THRESHOLD RESUMMATION FOR Z BOSON PAIR PRODUCTION

Pulak Banerjee

INFN Cosenza

ongoing work with Chinmoy Dey, M.C.Kumar and Vaibhav Pandey

DIFFRACTION AND LOW-X 2024

PALERMO, ITALY

14.09.2024

MOTIVATION

Les Houches 2005:

NLO revolution

- **4 jet production**
- **W+5 jet**
- $\gamma\gamma$ **+ 3 jet**
- ....

Butter et. al., 2005

~ 2015

NNLO revolution

- $pp \to H + j$ $\mathrm{NNLO}_{\mathrm{HTL}}$
- $pp \to H + 3j$ $\mathrm{NLO}^{\mathrm{VBF}}_{\mathrm{HTL}}$
- $pp \to VV'$ $\mathrm{NNLO}_{\mathrm{QCD}} + \mathrm{NLO}_{\mathrm{EW}}$
- ....

Huss et. al. 2021

Huge effort towards NNNLO

PROCESS OF INTEREST

$$h_1(p_1) + h_2(p_2) \to Z + Z + X$$

Inclusive hadronic state

Collinear factorization:

$$q^2 \frac{d\sigma(S, q^2)}{dq^2} = \sum_{a,b} \int dx_1 f_a(x_1, \mu_F^2) \int dx_2 f_b(x_2, \mu_F^2) q^2 \frac{d\hat{\sigma}_{ab}(s, q^2, \mu_F^2)}{dq^2}$$

$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{(0)} + \alpha_s \hat{\sigma}_{ab}^{(1)} + \alpha_s^2 \hat{\sigma}_{ab}^{(2)} + \ldots$$

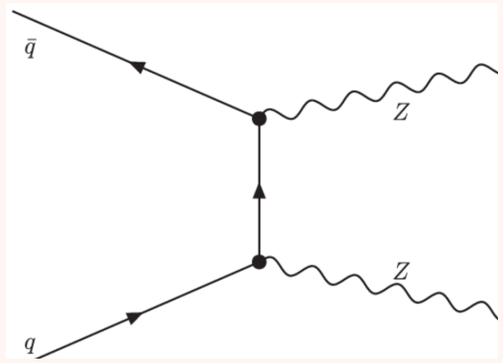
$$q^2 = q_1^2 + q_2^2$$

$$s = x_1 x_2 S$$

$$z = q^2/s$$

HIGHER ORDER CORRECTIONS

- **ZZ production: Study of electroweak theory**
- **ZZ production: Background for Higgs production**
- **Leading order:**



J Ohnemus, 1991

- **NLO QCD, EW corrections, Polarised ZZ**

Ohnemus et al., 1991
Mele et al., 1991,
Dixon et.al, 1998

Accomando et al., 2005, 2006, Bierweiler et al., 2013, Denner et al., 2021
Baglio et al., 2013, Biedermann et al., 2016, Biedermann et al., 2016,

- **Combination of NLO EW and NLO QCD**

Chiesa et al., 2018

- **NNLO QCD and NLO EW**

Cascioli et al., 2014, Gehrmann et al., 2014

Henn et al., 2014, Caola et al, Papadapoulus et. al, 2014, Heinrich et. al. 2017

HIGHER ORDER CORRECTIONS

Differential distributions: MATRIX

Grazzini et. al., 2017, 2020

NNLO corrections increase NLO inclusive xsection by 15%

Scale uncertainties ~ 3%

NLO QCD + PS

Melia et. al, 2011 Frederix et. al, 2011

NLO QCD+ NLO EW + PS

Chiesa et. al, 2020

gg -> ZZ @ NLO QCD + PS

Alioli et. al, 2020

Large impact on p_T of 4 leptons

W^+W^- NNLO + PS (only qQ initiated)

Lombardi et. al, 2021

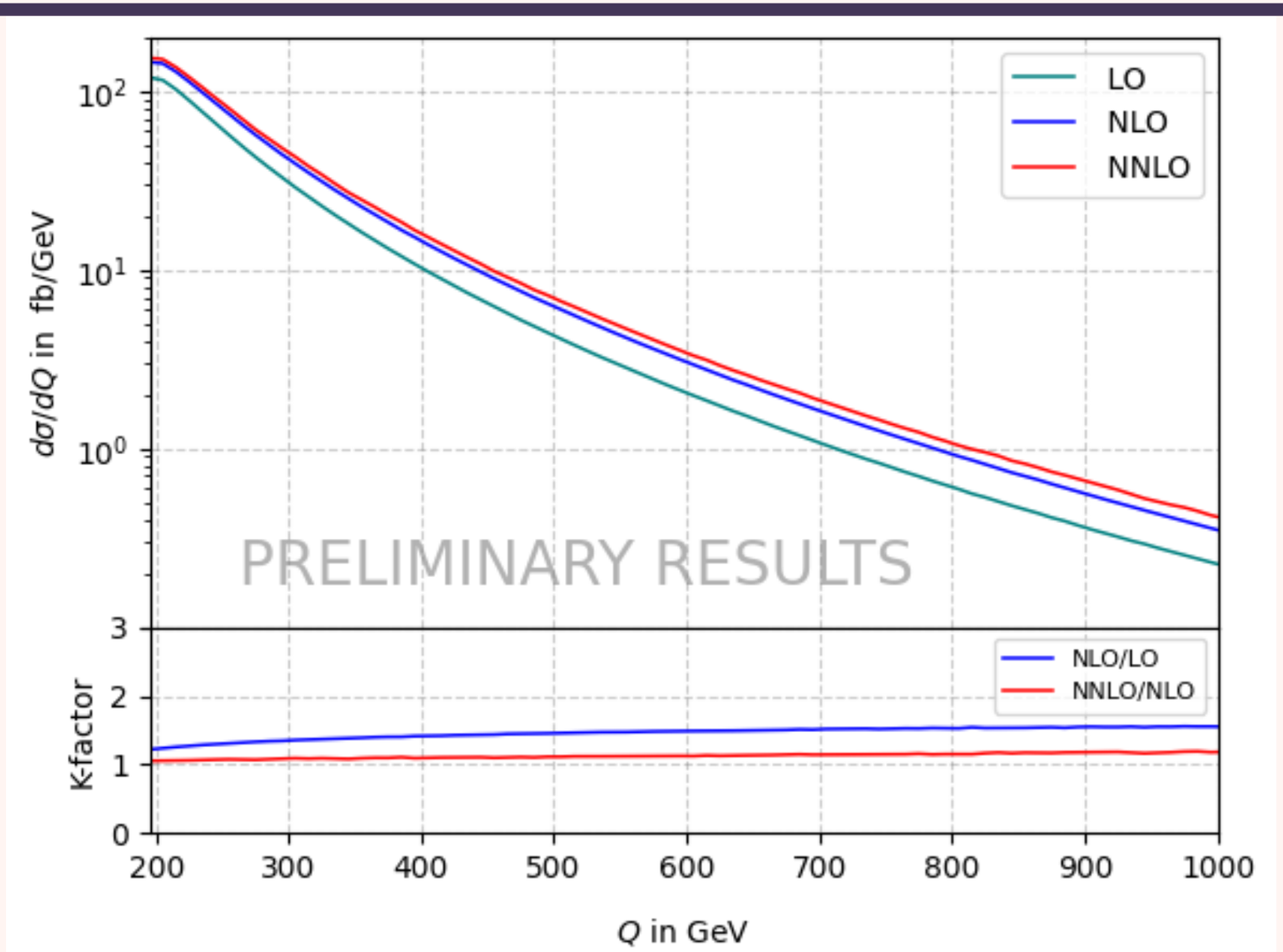
~ 1% scale uncertainties for inclusive xsection

HIGHER ORDER CORRECTIONS

- **Z Z NNLO+NNLL @** p_T — Kallweiti et. al, 2020
- **Z Z NNLO + PS** — Buonocore et. al, 2021
- **NLO + NNLL threshold corrections for two on-shell Z bosons** — **SCET approach** — Wang et. al, 2014
- **This work: NNLO + NNLL threshold corrections for two on-shell Z bosons**

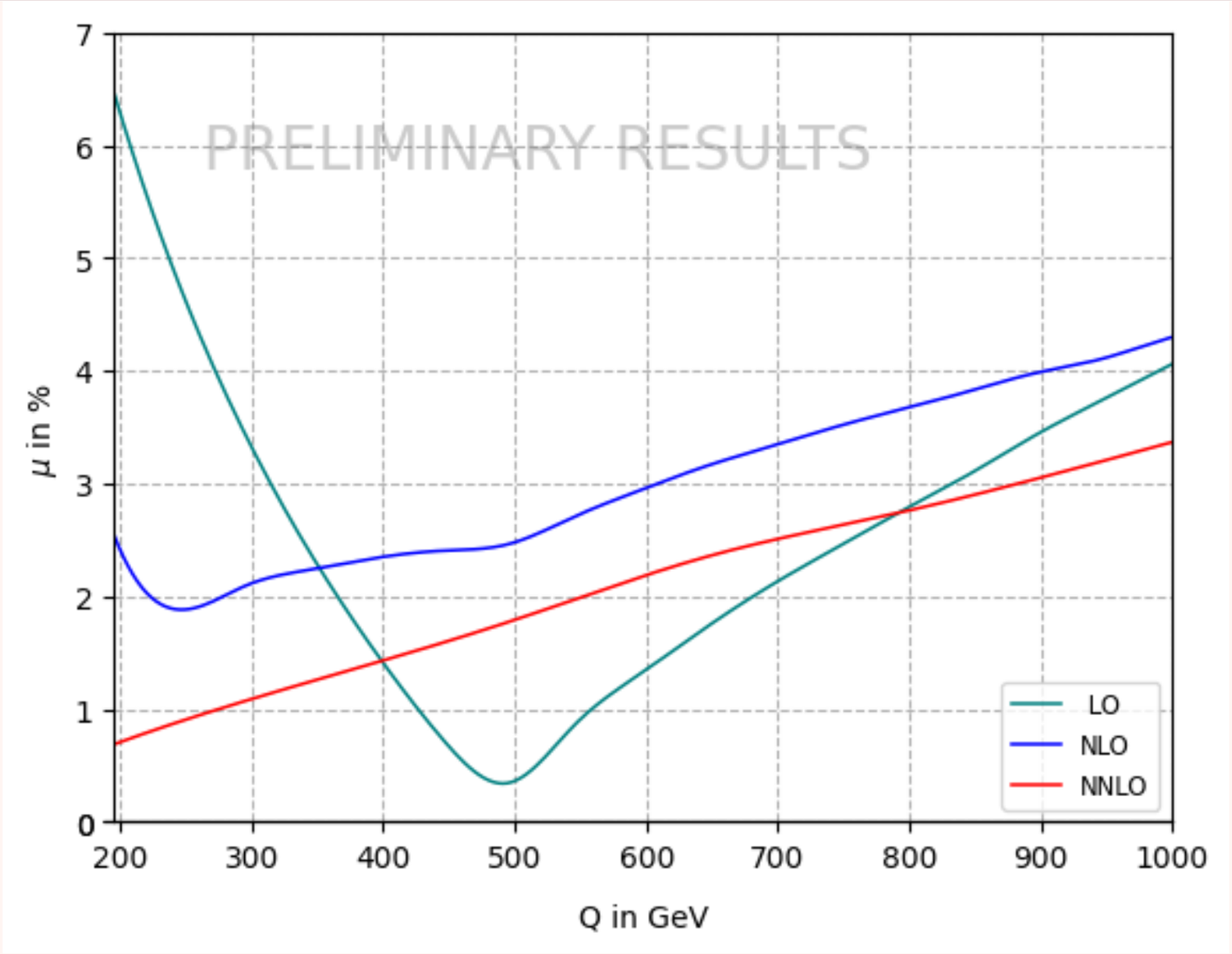
FIXED ORDER DISTRIBUTIONS

MSHT 2020



Q in GeV / $\frac{d\sigma}{dQ}$ in fb/GeV	LO	NLO	NNLO(no gg)	NNLO(all)
195	119.2091	145.4280	153.2727	165.4677
595	2.1128	3.1440	3.5398	3.6310
995	0.2303	0.3578	0.4222	0.4272

FIXED ORDER SCALE VARIATION



MSHT 2020

NNLO scale variation ~ 2% - 3.5% in high Q regions

Q in GeV / μ in %	LO	NLO	NNLO(no gg)	NNLO(all)
195	6.4738	2.5490	0.6869	2.0595
595	1.3091	2.9393	2.1817	2.8118
995	4.0309	4.2820	3.4275	3.6989

THRESHOLD RESUMMATION

Scale variation at NNLO increases with Q

$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{(0)} + \alpha_s \hat{\sigma}_{ab}^{(1)} + \alpha_s^2 \hat{\sigma}_{ab}^{(2)} + \underbrace{\ldots}$$

What are the dominant higher order contributions?

$$z \to 1 \implies \text{Soft limit}$$

$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{\mathrm{SV}} + \hat{\sigma}_{ab}^{\mathrm{hard}}$$

$$\sigma_{a\bar{a}}^{\mathrm{sv}}\left(z, q^2, \mu_F^2\right) = |\mathcal{M}_{a\bar{a}}^{(0)}|^2 |\mathcal{F}_{a\bar{a}}(q^2, \mu_R^2, \epsilon)|^2 \delta(1-z) \otimes \mathcal{C} \exp\left(2\Phi_{a\bar{a}}\left(z, q^2, \underbrace{\mu_R^2, \epsilon}\right) - 2\mathcal{C} \log \Gamma_{a\bar{a}}(z, \mu_F^2, \mu_R^2, \epsilon)\right)$$

Universal soft-collinear operator →

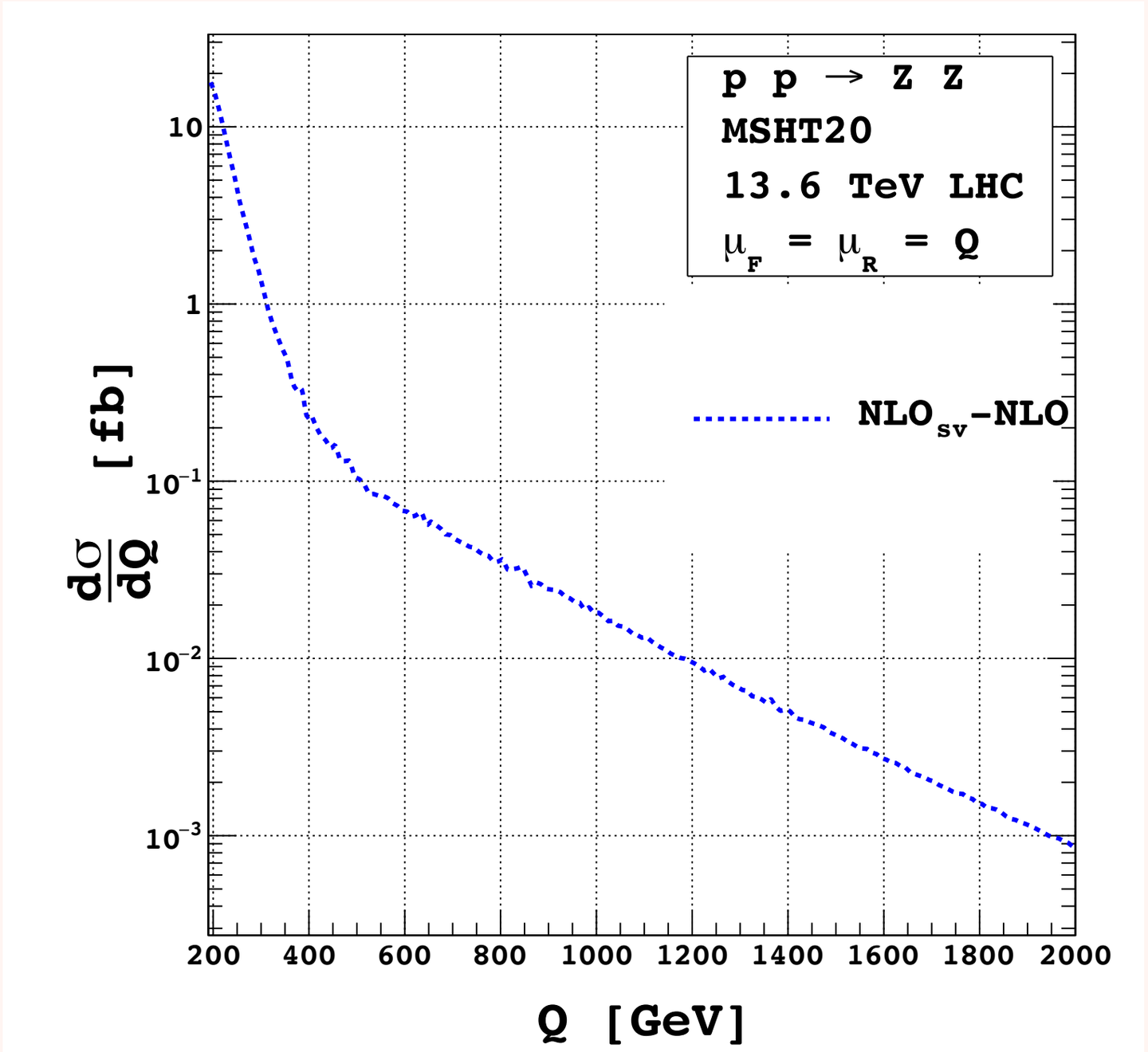
$$\delta(1-z)$$
$$\left[\frac{\ln^i(1-z)}{1-z}\right]_+$$

Ravindran 2006 Ahmed et. al, 2020

THRESHOLD RESUMMATION

$$\sigma^{\rm sv}_{a\bar{a}}\left(z,q^2,\mu_F^2\right) = C_0^{a\bar{a}}(q^2,\mu_F^2)\otimes\mathcal{C}\exp\left(2\Phi^{\rm res}_{a\bar{a}}\left(z,q^2,\mu_R^2,\epsilon\right)\right)$$

$$\left[\frac{\ln^i(1-z)}{1-z}\right]_+$$



In soft limit, dominant contributions

Resum these contributions

THRESHOLD RESUMMATION

$$\phi_{a\bar{a}}^{\mathrm{res}} = \left(\frac{1}{1-z} \left\{ \int_{\mu_F^2}^{(1-z)^2 q^2} \frac{d\lambda^2}{\lambda^2} 2A_{a\bar{a}}(a_s(\lambda^2)) + D_{a\bar{a}}(a_s((1-z)^2 q^2)) \right\} \right)_+$$

Ravindran 2006

Resummation coefficients in Mellin space

$$\sigma_{a\bar{a}}^{\mathrm{SV}}(\bar{N}) = \bar{g}_{a\bar{a}} \exp(\bar{G}_{\bar{N}}^{a\bar{a}}(\omega))$$

$$\omega = \alpha_s \beta_0 \log(\bar{N})$$

$$\bar{G}_{\bar{N}}^{a\bar{a}}(\omega) = \bar{G}_1^{a\bar{a}}(\omega)\log(\bar{N}) + \bar{G}_2^{a\bar{a}}(\omega) + \alpha_s \bar{G}_3^{a\bar{a}}(\omega) + \ldots$$

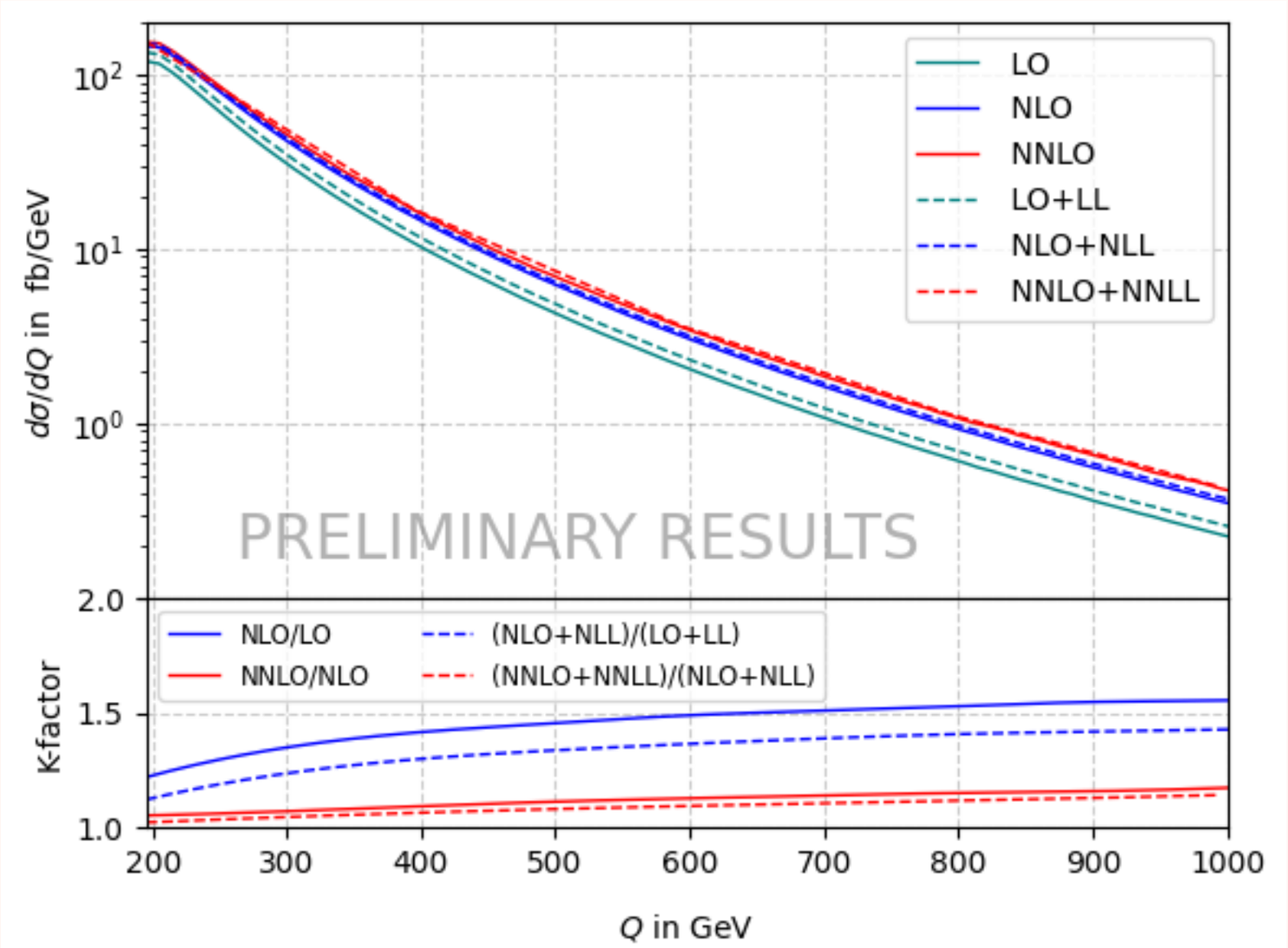
Catani et. al, 2003

Leading log(LL)

Next-to-Leading log(NLL)

Next-to-Next-to-Leading log(NNLL)

RESUMMED DISTRIBUTIONS

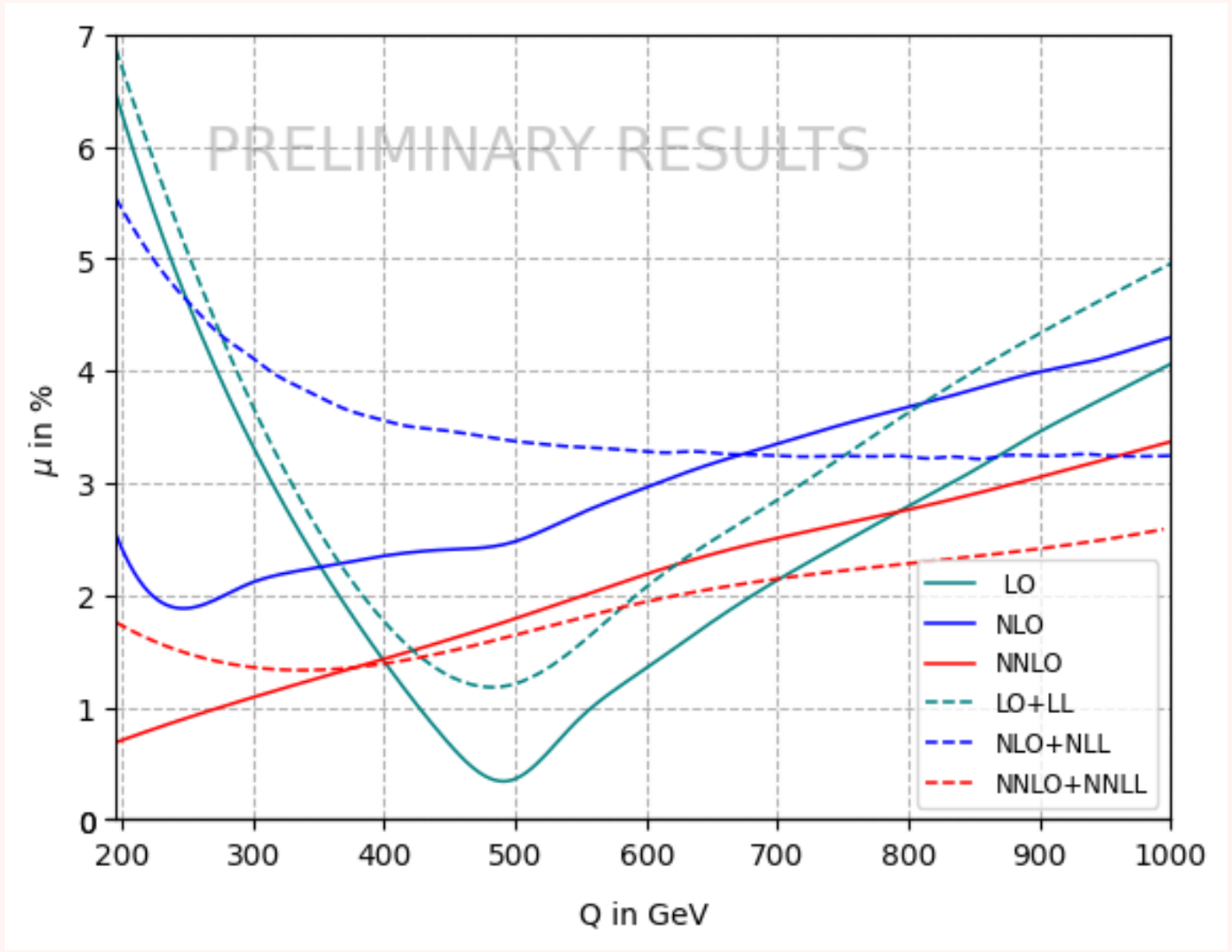


only qQ

NNLO+NNLL Xsection increases by 1% - 2% in high Q regions

Q in GeV / $\frac{d\sigma}{dQ}$ fb/GeV	LO	LO+LL	NLO	NLO+NLL	NNLO	NNLO+NNLL
195	119.2091	134.2247	145.4280	150.6777	153.2727	154.2949
595	2.1128	2.3909	3.1440	3.2722	3.5398	3.5831
995	0.2303	0.2634	0.3578	0.3771	0.4222	0.4311

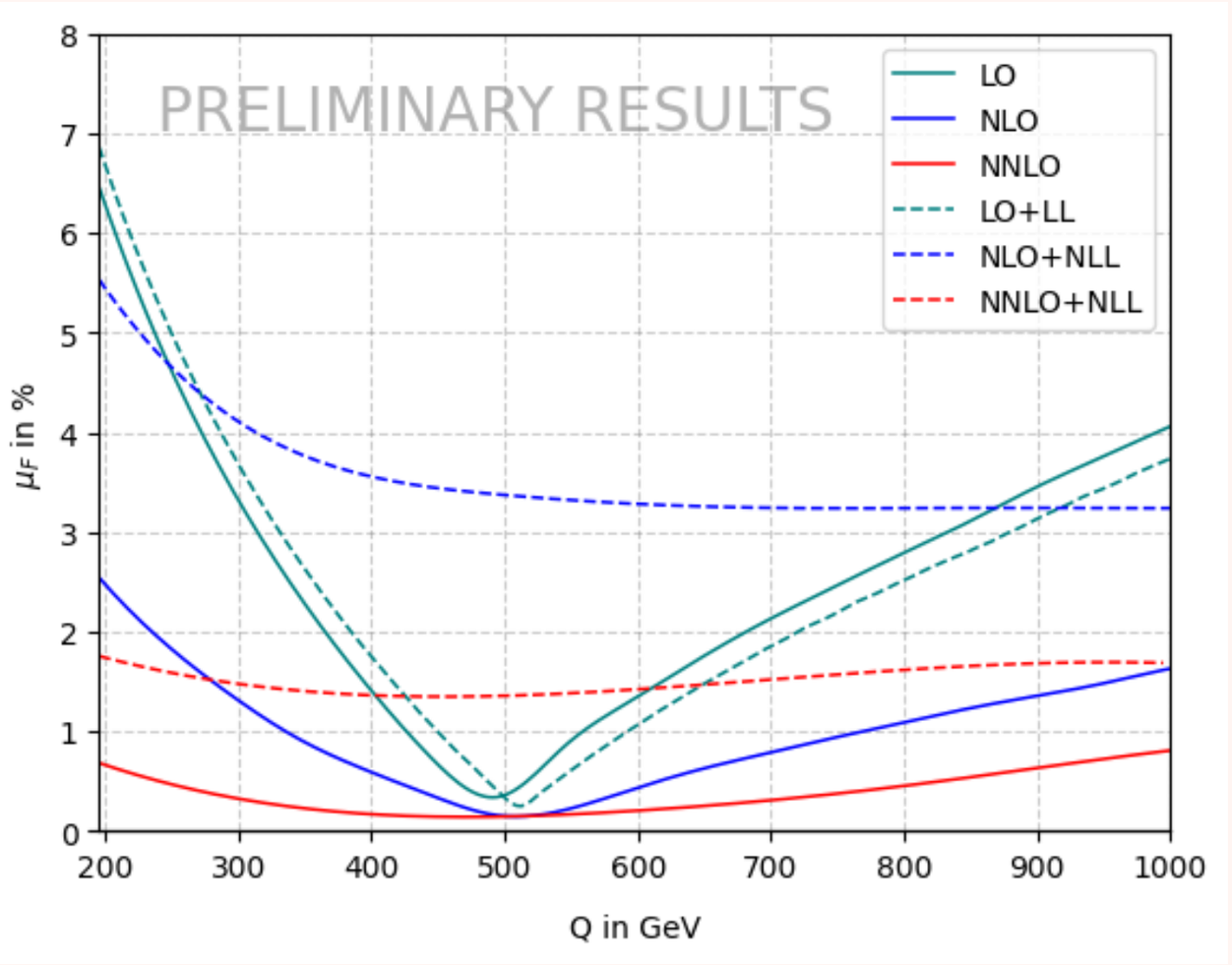
RESUM SCALE VARIATION

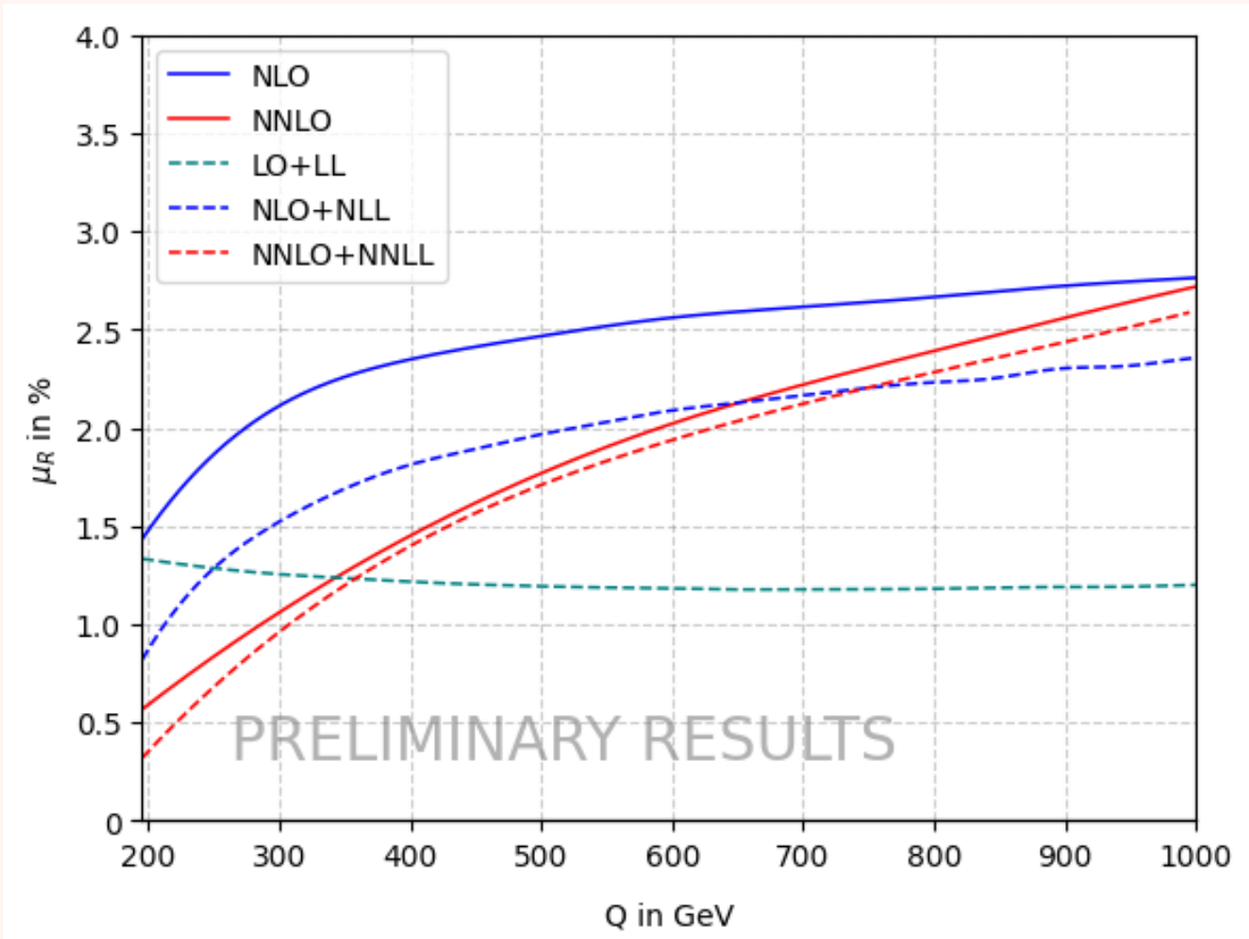


Improved scale variation at NNLO+NNLL compared to NNLO

Q in GeV / μ in %	LO	LO+LL	NLO	NLO+NLL	NNLO	NNLO+NNLL
195	6.4738	6.8730	2.5490	5.5395	0.6869	1.7587
595	1.3091	2.0257	2.9393	3.2867	2.1817	1.9287
995	4.0309	4.9242	4.2820	3.2408	3.4275	2.5882

RESUM SCALE VARIATION





INCLUSIVE CROSS SECTION

Q integrated from 190 GeV to 13/13.6 TeV

COM energy	σ_{LO} (pb)	σ_{LO+LL} (pb)	σ_{NLO} (pb)	$\sigma_{NLO+NLL}$ (pb)	σ_{NNLO} (pb)	$\sigma_{NNLO+NNLL}$ (pb)
13 TeV	$10.957^{+3.99\%}_{-3.99\%}$	$12.35^{+4.36\%}_{-4.36\%}$	$14.37^{+1.91\%}_{-1.91\%}$	$14.89^{+4.48\%}_{-4.48\%}$	$15.42^{+1.01\%}_{-1.01\%}$	$15.66^{+2.78\%}_{-2.78\%}$
13.6 TeV	$11.66^{+4.23\%}_{-4.23\%}$	$13.14^{+4.61\%}_{-4.61\%}$	$15.28^{+1.90\%}_{-1.90\%}$	$15.82^{+4.56\%}_{-4.56\%}$	$16.43^{+1.06\%}_{-1.06\%}$	$16.69^{+2.85\%}_{-2.85\%}$

Q integrated from 1500 GeV to 13/13.6 TeV

COM energy	σ_{NLO} (fb)	$\sigma_{NLO+NLL}$ (fb)
13 TeV	$14.06^{+6.33\%}_{-6.33\%}$	$15.30^{+3.22\%}_{-3.22\%}$
13.6 TeV	$16.15^{+6.20\%}_{-6.20\%}$	$17.53^{+3.37\%}_{-3.37\%}$

CONCLUSION

- Resummation for invariant mass of two on-shell Z bosons, in qQ channel.

- Universal soft-collinear operator constructed using factorization and renormalization group evolution of amplitudes in QCD, and the universality of soft gluon contributions.

- Resummed Xsection increases fixed order counterpart by 1% - 2%, in high Q regions

- Improved scale variation observed in high Q regions.

THANK YOU

BACKUPS

FIXED ORDER SCALE VARIATION