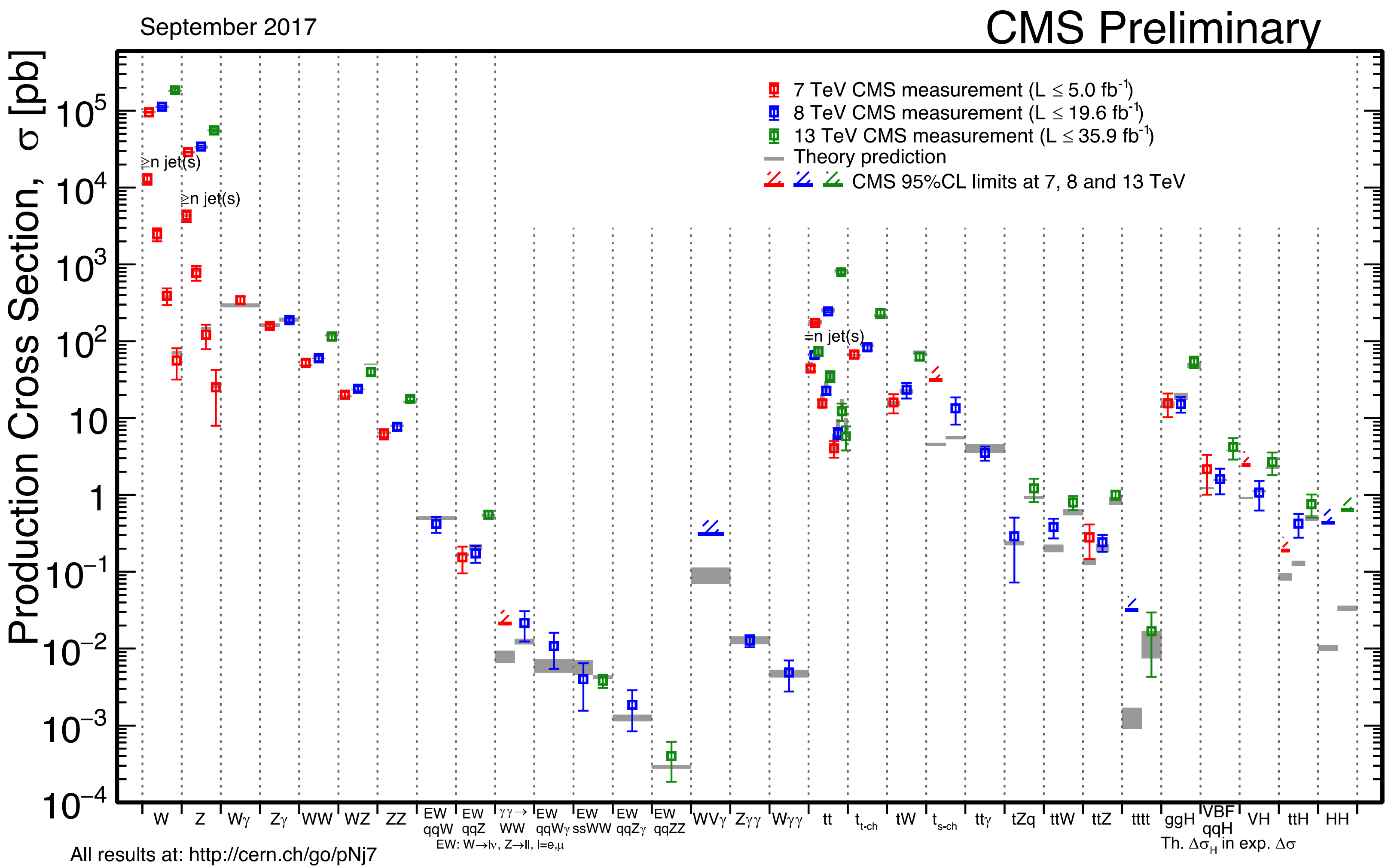
	Fermions			Bosons	
Quarks	u up	c charm	t top	γ photon	Force carriers
	d down	s strange	b bottom	Z Z boson	
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
	e electron	μ muon	τ tau	g gluon	
				Higgs boson	

Source: AAAS

2013

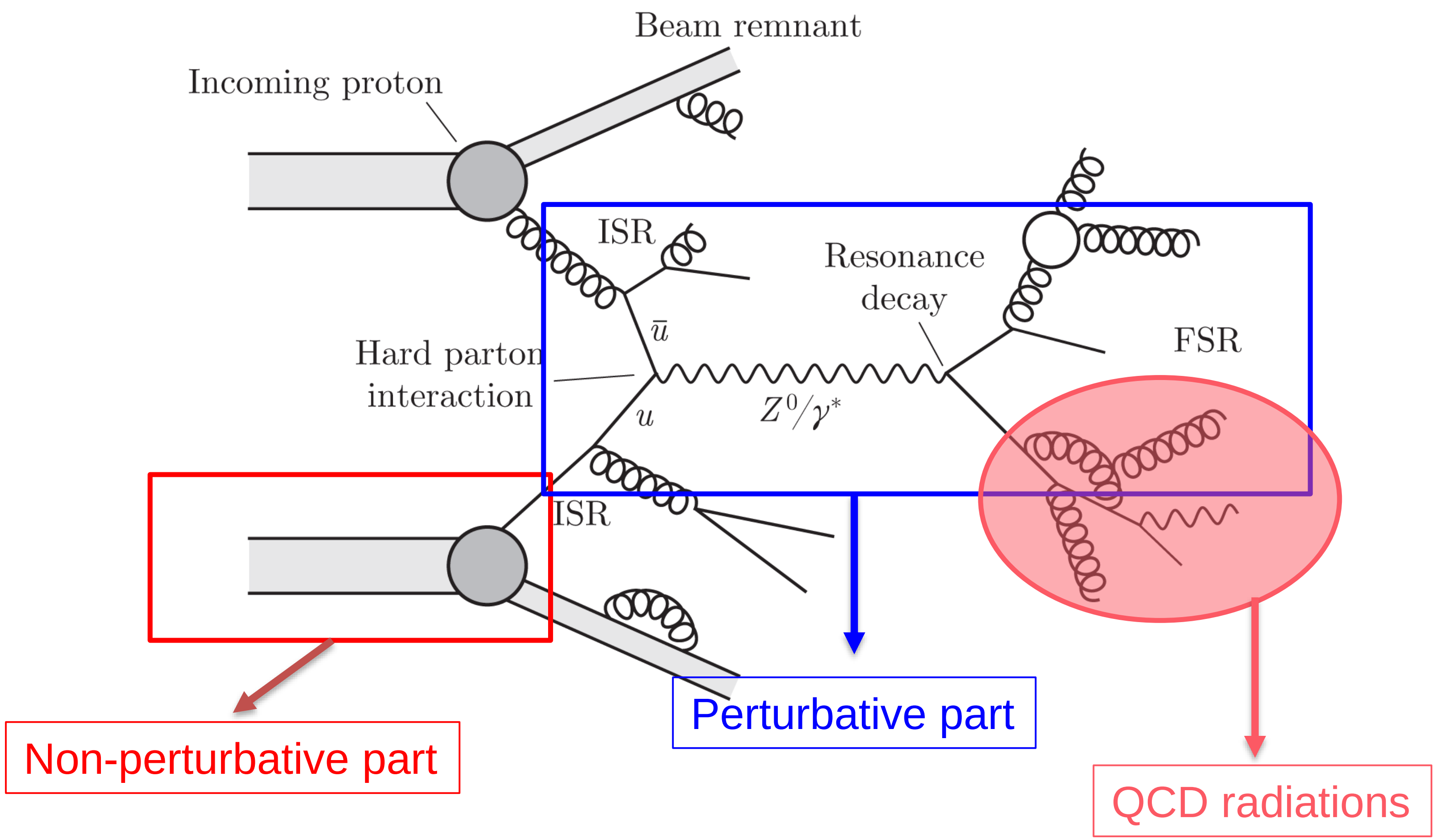
Electroweak spontaneous symmetry breaking

Summary of the cross section measurements of SM processes.



Parton model

Physics programs involving hadrons rely on QCD parton model calculations



At the LHC, QCD controls the theoretical predictions for the production of any particle in both the SM and NP at hadron colliders.

QCD fixed order calculations and resummation

Fixed order calculations

$$d\sigma = f_a f_b \otimes \hat{\sigma} \otimes F$$

Proton parton distributions

Perturbative partonic cross section (virtual & real radiation)

Fragmentation models

Schematically:

$$\hat{\sigma} = \sigma_0 [1 + \alpha_s + \alpha_s^2 + \cdots]$$

Contains α_s^n of tree level process

NLO

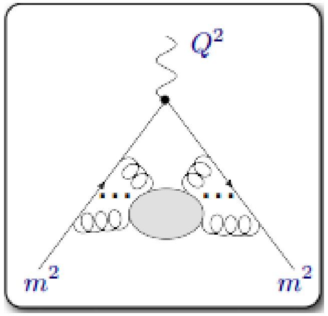
NNLO , current frontier

What Is Resummation

large logarithms $L = ln\frac{Q}{m}$, arising from hierarchy between small variable m and large scale Q, 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		
$\sigma = \sigma_0[$	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**
			$+\ \alpha_s^2$	$+\ \alpha_s^3 L^2$	$+\cdots$	**…**
				$+\ \alpha_s^3 L$	$+\cdots\ ]$	

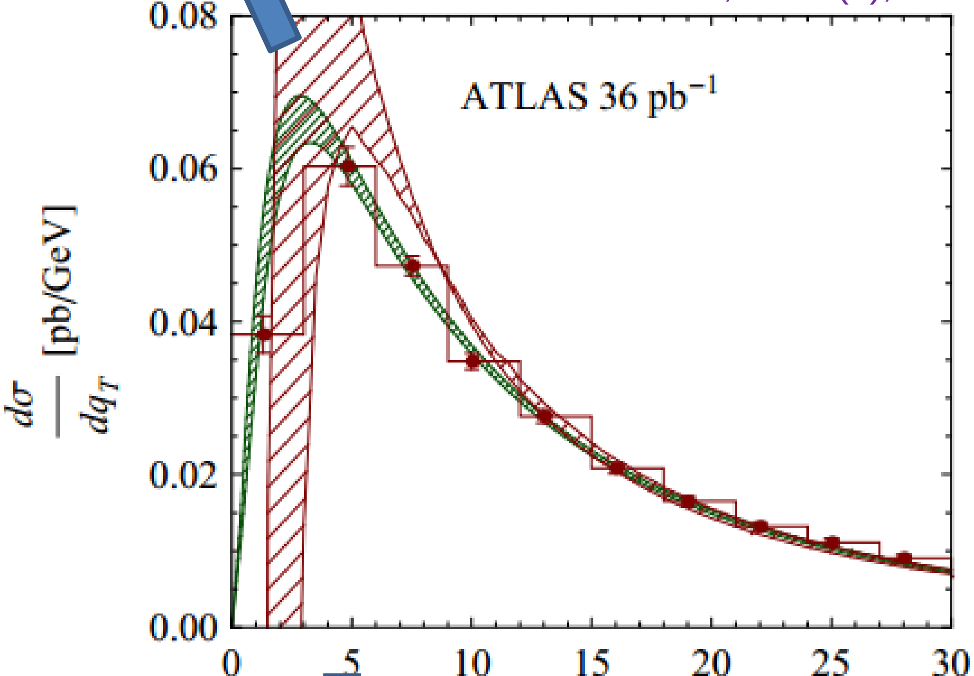
Fixed order

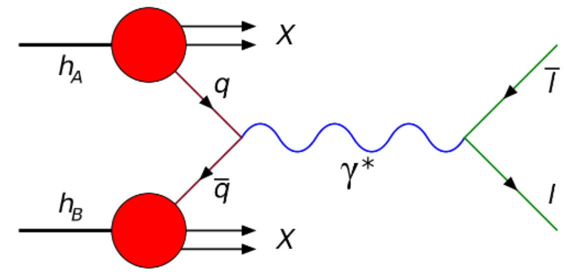
Example: Why Resummation

Fix order is invalid

Drell-Yan production

T. Becher. etc. JHEP, 2012 (2), 34.



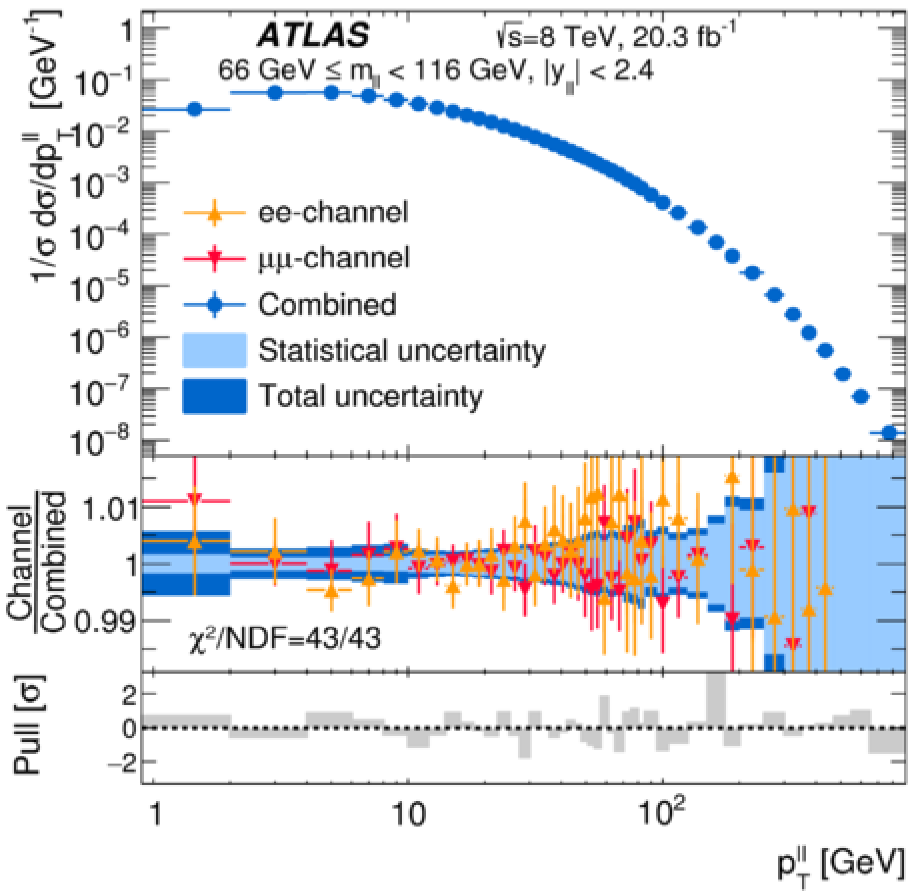


$$L = ln\frac{Q}{q_T}$$

experiment data
fix order
resummation

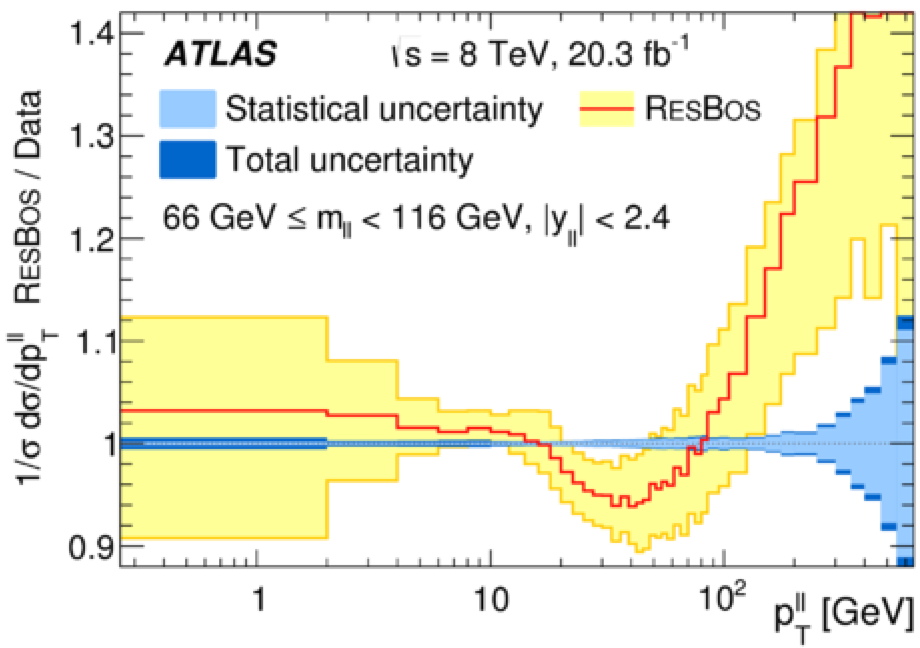
Cross section dominates at small q_T

LHC physics at 1% precision



Experimental uncertainties for Drell-Yan pT distribution at the level of 1%.

ATLAS 8 TeV
arXiv:1512.02192



Current theoretical uncertainties is significantly larger than experimental uncertainties.

Processes with Large Logs

Case 1: parton shower Monte Carlo

$$d\sigma = f_a f_b \otimes \underbrace{\hat{\sigma} \otimes PS_i}_{\text{Matrix elt. \& parton shower merging}} \otimes F$$

LO	NLO	NNLO	NNNLO	

$$\sigma = \sigma_0[1 + \alpha_s L^2 + \alpha_s^2 L^4 + \alpha_s^3 L^6 + \dots \text{ LL}$$
$$+ \alpha_s L + \alpha_s^2 L^3 + \alpha_s^3 L^5 + \dots$$
$$+ \alpha_s + \alpha_s^2 L^2 + \alpha_s^3 L^4 + \dots$$
$$+ \alpha_s^2 L + \alpha_s^3 L^3 + \dots$$
$$+ \alpha_s^2 + \alpha_s^3 L^2 + \cdots$$
$$+ \alpha_s^3 L + \cdots]$$

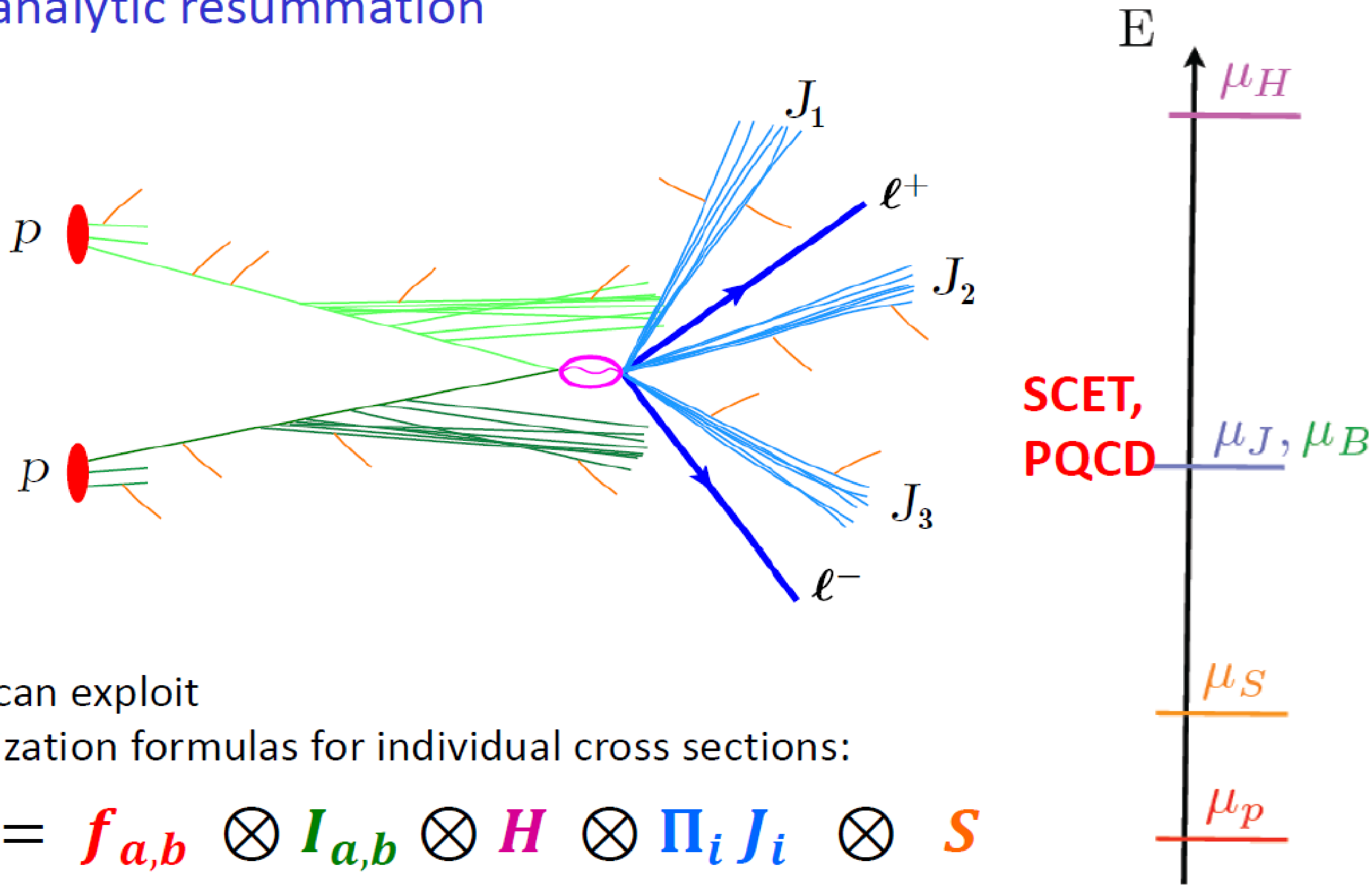
eg. $L = \ln(P_T^{cut}/m_H)$

Parton Shower
eg. Pythia is LL (+ tunning)
eg. MC@NLO is NLO+LL

- Automatically done for given hard process
- Full kinematics
- Difficult to go to higher orders

Processes with Large Logs

Case 2: analytic resummation



Often can exploit
Factorization formulas for individual cross sections:

$$d\sigma = f_{a,b} \otimes I_{a,b} \otimes H \otimes \Pi_i J_i \otimes S$$

Scales: Λ_{QCD} μ_B μ_H μ_J μ_S

Part 2

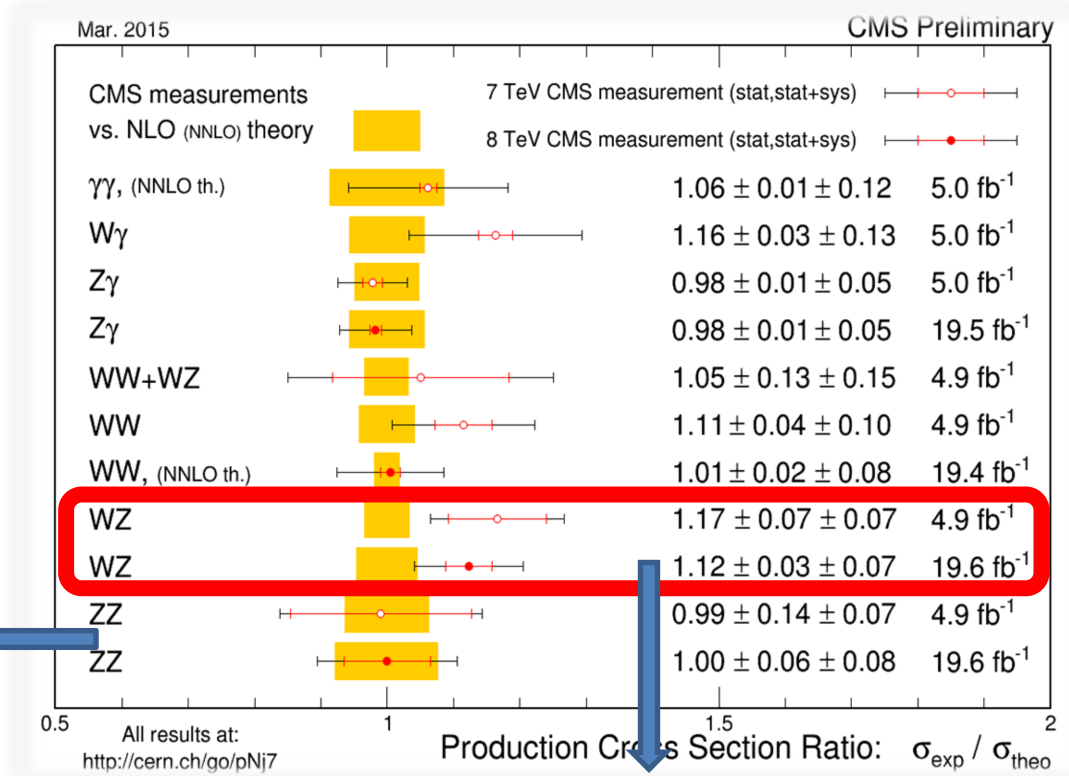
Electroweak Gauge Boson Pair production

- Threshold resummation
- Transverse momentum resummation
- Jet veto resummation

The Total Cross Section for WZ Production

ATLAS	8	13	$20.3^{+0.8}_{-0.7}(stat.)\ ^{+1.2}_{-1.1}(syst.)^{+0.7}_{-0.6}(lumi.)$	20.3 ± 0.8
CMS	8	19.6	$24.61 \pm 0.76(stat.) \pm 1.13(syst.) \pm 1.08(lumi.)$	$21.91^{+1.17}_{-0.88}$

lumi. exp. NLO



The measurements for ZZ production is consistent with NLO predictions, But the NNLO corrections for ZZ production increase the NLO result by 12% when $\sqrt{s}$=8 TeV

CMS PAS SMP-13-005

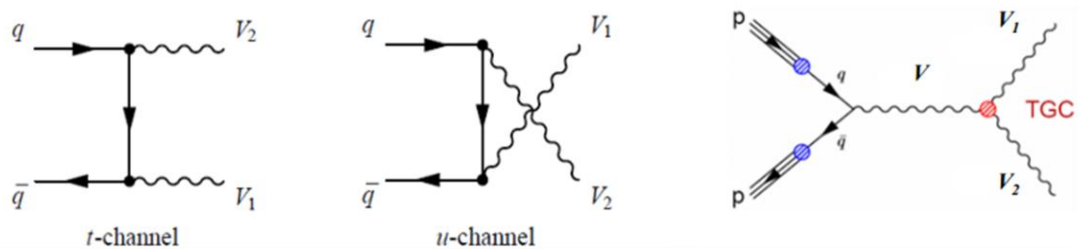
F. Cascioli, et al., PLB 735, 311 (2014)

There are about 2σ discrepancies for WZ productions in the CMS measurements

CMS PAS SMP-12-006

Testing Standard Model (TGCs)

LO production diagram



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

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

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

TGC ---- fundamental predictions of the non-Abelian SU(2)×U(1) gauge structure of electroweak theory.

带电规范玻色子和中性规范玻色子耦合的一般形式，可以有效拉式量表示为（Hagiwara et al, NP,1987）：

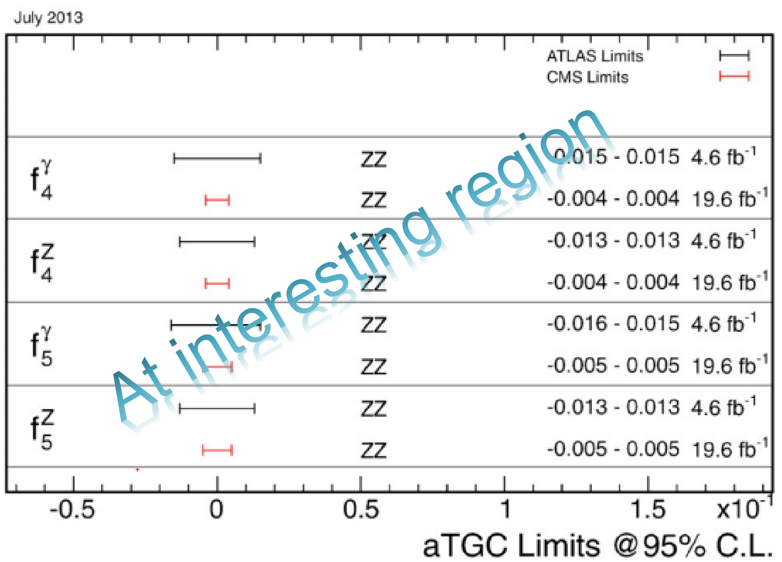
In SM, no neutral TGC vertex at LO.

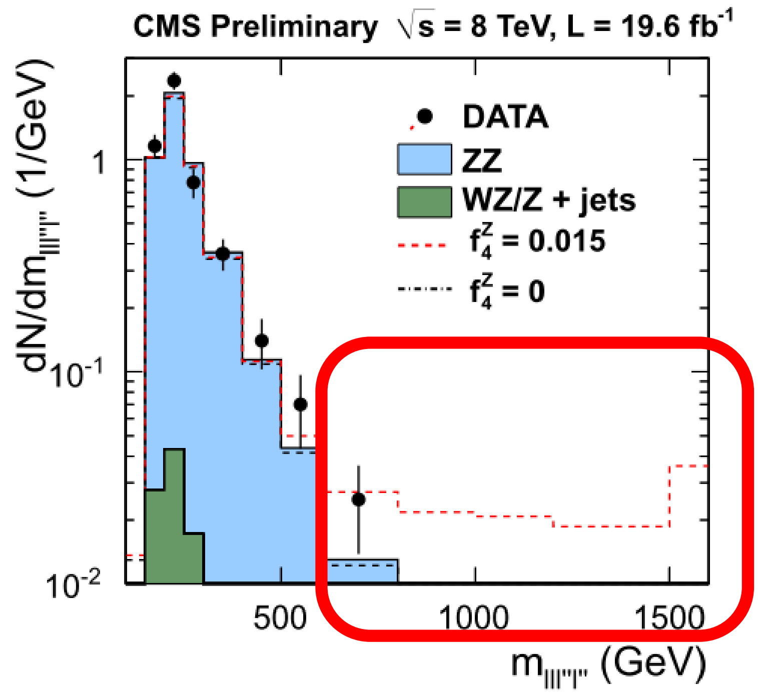
Charged TGC vertex at LO are only

$$\lambda_\gamma = \lambda_Z = 0$$
$$g_Z^1 = \kappa_\gamma = \kappa_Z = 1$$

G. J. Gounaris, et. al. Phys. Rev. D 62, 073013 (2000).
K. Hagiwara, et. Al. NPB 282 253 (1987).

Testing Standard Model (TGCs)





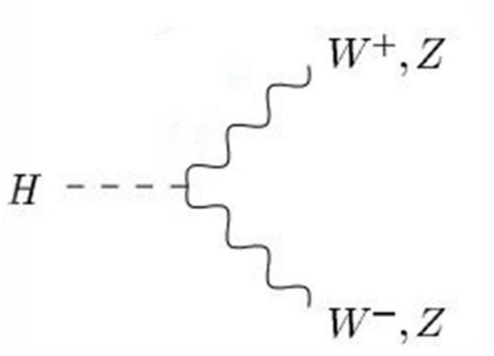
At the one-loop level, fermion triangles generate nTGCs : 10^{-4},
G. J. Gounaris, et. al. PRD 62, 073013 (2000).

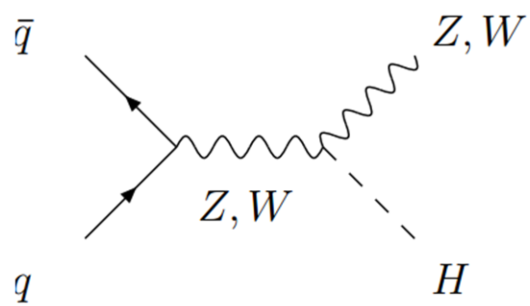
Many new physics models predict values of nTGCs :$10^{-4} \sim 10^{-3}$.
J. Ellison and J.Wudka, Annu. Rev. Nucl. Part. Sci. 48,33 (1998).

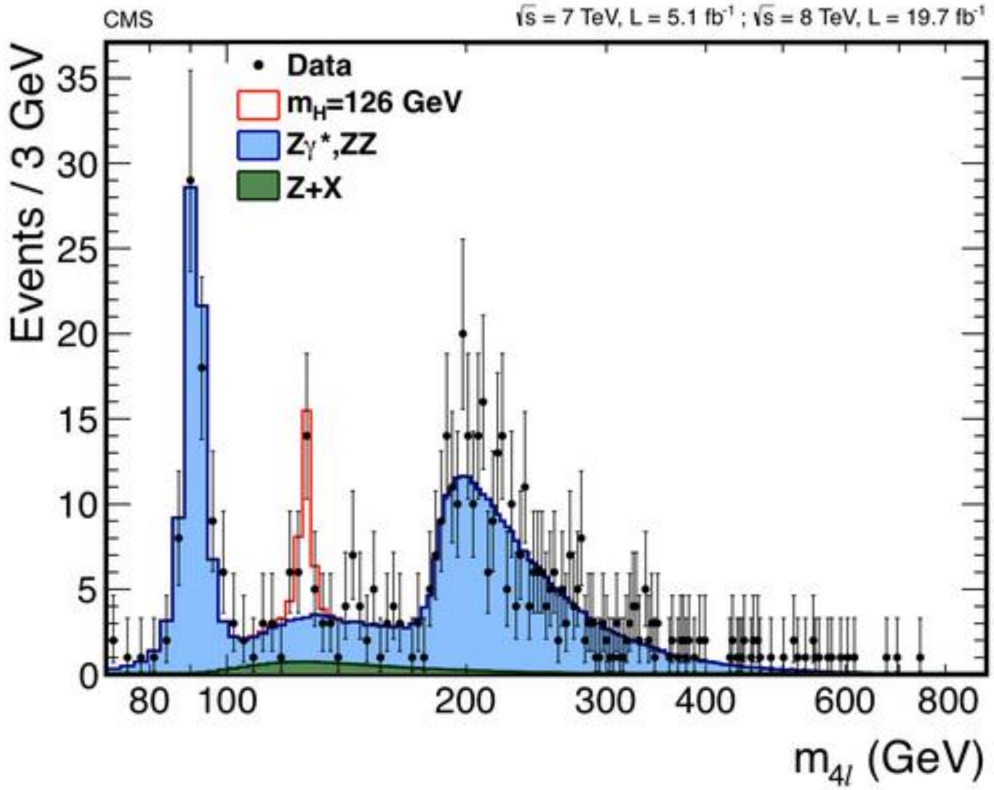
aTGC effects: often increase cross sections at high invariant mass (M_{VV}) and its proxies (q_T)

U. Baur et. al. PRD 53, 1098 (1996)

Irreducible Background



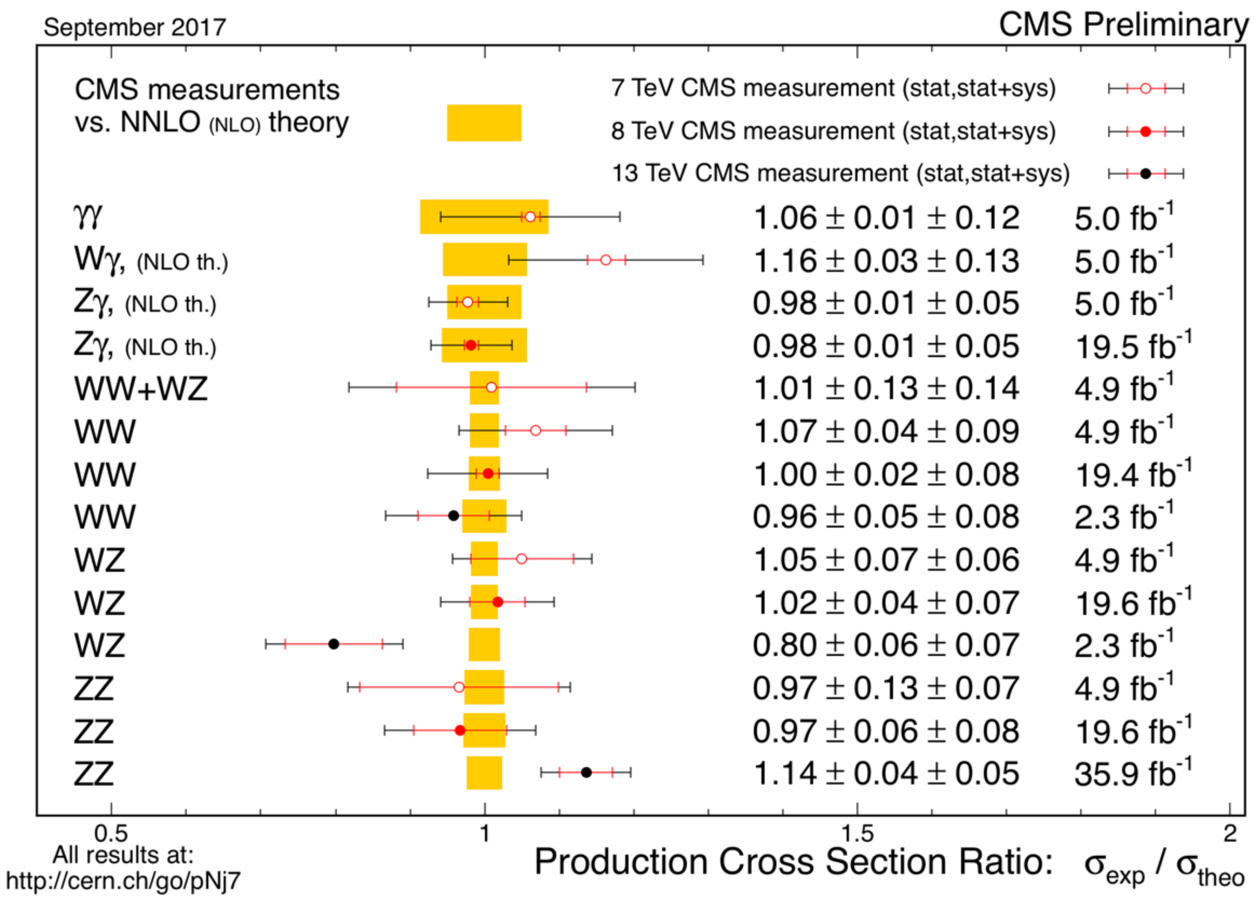




CMS Collaboration, Phys. Rev. D 89, 092007 (2014)

Also: **models with extended Higgs sectors, extra vector bosons, extra dimensions or models such as Supersymmetry and Technicolor.**

Fixed-Order QCD Correction



WW NNLO: T. Gehrmann, et al., Phys.Rev.Lett. 113, 212001 (2014)
ZZ NNLO: F. Cascioli, et al., Phys.Lett. B 735, 311 (2014)

Threshold Resummation

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

Generic observable in hadronic collisions :

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

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

$$C(z, \alpha_s) = \delta(1-z) + \sum_n^\infty C_n(z) \alpha_s^n; \quad z = \frac{M^2}{\hat{s}}$$

When z $\rightarrow 1$

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

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

Factorization Formulas

In the threshold limit , the cross section can be factorized as

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

The renormalization-group equation for the hard function is

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

The soft function is defined as

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

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

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

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

where

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

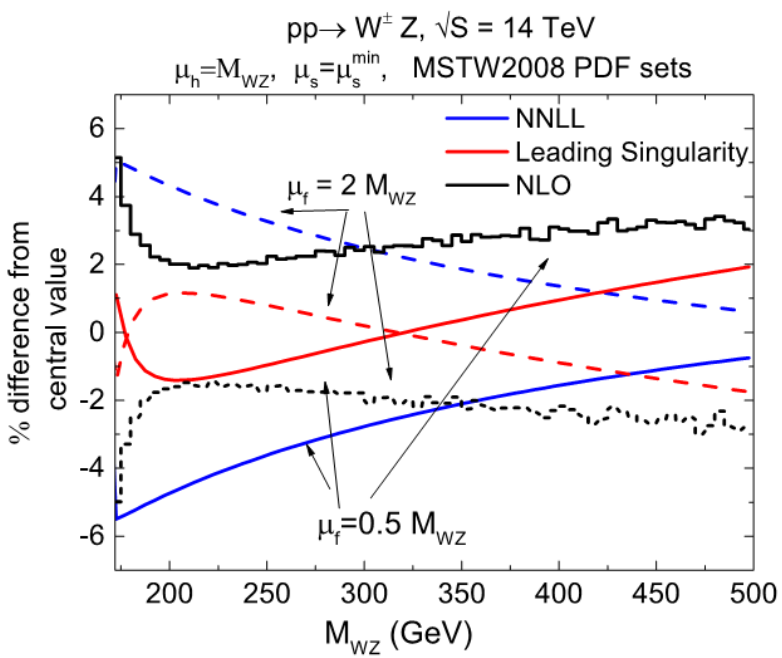
and $C(M_{VZ},\mu_h,\mu_s,\mu_f)$ can be written as

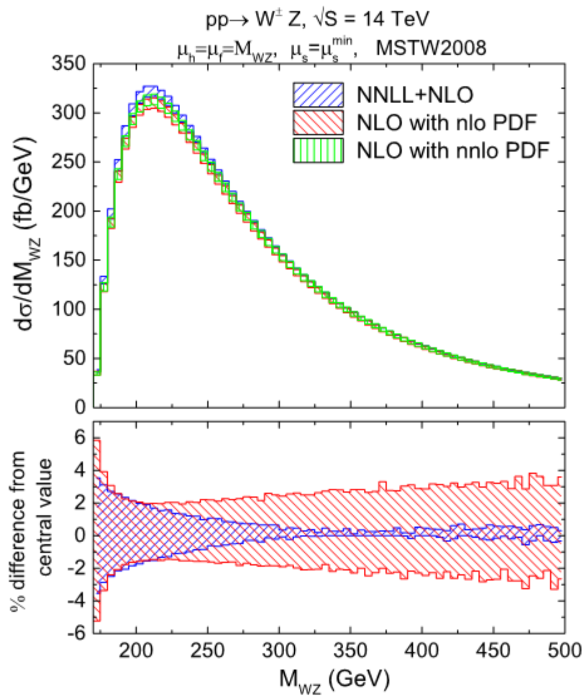
$$\begin{aligned}
&C(M_{VZ},\mu_h,\mu_s,\mu_f) \\
&\quad = \exp\left[4S(\mu_h,\mu_s) - 2a_{\gamma^V}(\mu_h,\mu_s) + 4a_{\gamma^\phi}(\mu_s,\mu_f)\right] \\
&\qquad \times \left(\frac{M_{VZ}^2}{\mu_h^2}\right)^{-2a_\Gamma(\mu_s,\mu_h)} \frac{(1-z)^{2\eta-1}}{z^\eta} \\
&\qquad \times \tilde{s}\left[\ln\left(\frac{(1-z)^2 M_{VZ}^2}{z\mu_s^2}\right) + \partial_\eta,\mu_s\right] \frac{e^{-2\gamma\eta}}{\Gamma(2\eta)}.
\end{aligned}$$

Factorization Scale Dependence

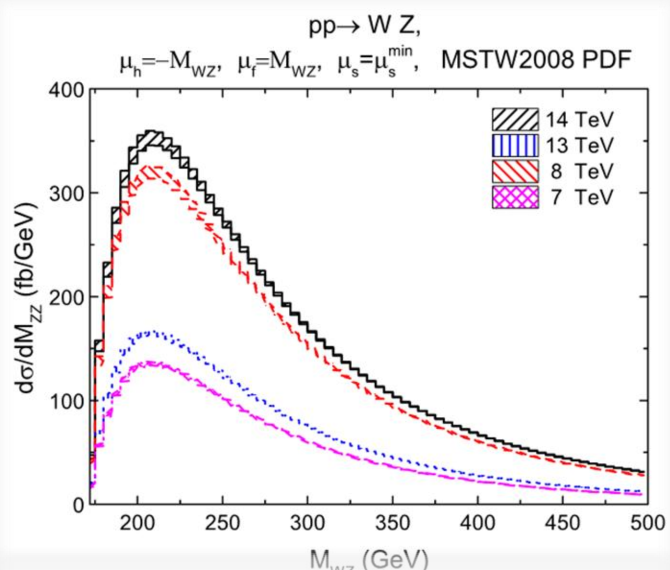
In order to get the total cross section, we should including the nonsingular terms ：

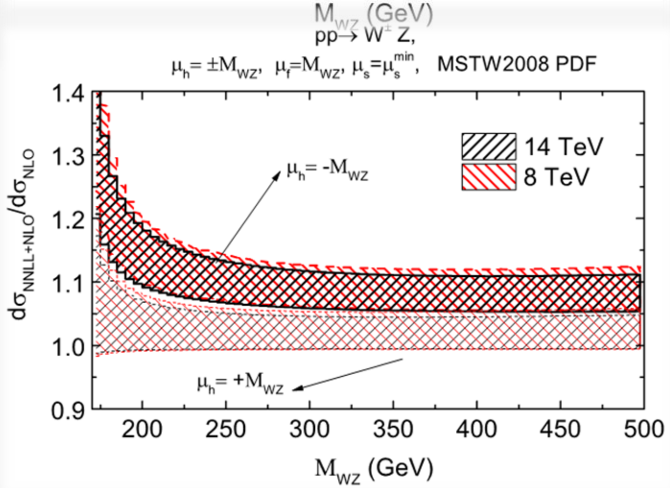
$$\frac{d\sigma^{\mathrm{NNLL+NLO}}}{dM_{VZ}^2} = \frac{d\sigma^{\mathrm{NNLL}}}{dM_{VZ}^2} + \left(\frac{d\sigma^{\mathrm{NLO}}}{dM_{VZ}^2} - \frac{d\sigma^{\mathrm{NNLL}}}{dM_{VZ}^2}\right)_{\text{expanded to NLO}}.$$



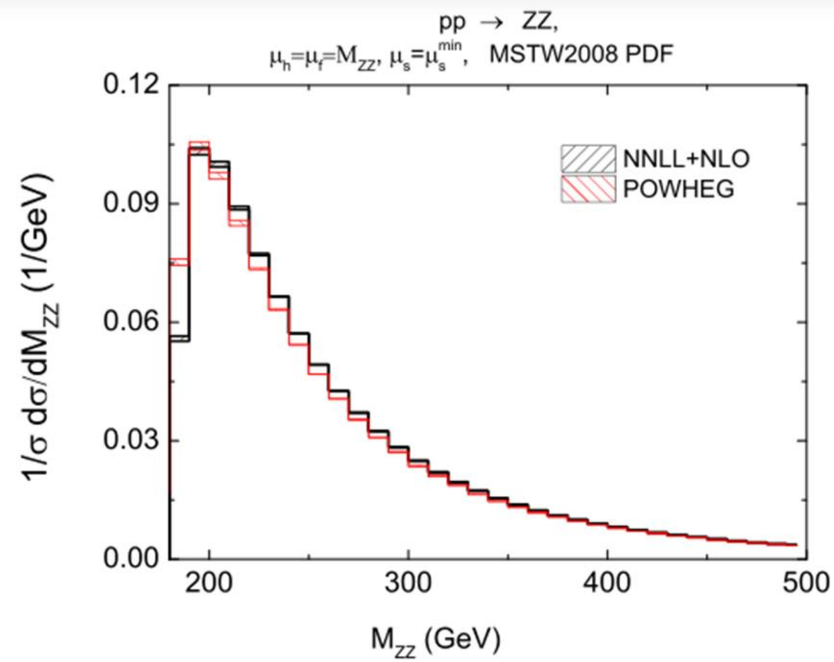


The Invariant Mass Distribution



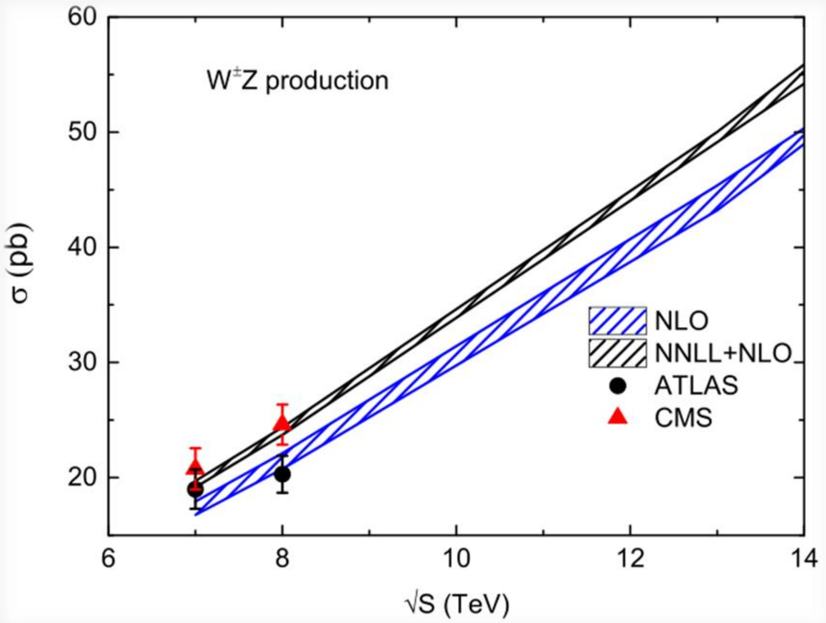


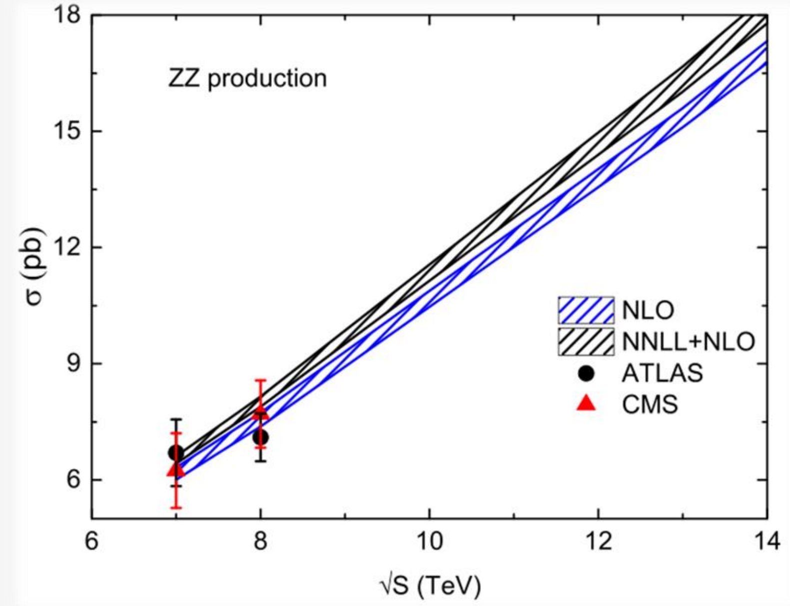
Compare the normalized invariant mass distribution with the predictions by POWHEG



The invariant mass distributions with $\mu_h^2 = -M_{V_1V_2}^2, \mu_f = M_{V_1V_2}, \mu_s = \mu_s^{min}$.

Compare with Experiments: The Total Cross Section





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

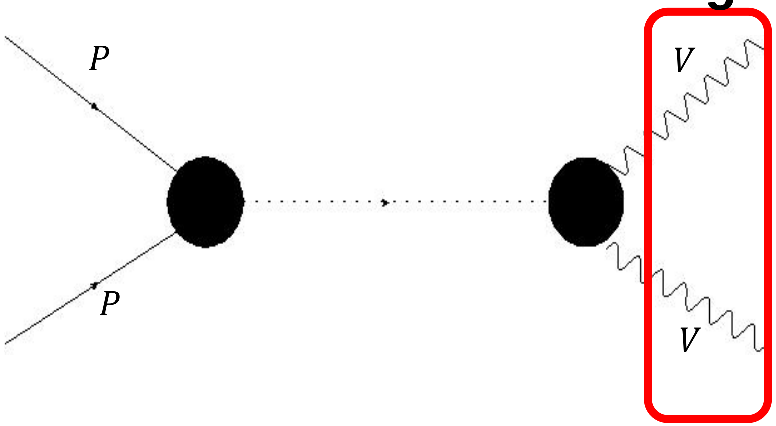
Transverse-momentum resummation

Y. Wang, C.S. Li, L.Z. Liu, D.Y. Shao and H.T. Li, PRD, 88,114017(2013)

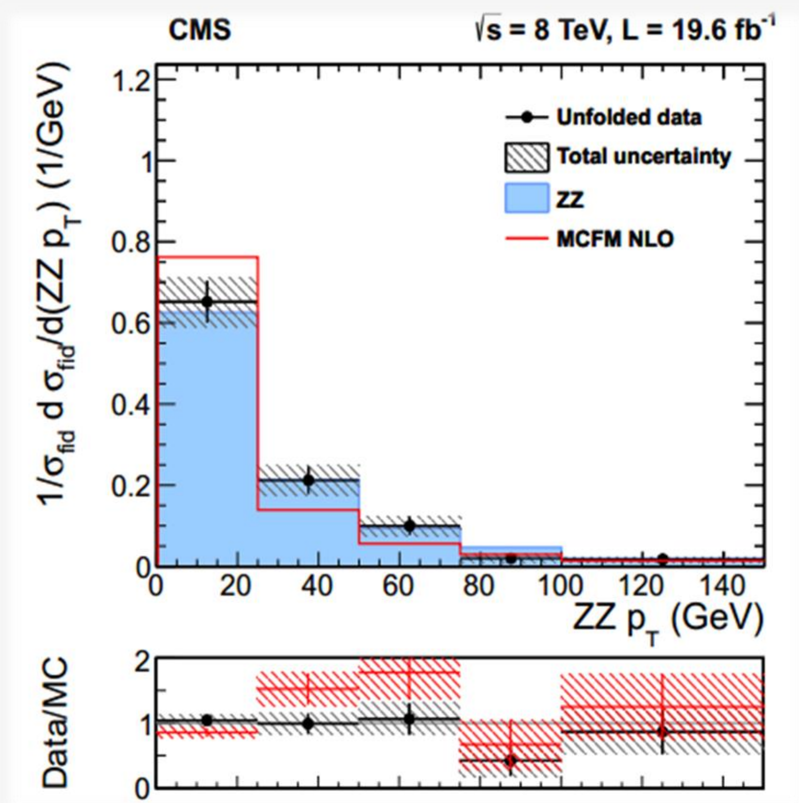
如果新物理的一个大质量共振态与规范玻色子对之间存在耦合，则在对撞机上该共振态可通过s 道衰变得到规范玻色子对，其运动学分布与标准模型情形可能存在很大差异，因而将规范玻色子对当作一个整体，其整体横动量分布可以作为探测新物理的一个重要观测量。

q_T **Distribution**

bind together



CMS-PAS-SMP-13-005



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

Factorization Formulas In SCET

The factorized differential cross section can be written as

$$\frac{d^3\sigma}{dq_T^2 dy dM^2} = \frac{1}{S}\mathcal{H}_{V_l V_m}(M,\mu_f)\frac{1}{4\pi}\int d^2x_\perp e^{-iq_\perp\cdot x_\perp} \times \sum_{q,q'}[\mathcal{B}_{q/N_1}(z_1,x_T^2,\mu_f)\mathcal{B}_{q'/N_2}(z_2,x_T^2,\mu_f) + (q\leftrightarrow q')], \quad ($$

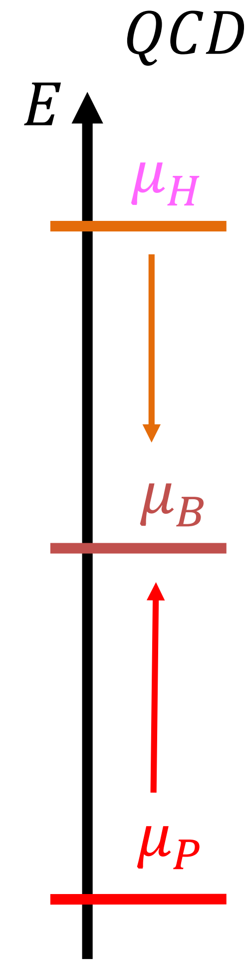
where $\mathcal{B}_{q/N}$ is the transverse-momentum-dependent PDFs, which is defined by operator product expansion.

Combining the evolution effects of the hard function and beam function, the factorized differential cross section is

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

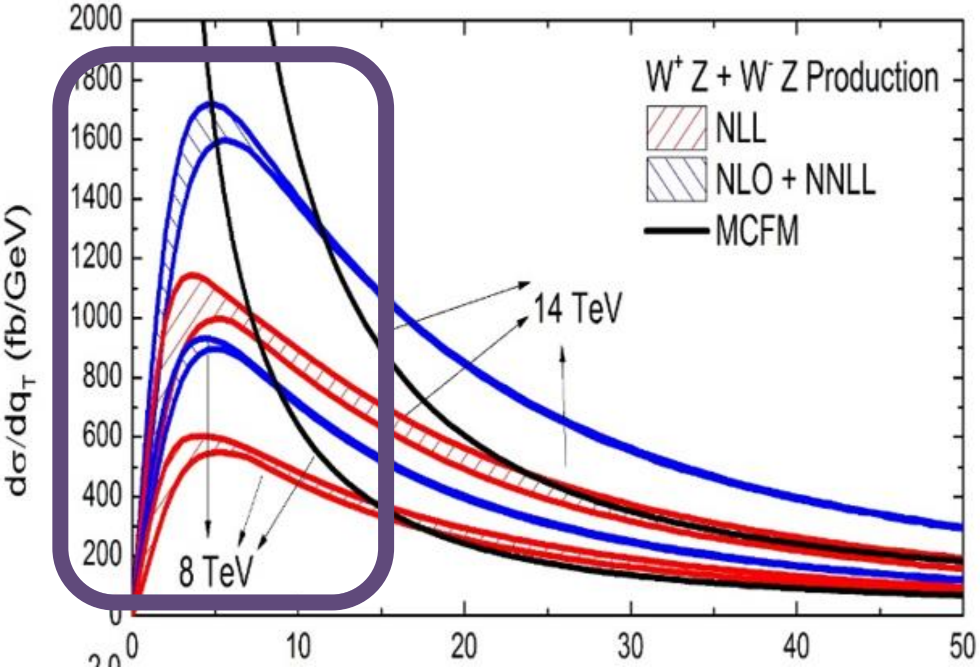
where

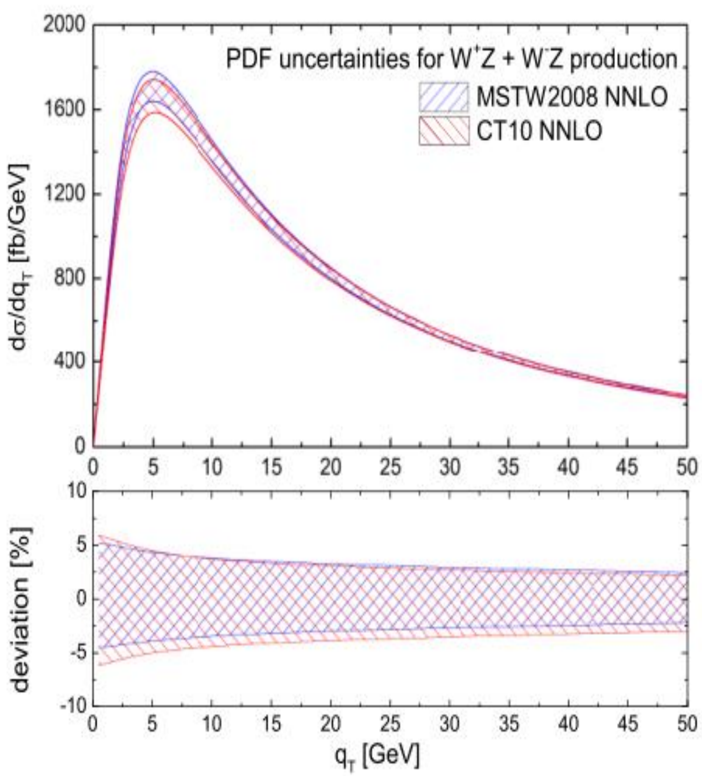
$$\bar{C}_{qq'\to ij}\left(z_1,z_2,q_T^2,\mu_f\right) = \frac{1}{2}\int_0^\infty dx_T x_T J_0(x_T q_T)\ \exp\left[g_F(\eta,L_\perp,\alpha_s)\right] \times\left[\bar{I}_{q\leftarrow i}(z_1,L_\perp,\alpha_s)\bar{I}_{q'\leftarrow j}(z_2,L_\perp,\alpha_s)\right],$$



Theoretical Uncertainties

Scale uncertainties:
$\Delta\sigma \leq$ **1%, when** $q_T > 10$ **GeV.**
$\Delta\sigma \leq$ **4%, at peak position.**

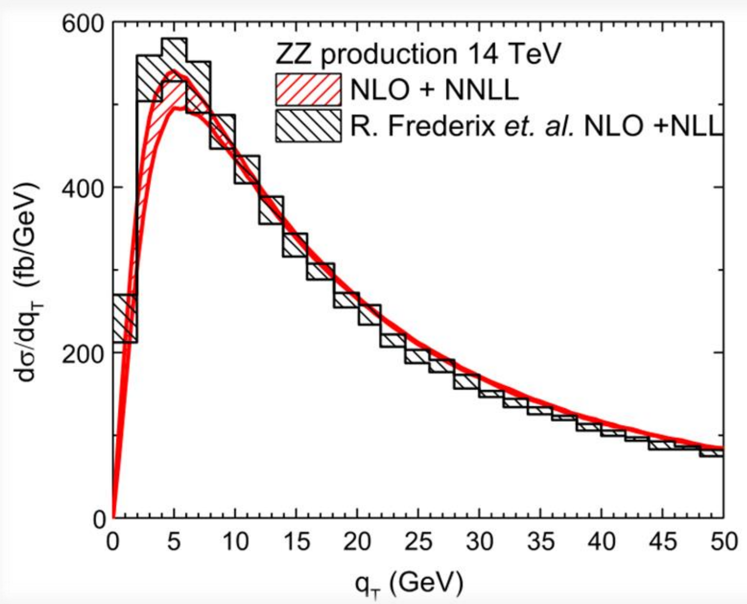


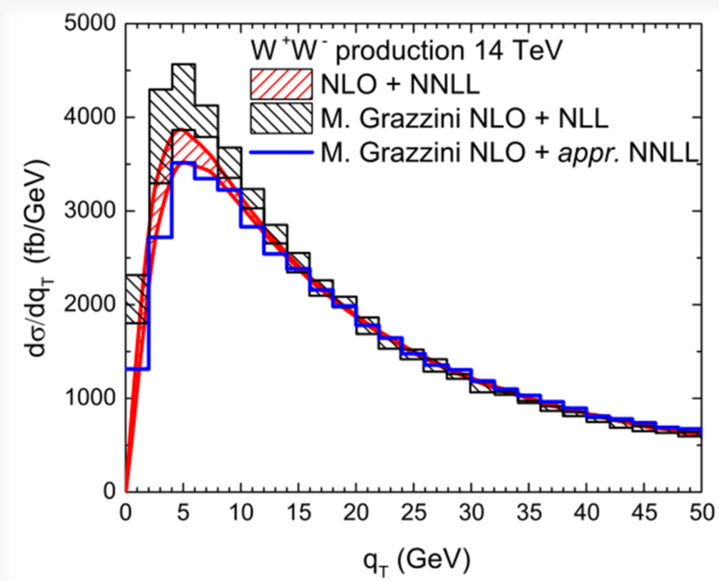


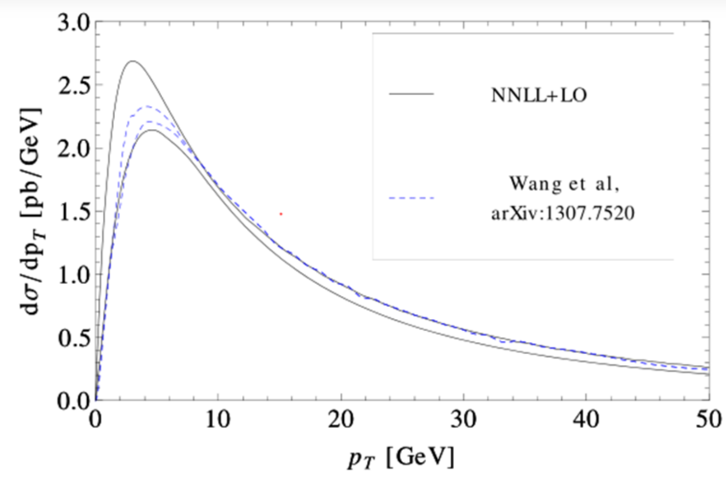
PDF uncertainties
In the large q_T **region: <2.5%**
In the peak position: <4%,

with MSTW2008 NNLO 90cl and CT10 NNLO 90cl.

Compare With Other Work



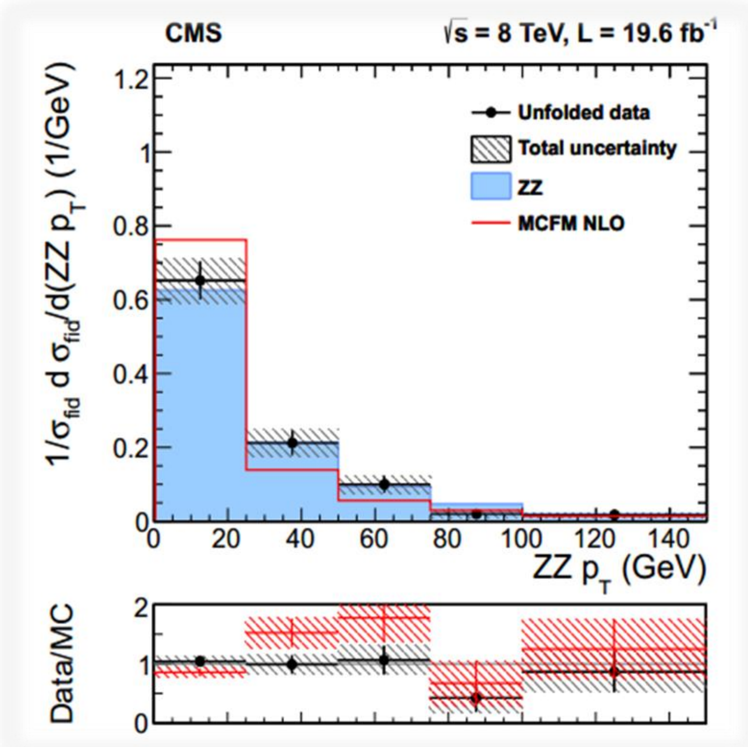




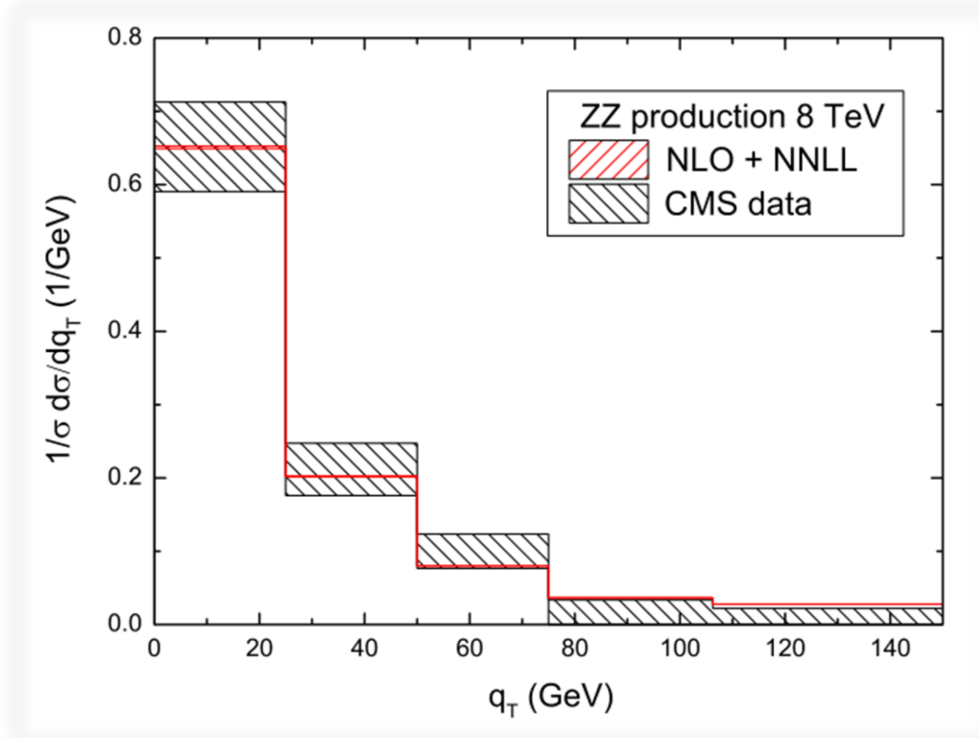
Compare the results in the SCET framework with the prediction in CSS framework.

P. Meade, H. Ramani, M. Zeng, Phys. Rev. D 90, 114006 (2014)

Compare With Experiments



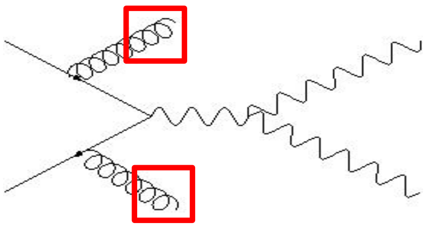
CMS-PAS-SMP-13-005

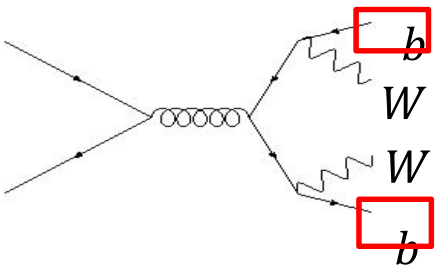


Compare with the data with $19.6\ fb^{-1}$ at $\sqrt{s} = 8$ TeV at the LHC by the CMS collaboration.

Jet Veto Resummation

Required $p_T < p_{T,veto}$





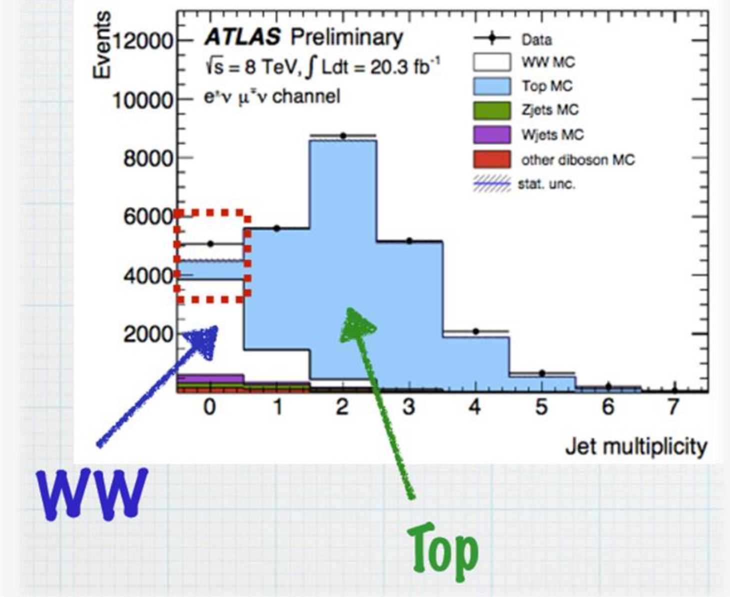
Jet veto: **Allow jets with low transverse momentum** $p_T^{jet} < p_T^{veto} \sim 15 - 30$ **GeV**

why ?

Suppress backgrounds

(particularly top-quark backgrounds)

ATLAS-CONF-2014-033

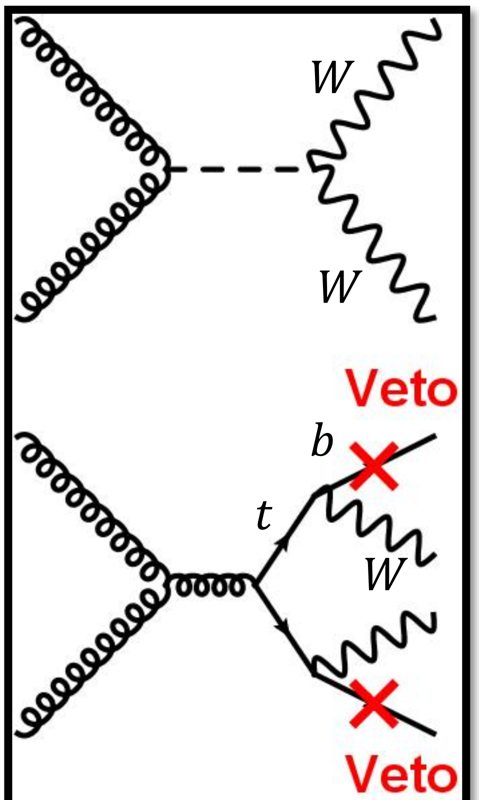


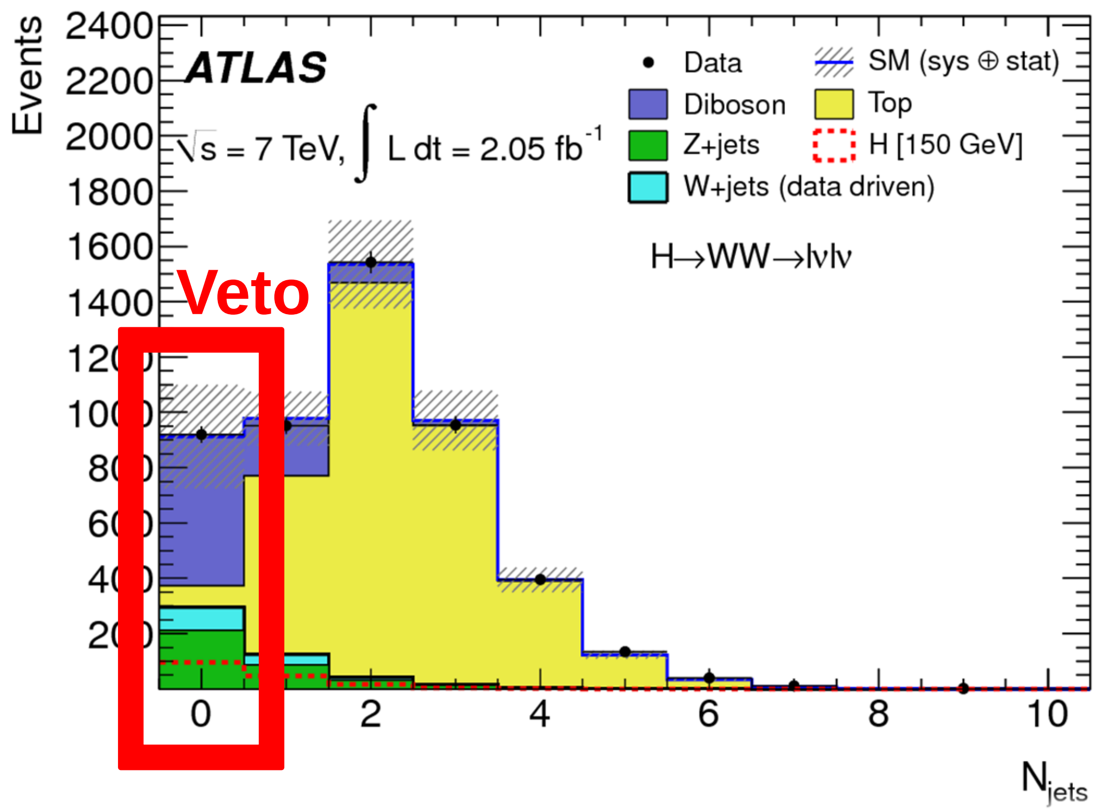
Multiple scales $\Rightarrow$ $\alpha_s^n \ln^k\left(\frac{p_T^{veto}}{Q}\right)$

Resummation

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.

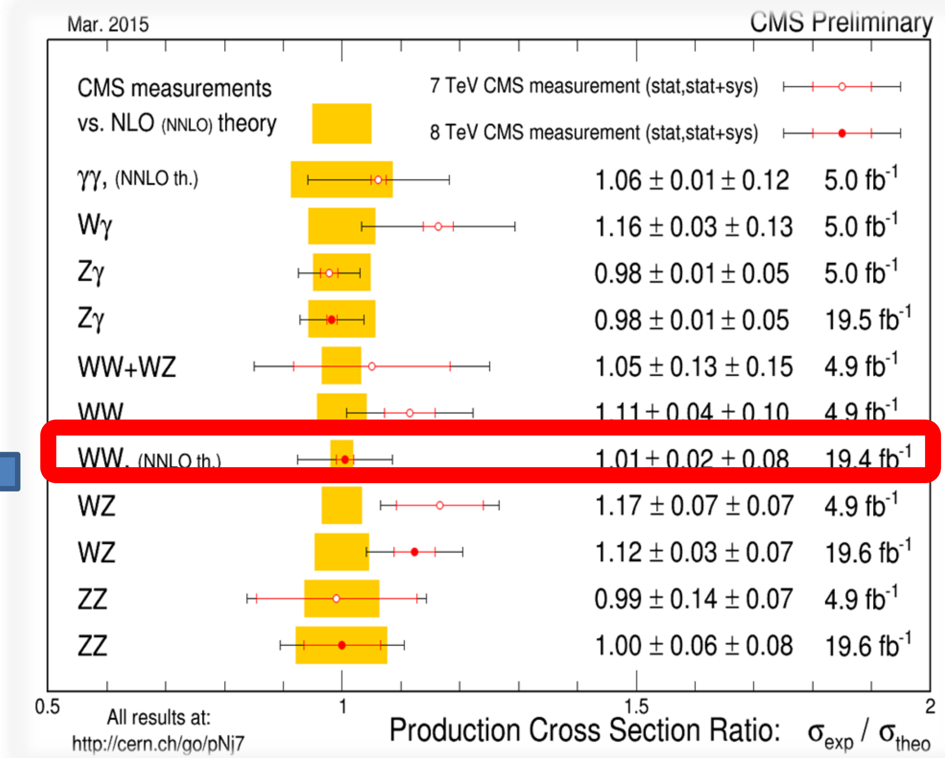




The Total Cross Section for WZ, ZZ Production with a jet veto

Y.Wang, C.S. Li and Z.L. Liu, PRD,93,094023 (2016)

CMS PAS SMP-14-016



The WW cross section is consistent with the NNLO theoretical prediction, where the simulated signal events generated by POWHEG are reweighted by the NNLL transverse momentum resummation predictions.

Experimental data for WW production

ATLAS	8	20.3	$71.4^{+1.2}_{-1.2}(stat.)$ $^{+5.0}(syst.)^{+2.2}(lumi.)$	$58.7^{+3.0}_{-2.7}$
CMS	8	3.5	$69.9 \pm 2.8(stat.) \pm 5.6(syst.)$ $\pm 3.1(lumi.)$	$57.3^{+2.3}_{-1.6}$ (NLO)
CMS	8	19.4	$60.1 \pm 0.9(stat.) \pm 3.2(exp.)$ $\pm 3.1(th.) \pm 1.6(lumi.)$	$59.8^{+1.3}_{-1.1}$ (NNLO)

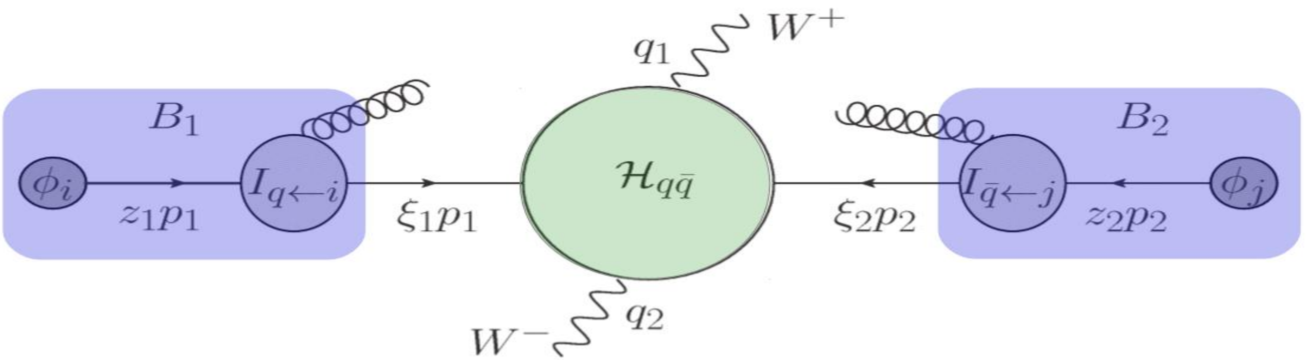
We may apply this method to WZ and ZZ productions

RG-improved cross section

$$\frac{d\sigma}{dy} = \sigma_0 \mathcal{H}_{VV}(-q^2,\mu)\mathfrak{B}_c(\xi_1, p_T^{\text{veto}},\mu)\mathfrak{B}_{c'} \times (\xi_2, p_T^{\text{veto}},\mu)\mathcal{S}(p_T^{\text{veto}},\mu)$$

$$\mathfrak{B}_c(\xi_1,p_T^{\text{veto}},\mu)\mathfrak{B}_{c'}(\xi_2,p_T^{\text{veto}},\mu)\mathcal{S}(p_T^{\text{veto}},\mu) = \left(\frac{M^2}{p_T^{\text{veto}2}}\right)^{-F_{cc'}(p_T^{\text{veto}},\mu)} e^{2h_F(p_T^{\text{veto}},\mu)} \bar{B}(z_1,p_T^{\text{veto}},\mu)\bar{B}(z_2,p_T^{\text{veto}},\mu).$$

$$\bar{B}_c(\xi, x_T^2,\mu) = \sum_i \int \frac{dz}{z}\phi_c(\xi/z,\mu)\bar{I}_{i\leftarrow j}(z,x_T^2,\mu).$$



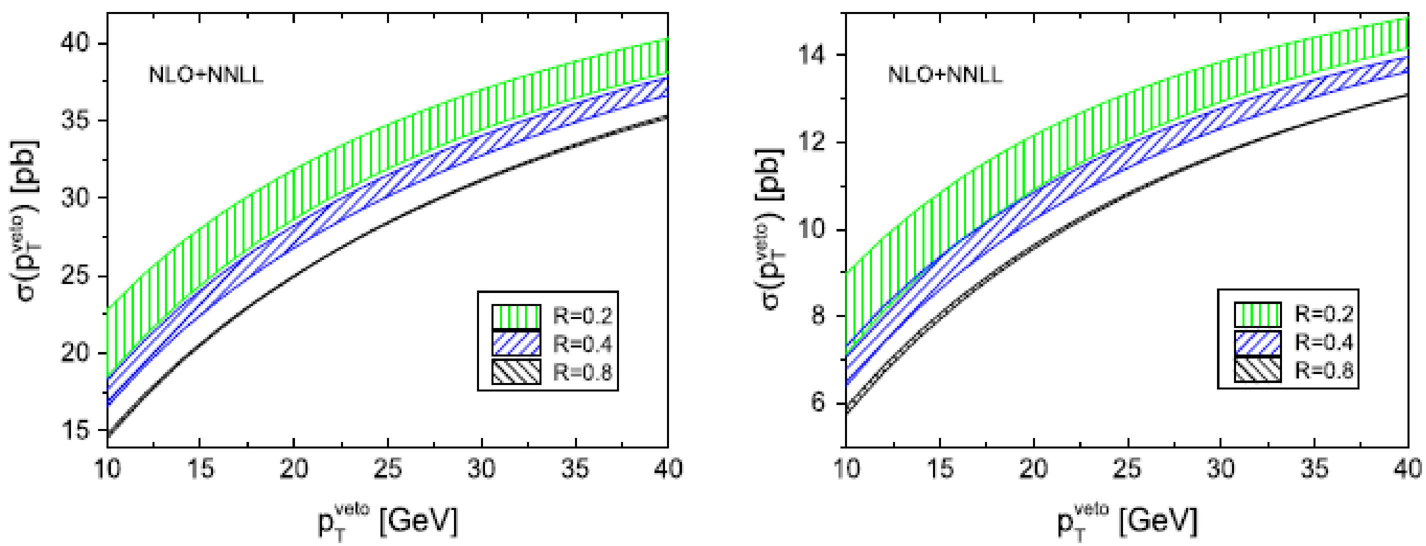


FIG. 6. The NLO + NNLL total cross sections for different R with $\sqrt{S} = 14$ TeV. The left figure is for $W^{\pm}Z$ production and the right one is for ZZ production.

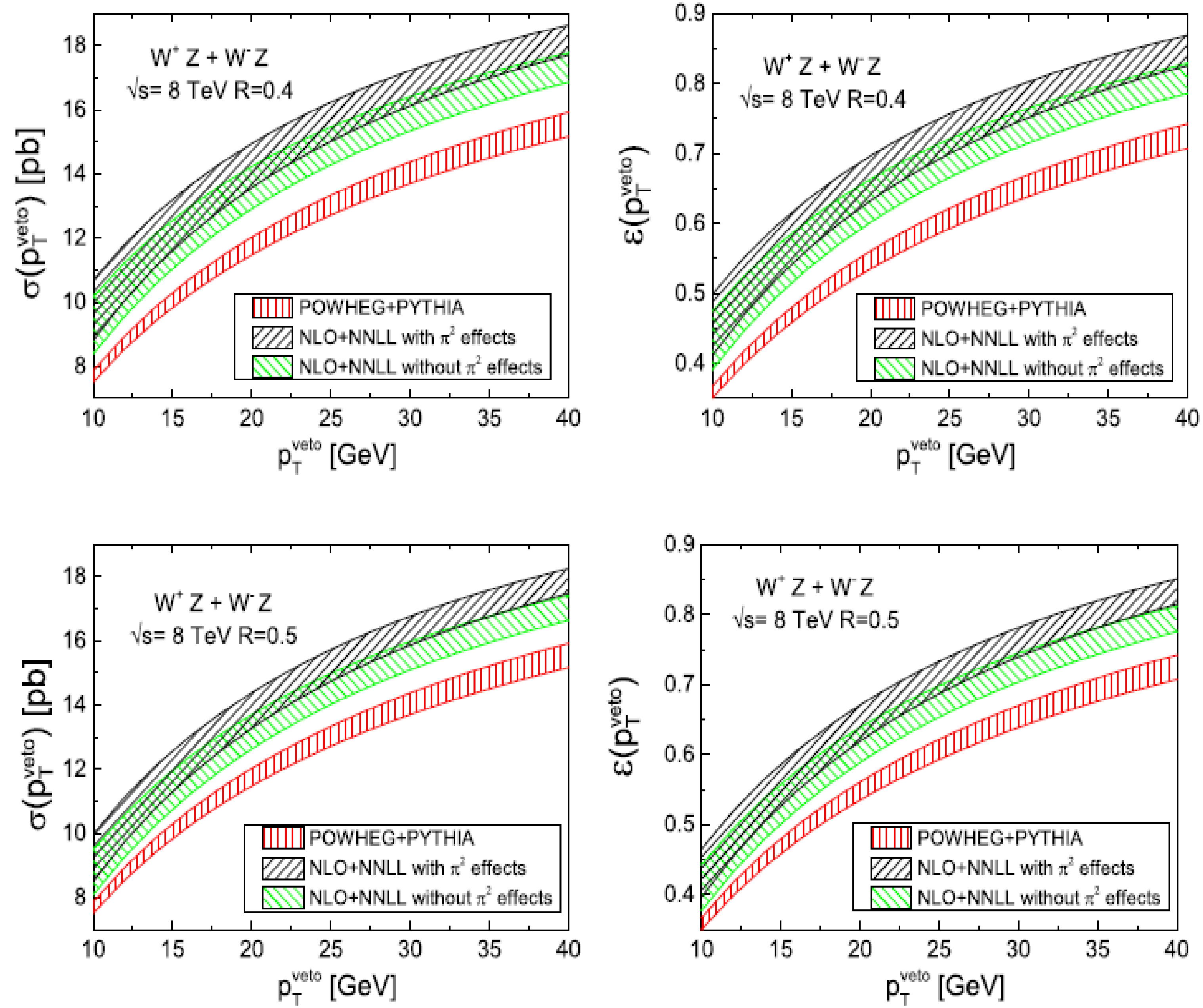


FIG. 8. Comparison of the POWHEG+PYTHIA results and the NLO + NNLL predictions, as well as their efficiencies, for $W^{\pm}Z$ production with $R = 0.4$ and $R = 0.5$ at $\sqrt{S} = 8$ TeV, respectively.

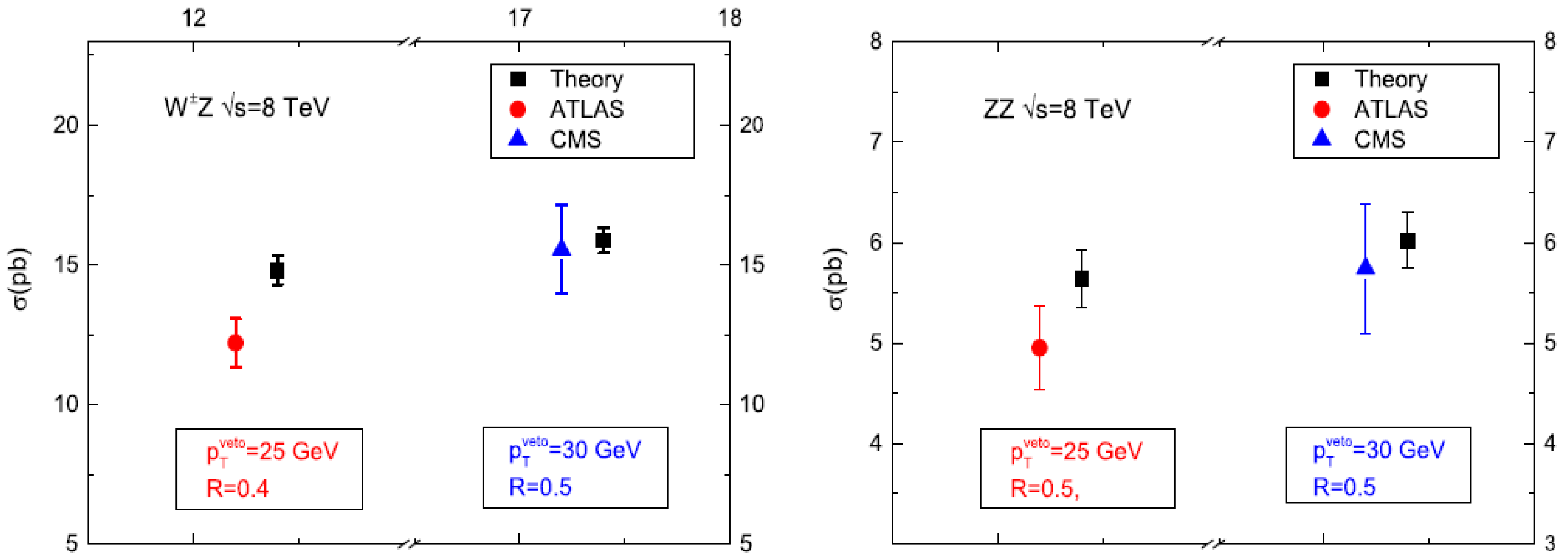
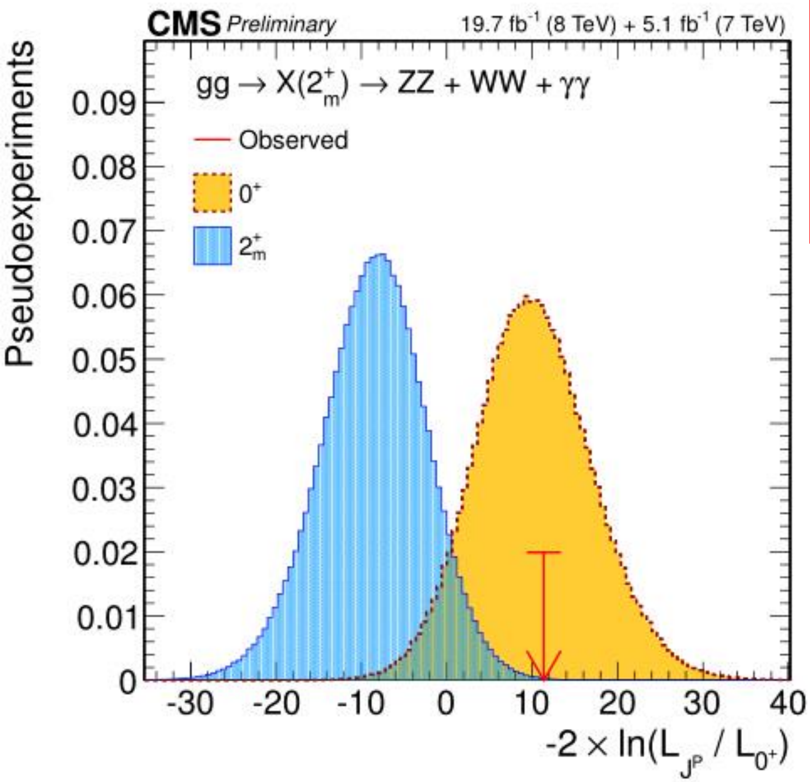


FIG. 15. Comparison of total cross sections for $W^{\pm}Z$ and ZZ production between experimental data and the resummation prediction at the LHC with $\sqrt{S} = 8$ TeV.

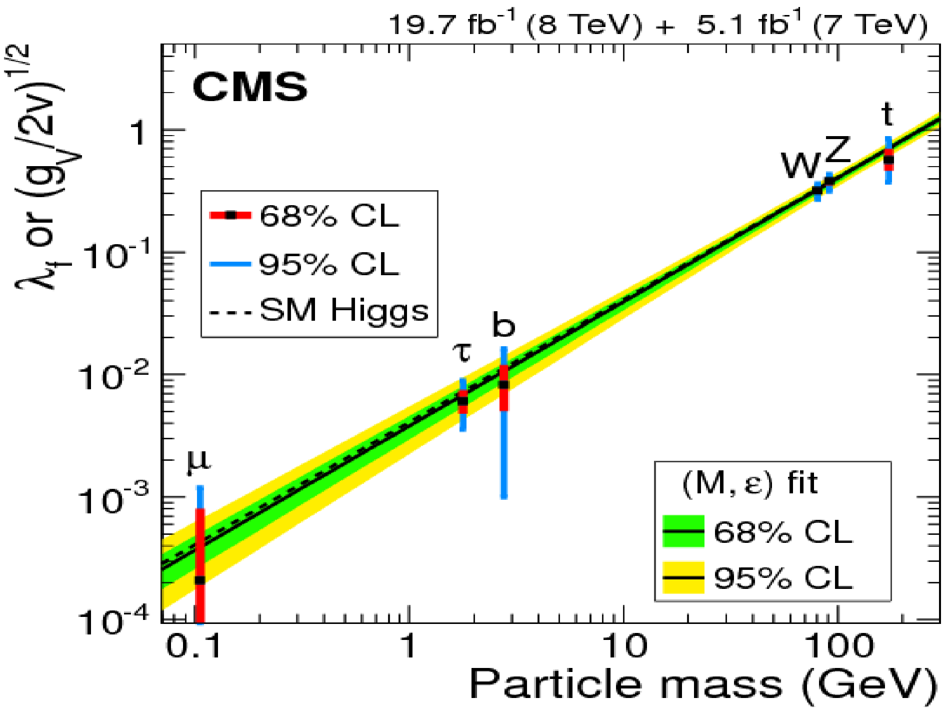
Part 3

Vhh production at NNLO

Measuring Higgs couplings



CP-even spin 0 hypothesis strongly preferred.
No significant deviations from SM couplings.
Data up to now are consistent with a SM Higgs boson.



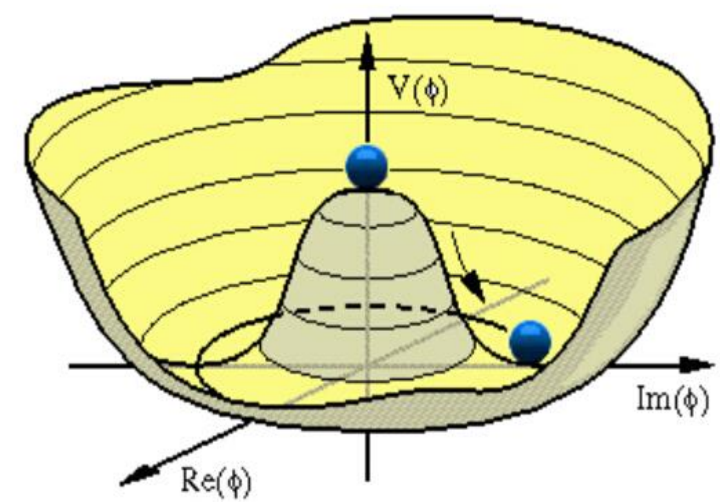
Higgs self-couplings

In SM, the electroweak symmetry breaking is triggered by a special Higgs potential

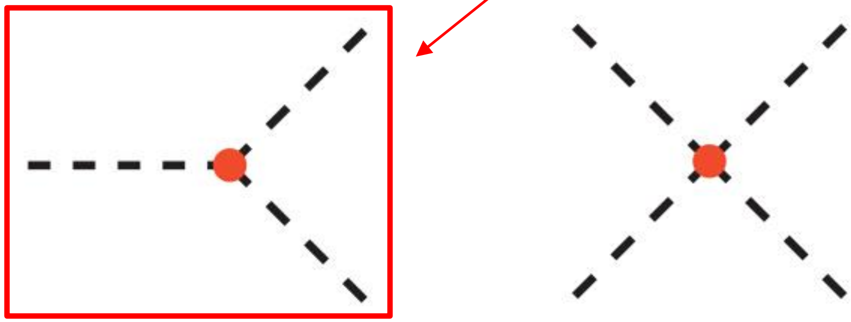
Measuring Higgs self-couplings is important

- ✓ clarify the Higgs potential
- ✓ test the electroweak symmetry breaking mechanism

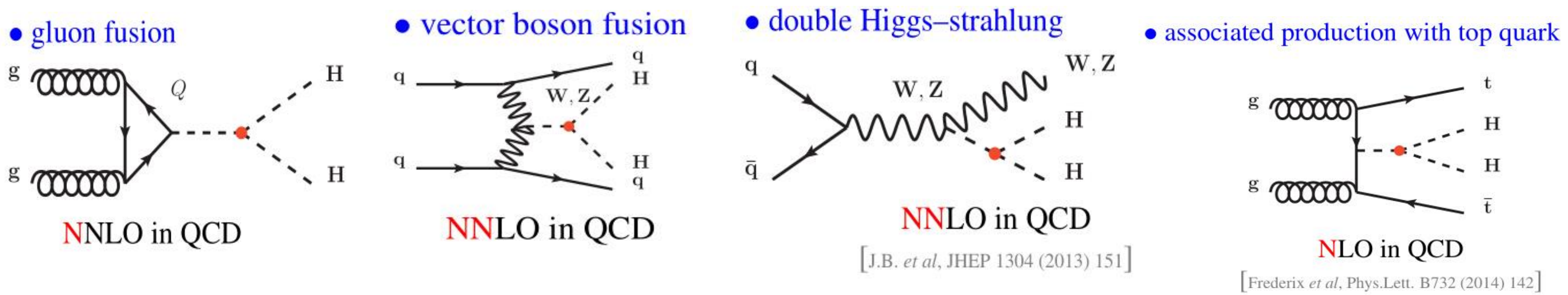
$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

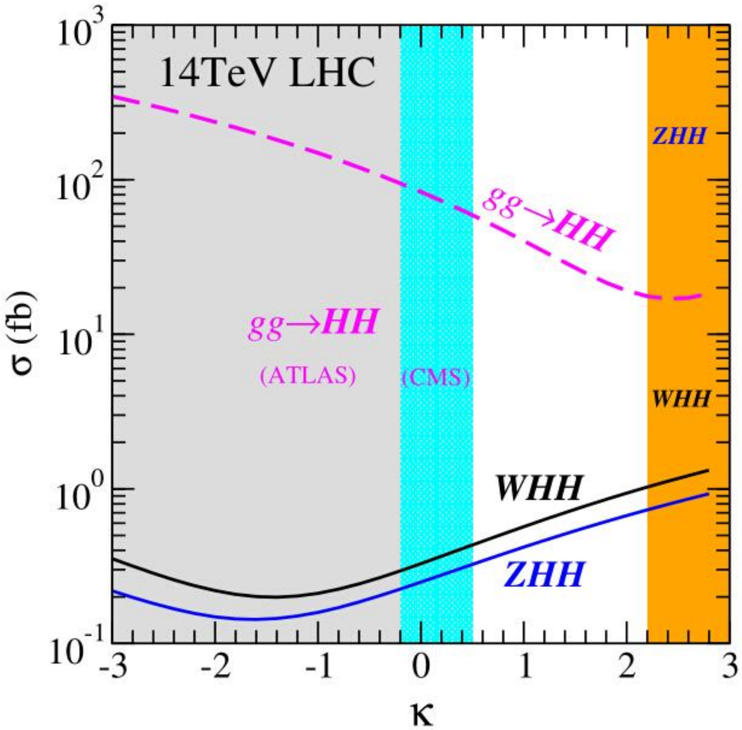


$$\phi = \left(\begin{array}{c} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{array}\right) \Rightarrow V(H) = \frac{1}{2}M_H^2 H^2 + \frac{1}{2}\frac{\mathbf{M_H^2}}{\mathbf{v}}\mathbf{H^3} + \frac{1}{8}\frac{M_H^2}{v^2}H^4$$



The trilinear Higgs self-coupling can be measured through:





$$\sigma(W^\pm HH)\times \mathrm{BR}(W^\pm\to\ell^\pm\nu_\ell, HH\to b\bar{b}b\bar{b}) = 0.042\mathrm{fb},$$
$$\sigma(ZHH)\times \mathrm{BR}(Z\to\nu\bar{\nu}, HH\to b\bar{b}b\bar{b}) = 0.028\mathrm{fb},$$
$$\sigma(gg\to HH)\times \mathrm{BR}(HH\to\gamma\gamma b\bar{b}) = 0.053\mathrm{fb},$$

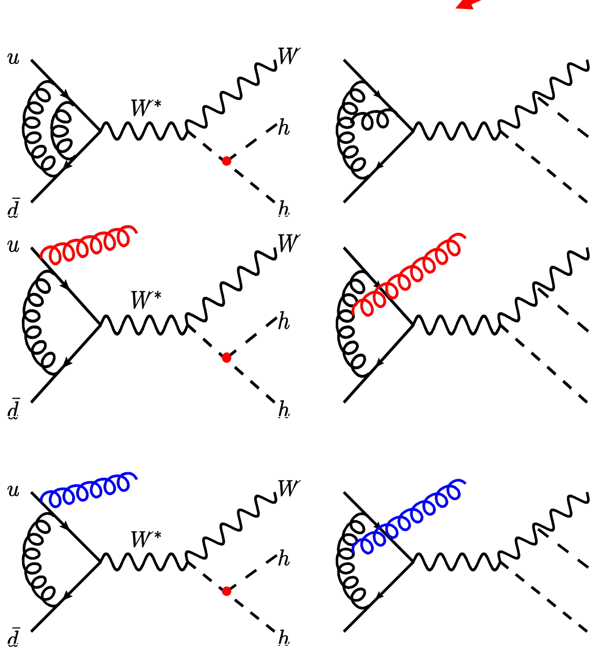
The different channels are complementary to each other and deserve discussion on the same footing.

Qing-Hong Cao, Yandong Liu, Bin Yan,arXiv:1511.03311

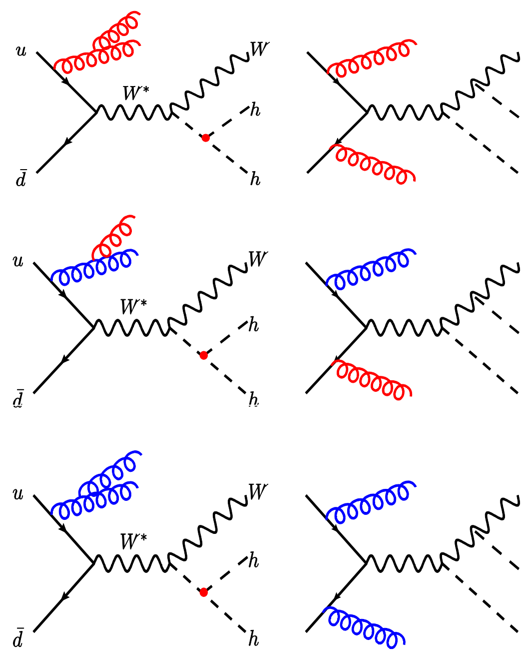
NNLO corrections to Vhh production

H. T. Li, J.Wang, arXiv:1607.06382； H. T. Li, C.S.Li, J.Wang, arXiv:1710.02464

$$\left.\frac{d\sigma_3}{d\Phi_3 dy}\right|_{\rm NNLO} = \underbrace{\int_0^{q_T^{\rm cut}} dq_T \frac{d\sigma_3}{d\Phi_3 dy dq_T}}_{\rm SCET} + \underbrace{\int_{q_T^{\rm cut}}^{q_T^{\rm max}} dq_T \frac{d\sigma_{3+j}}{d\Phi_3 dy dq_T}}_{\rm NLO\ calculations}$$



Virtual Real



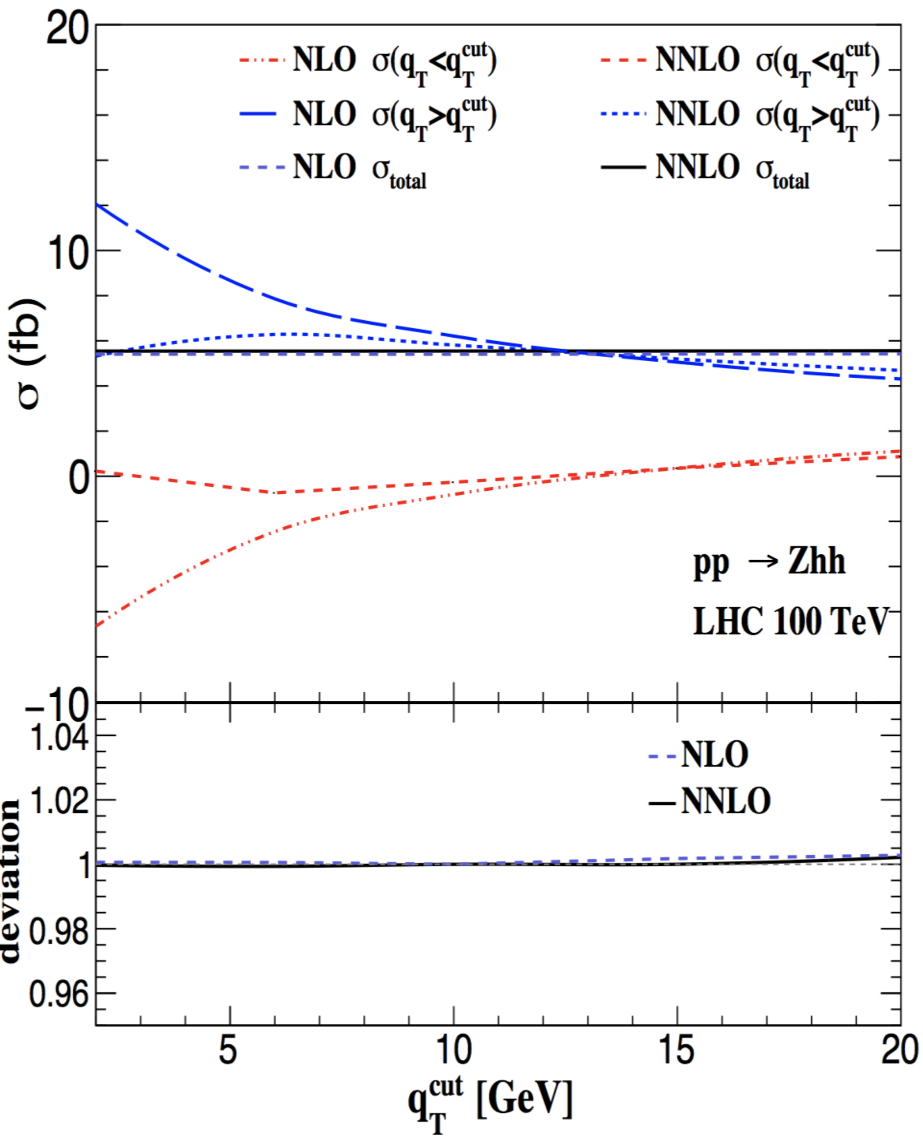
Double Real

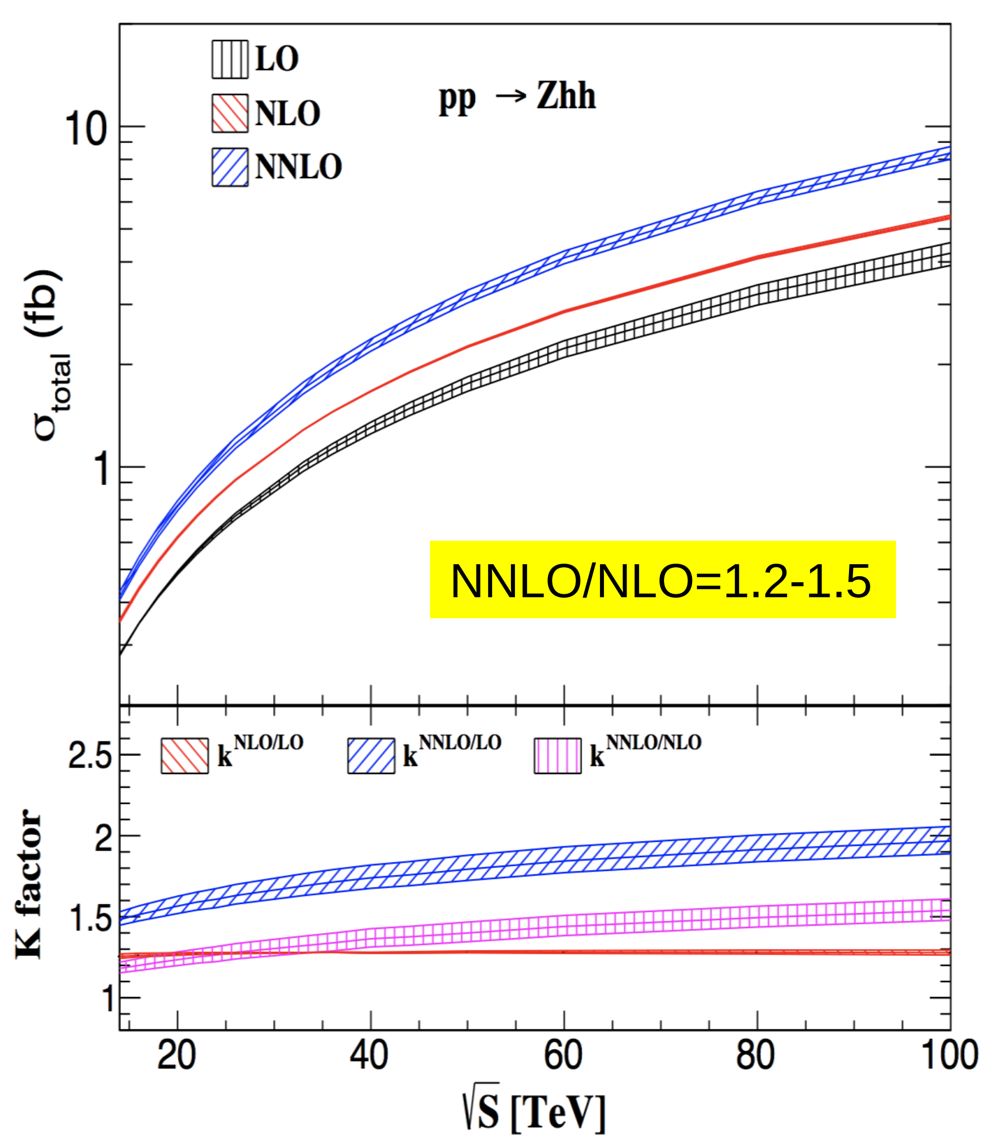
The others with
$q_T > q_T^{cut}$
Calculated in MG5

$$\frac{d\sigma}{dq_T^2 dy} = \frac{1}{2s}\sum_{i,j=q\bar{q}g}\int_{\zeta_1}^1 \frac{dz_1}{z_1}\int_{\zeta_2}^1 \frac{dz_2}{z_2}\int d\Phi_3 H_{q\bar{q}}(M,\mu) f_{i/N_1}(\zeta_1/z_1,\mu) f_{j/N_2}(\zeta_1/z_2,\mu) C_{q\bar{q}\leftarrow ij}(z_1,z_2,q_T,M,\mu) + \mathcal{O}(\frac{q_T^2}{M^2})$$

NNLO corrections to Vhh production

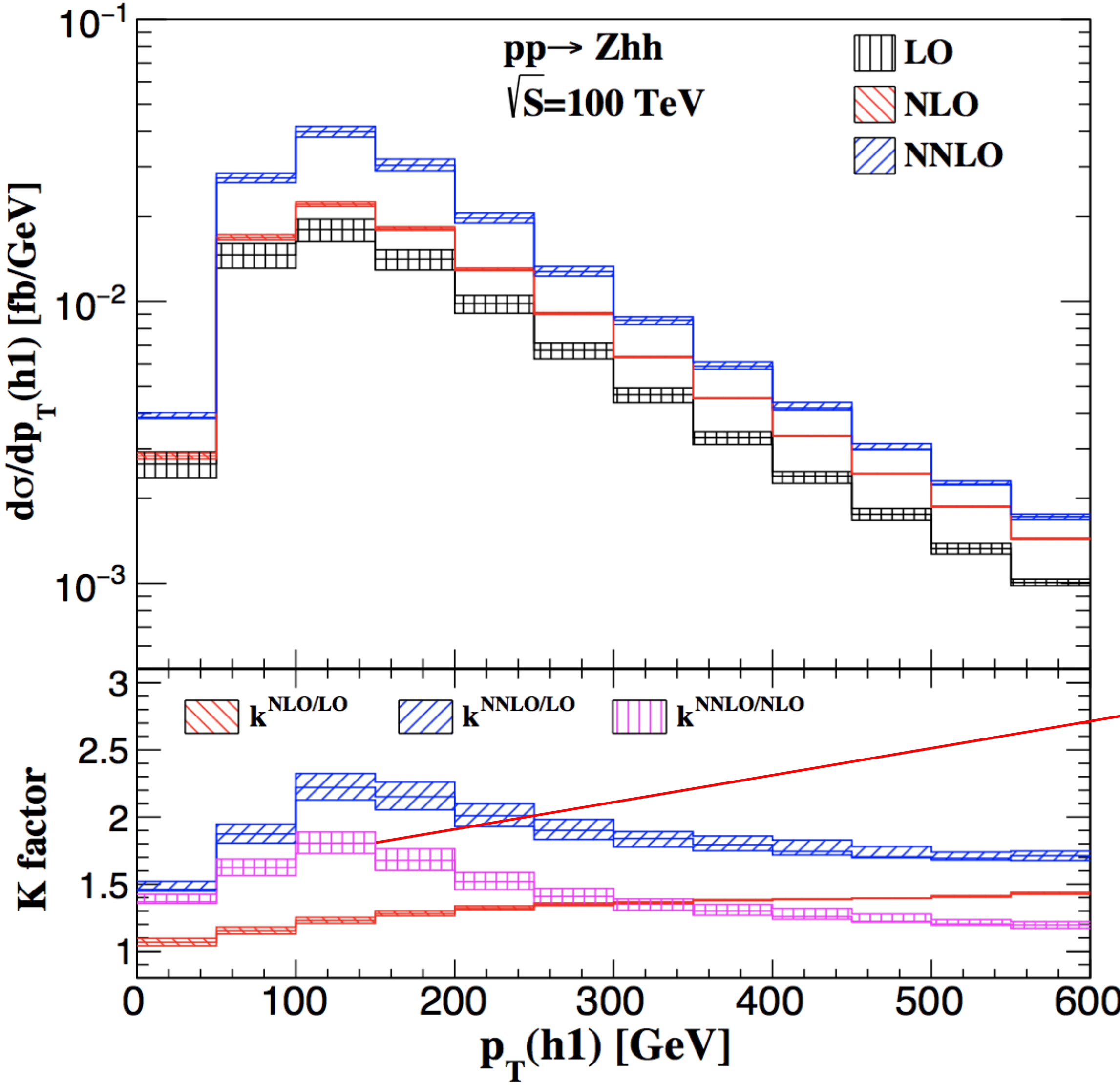
H. T. Li, C.S.Li, J.Wang, arXiv:1710.02464





NNLO corrections to Vhh production

H. T. Li, C.S.Li, J.Wang, arXiv:1710.02464

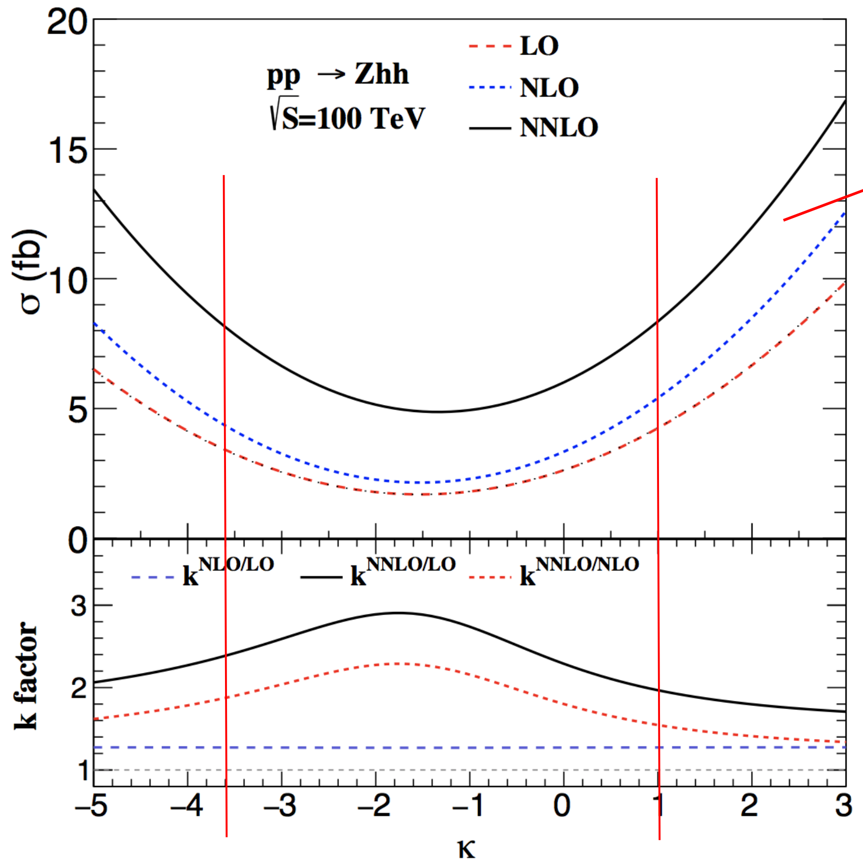


NNLO/NLO=1.8

Shape changed

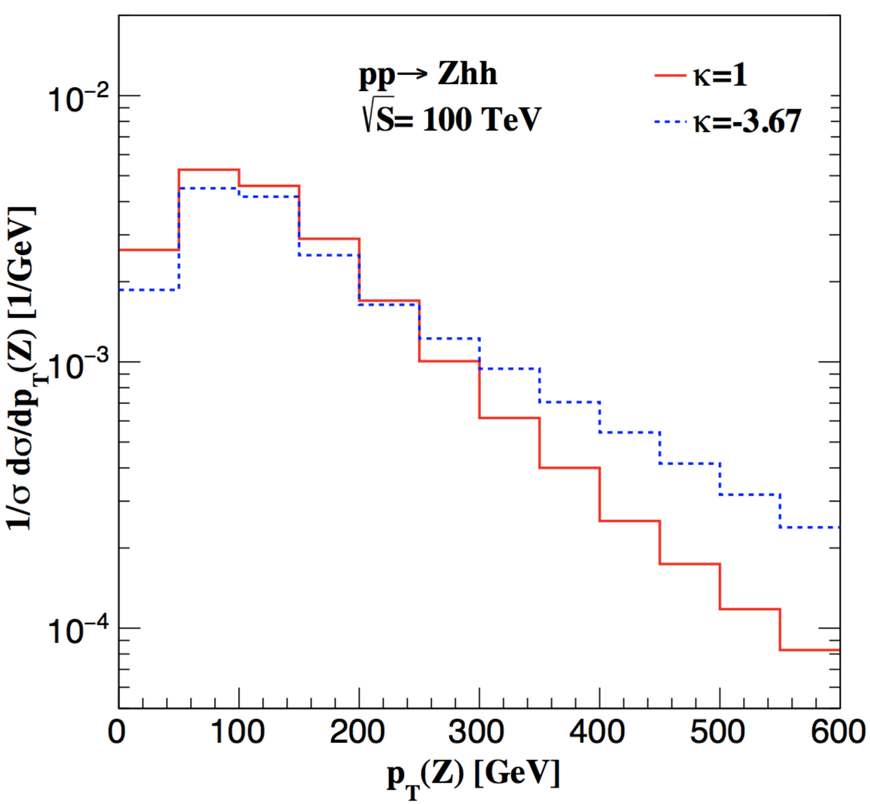
NNLO corrections to Vhh production

H. T. Li, C.S.Li, J.Wang, arXiv:1710.02464



Can be used to determine Higgs self-couplings

But suffer from degeneracy



CONCLUSIONS

- thershold resummations for $W^{\pm}Z$ and ZZ productions at NLO + NNLL accuracy at the LHC with SCET, including π^2 enhancement effects, which show that the resummation effects increase the NLO total cross section by about 7% for ZZ and 12% for WZ. Our results agree well with the data reported by the CMS and ATLA.
- transverse-momentum resummation for WW, ZZ, and WZ pair productions at the NNLL + NLO accuracy with SCET at the LHC. We also find that our results agree well with experimental data reported by the CMS Collaboration for the ZZ productions at $\sqrt{S}=8$ TeV within theoretical and experimental uncertainties.
- jet-veto resummation for WZ and ZZ pair production at NLO + NNLL accuracy with SCET at the LHC, and we present the invariant mass distributions and the total cross sections. Our results show that, in general, the jet-veto resummation can increase the jet-veto efficiencies and decrease the scale uncertainties, especially in large center-of-mass energies. In the WZ channel our resummed results agree with CMS experiment data within 2σ C.L. at $\sqrt{S}= 8$ TeV.

CONCLUSIONS

- fully differential NNLO QCD calculation of pp>Zhh, and find that the NNLO corrections are very sizable and change the shape of NLO kinematic distributions. In the peak region of some differential distributions, the NNLO corrections reach up to 80%, compared to NLO results. Our result is an important ingredient for extracting information on the Higgs self-couplings.

THANK YOU