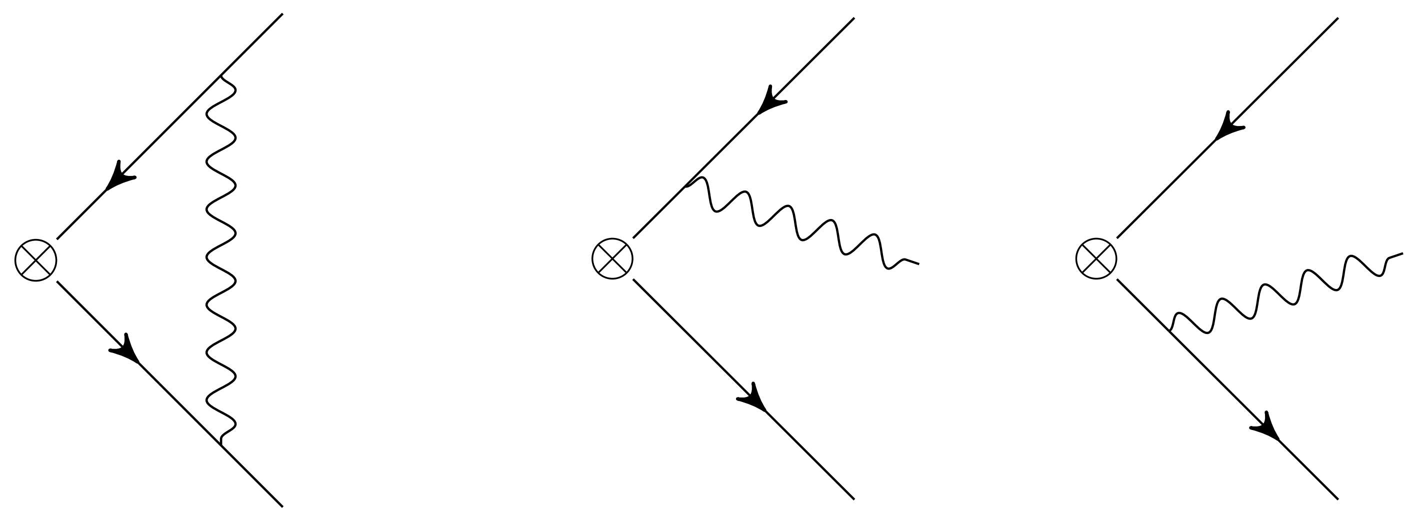
Resummation of EW Sudakov logarithms for real radiation

Work in collaboration with Nicolas Ferland

1601.07190 (JHEP)

Electroweak Sudakov logarithms arise from exchanges of electroweak gauge bosons

Consider example of qq production

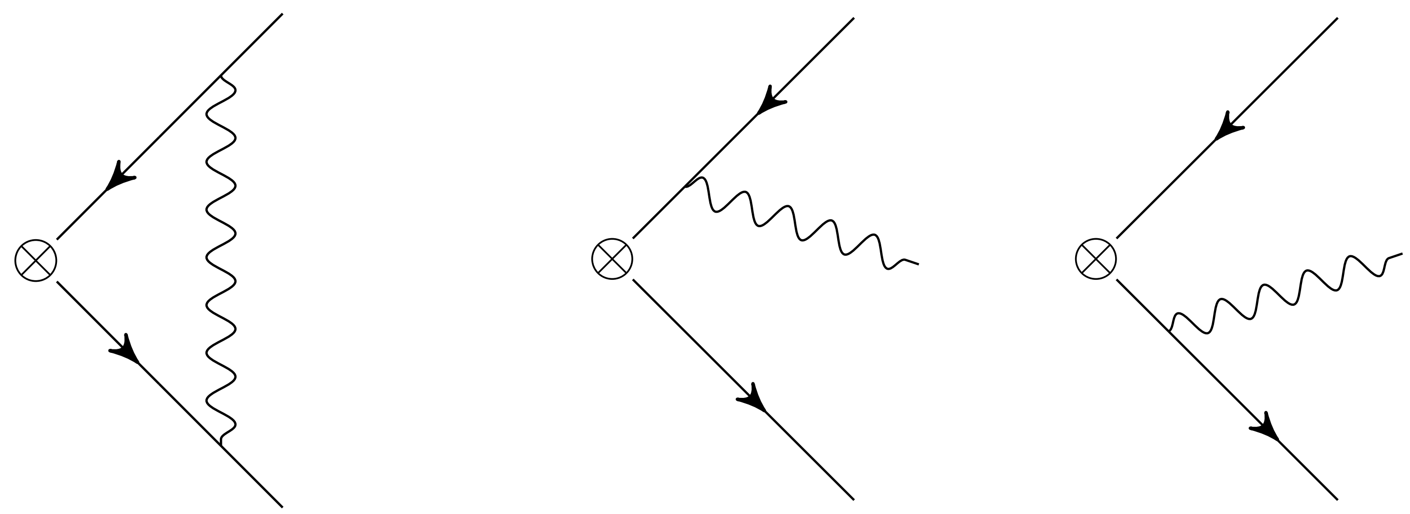


Have contributions from virtual and real emission

For massless gauge boson, get IR divergences in both virtual and real that cancel by KLN

Electroweak Sudakov logarithms arise from exchanges of electroweak gauge bosons

Consider example of qq production

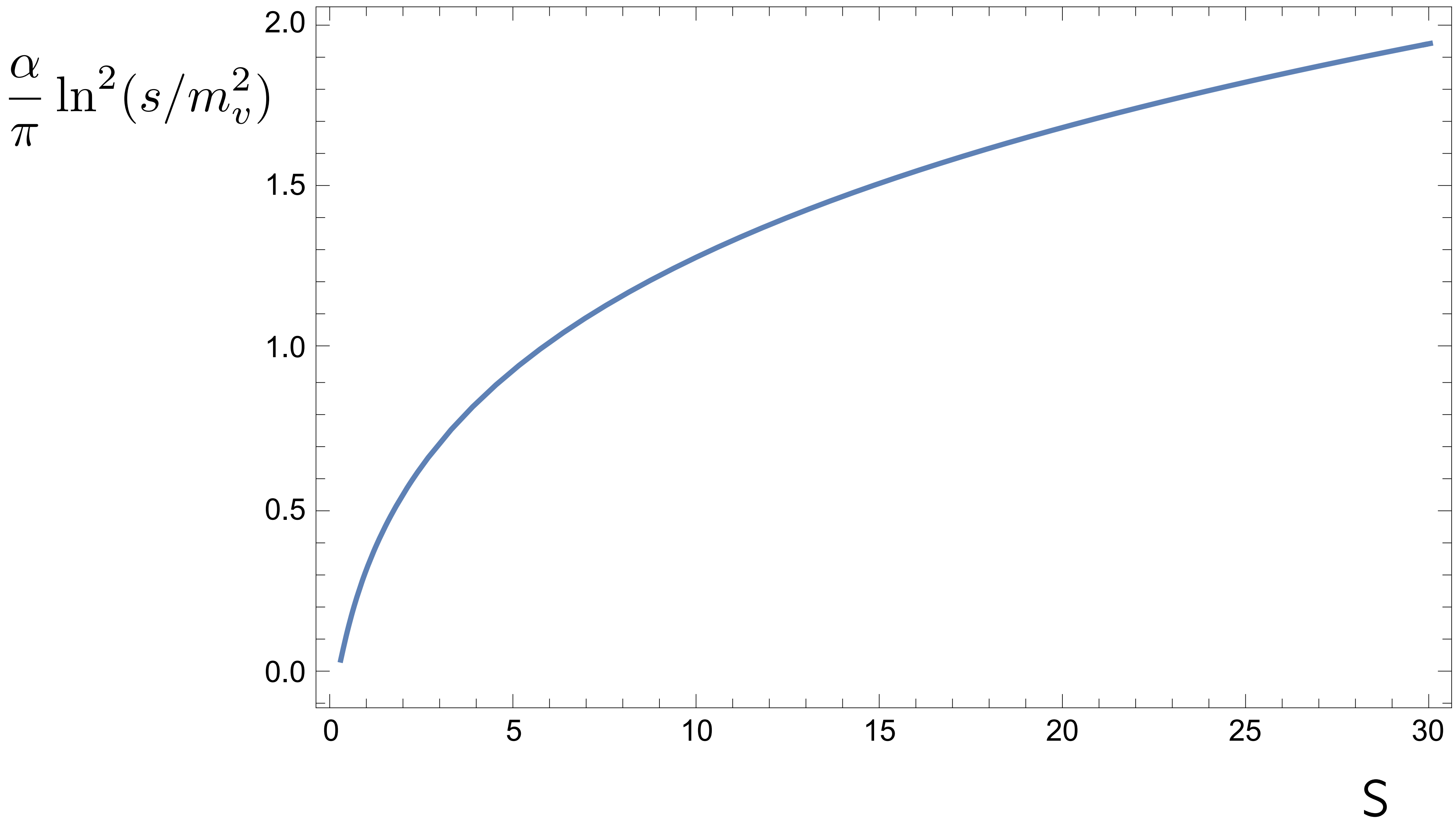


Have contributions from virtual and real emission

For massive W, IR divergences turn into $\log(m_W^2/s)$, and generally have two powers per power of alpha

Both virtual and real sensitive to $\log(m_W^2/s)$

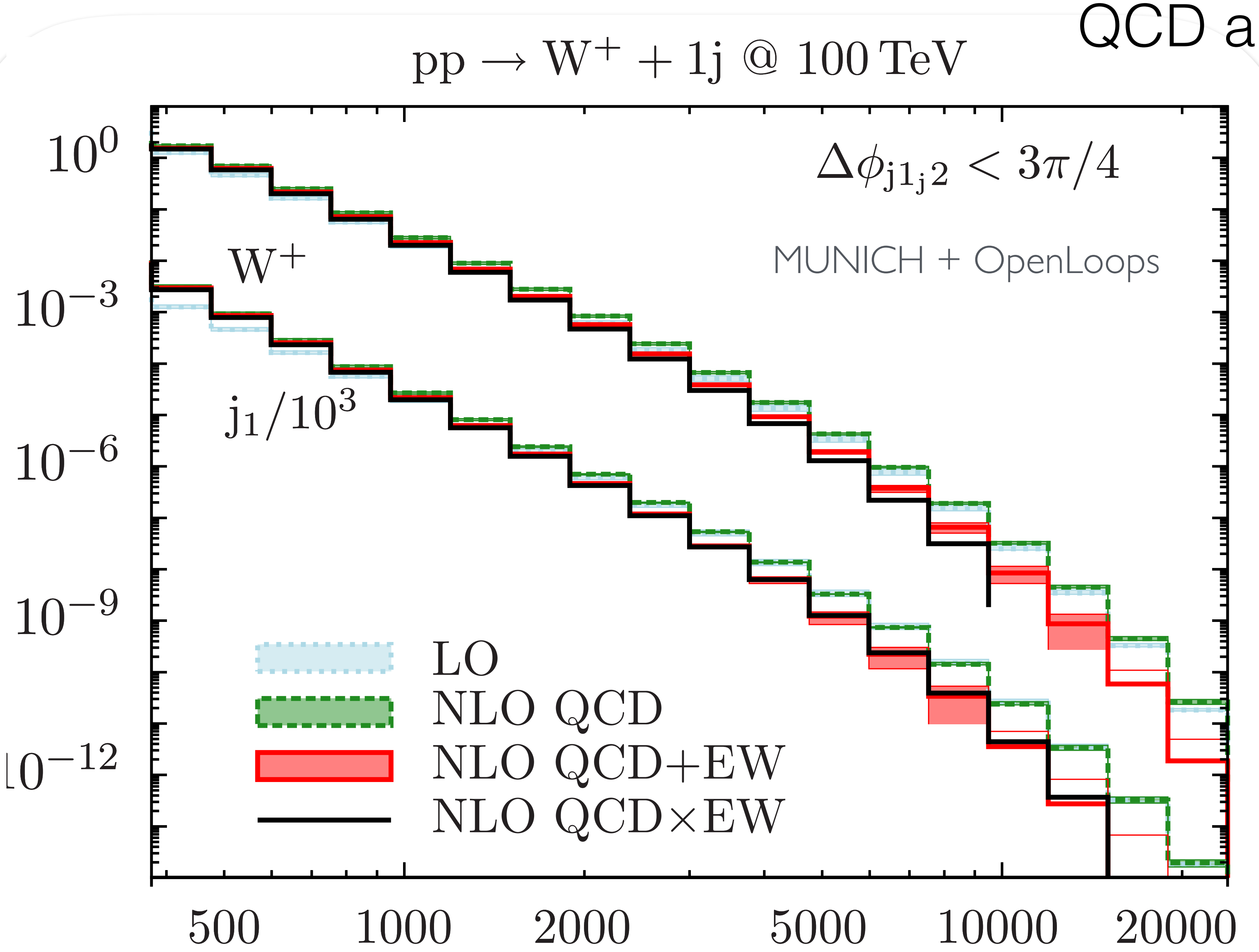
The numerical effect of EW Sudakov logarithms becomes large at high energies



No sense in which electroweak corrections are small

Fixed order results at a future 100 TeV machine show that EW corrections are much larger than QcD corrections

Lindert,
QCD and EW at 100 TeV colliders



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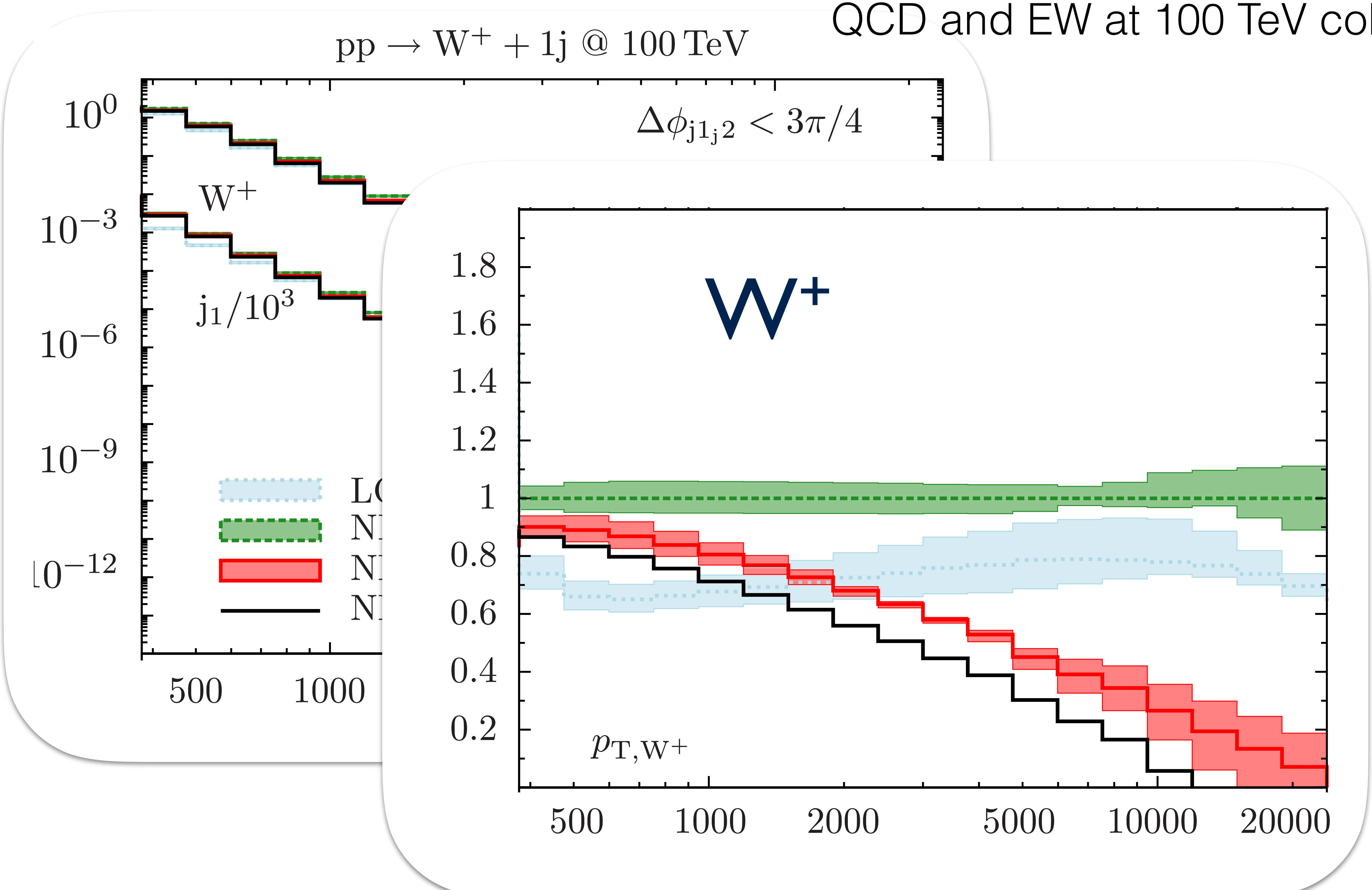

The cancellation between virtual and real corrections is very different from the usual story in QCD

Look at "Drell-Yan" production and keep onto terms with α_2. The coefficient of $\mathrm{Log}^2(m_V{}^2/s)/4\pi$ is

	V	R	V+R
uu	$2/3\ \alpha_2{}^2$	$-\ \alpha_2{}^2$	$-1/3\ \alpha_2{}^2$
dd	$2/3\ \alpha_2{}^2$	$-\ \alpha_2{}^2$	$-\ 1/3\ \alpha_2{}^2$
ud	$4/3\ \alpha_2{}^2$	$-\ \alpha_2{}^2$	$1/3\ \alpha_2{}^2$
du	$4/3\ \alpha_2{}^2$	$-\ \alpha_2{}^2$	$1/3\ \alpha_2{}^2$
sum	$4\ \alpha_2{}^2$	$-\ 4\ \alpha_2{}^2$	0

Cancellation for completely inclusive observables (KLN)

The cancellation between virtual and real corrections is very different from the usual story in QCD

Look at "Drell-Yan" production and keep onto terms with α_2. The double logarithmic terms are

	V	R	V+R
uu	$2/3\ \alpha_2^2$	$-\ \alpha_2^2$	$-1/3\ \alpha_2^2$
dd	$2/3\ \alpha_2^2$	$-\ \alpha_2^2$	$-\ 1/3\ \alpha_2^2$
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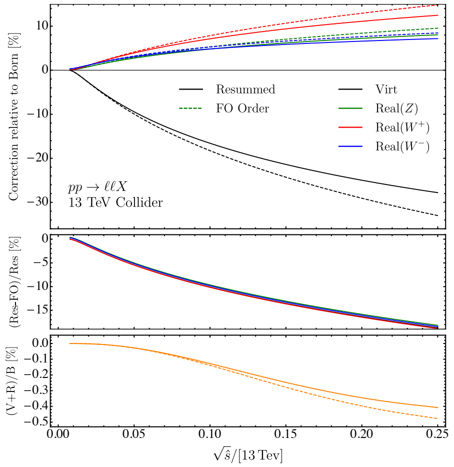
du	$4/3\ \alpha_2^2$	$-\ \alpha_2^2$	$1/3\ \alpha_2^2$
sum	$4\ \alpha_2^2$	$-\ 4\ \alpha_2^2$	0

Cancellation only happens if we include both real and virtual corrections, and average over initial states

1. Most experimental analyses are not inclusive over final states
2. Averaging over initial states is impossible, since beams (pdf's) are not SU(2) symmetric

Review of resummed virtual

Resummation of the real



Results

Kuhn, Penin, Smirnov (’95)
Ciafaloni, Comelli (’99, ‘00)
Fadin, Lipton, Martin, Melles (’00)
Denner, Pozzorini (’91)

Problem is tailor made for SCET. Was worked out in beautiful set of papers by Chiu, Golf, Kelley and Manohar

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Logarithms arise from collinear and soft "divergences" in loop diagrams

These "divergences" are regulated by the mass of the vector boson

Can be resummed using standard SCET RGE running

Chiu, Golf, Kelley, Manohar, ('08)

Problem is tailor made for SCET. Was worked out in beautiful set of papers by Chiu, Golf, Kelley and Manohar

$$\mu = Q \quad \frac{\text{Full theory}}{\text{SCET}_{W,Z,\gamma}\ (M=0)} \quad C(Q,\mu)$$

$$\Big\downarrow\ \gamma_{\text{SCET}}$$

$$\mu = m_V \quad \frac{\text{SCET}_{W,Z,\gamma}\ (M\neq 0)}{\text{SCET}_{\gamma}} \quad D(m_V,\mu)$$

Problem is completely solved at NLL'
for any process

Problem is tailor made for SCET. Was worked out in beautiful set of papers by Chiu, Golf, Kelley and Manohar

For Drell-Yan production, 7 operators in $\mathrm{SCET}_{Z,W,\gamma}$

$$
\begin{aligned}
\mathcal{L} = & C_{QLT}\, Q^T L^T + C_{QLS}\, Q^S L^S + C_{ULS}\, U^S L^S + C_{DLS}\, D^S L^S \\
& + C_{QES} Q^S E^S + C_{UES}\, U^S E^S + C_{DES}\, D^S E^S \,,
\end{aligned}
$$

with

$$
F^S = \bar{F}\gamma^\mu F \,, \qquad F^T = \bar{F}\tau^a\gamma^\mu F
$$

Q, L : left handed quark and lepton doublets
U, D, E : right handed u, d, e fields

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	NLL'	LL
C(Q,μ)	1-loop	tree
D(m_V,μ)	1-loop	tree
γ(Q,μ)	2-loop cusp 1-loop non-cusp op mixing	1-loop cusp no op mixing

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	NLL'	**LL**
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To LL accuracy, the results can be written in a very simple and compact form

$$\mathcal{L} = C_{QLT}\, Q^T L^T + C_{QLS}\, Q^S L^S + C_{ULS}\, U^S L^S + C_{DLS}\, D^S L^S \\ + C_{QES} Q^S E^S + C_{UES}\, U^S E^S + C_{DES}\, D^S E^S \,,$$

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Matching onto SCET

$$sC^{(0)}_{QLT}(Q) = 4\pi\alpha_2$$
$$sC^{(0)}_{IFS}(Q) = 4\pi\alpha_1 Y_I Y_F$$

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$$

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Running in SCET

$$\gamma_i(\mu) = \Gamma_i \log\frac{\mu^2}{s}$$

$$\Gamma_i = \sum_j \left[\frac{\alpha_1}{\pi} Y_j^2 + \frac{\alpha_2}{\pi} T_j^2 - \frac{\alpha_{\rm em}}{\pi} Q_j^2\right]_i$$

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Summation of logarithms

$$C_i(m_V) = U_i^{\rm LL}(m_V, Q) C_i Q)$$
$$U_i^{\rm LL}(m_V, Q) = \exp\left[-\Gamma_i \log^2\frac{m_V}{Q}\right]$$

To LL accuracy, the results can be written in a very simple and compact form

This gives the final result

$$\hat{\sigma}^{\mathrm{LL}}_{u\bar{u}\to e^- e^+} = N\,\frac{4\left(4\,U_{UL}^2 + U_{QE}^2 + 16\,U_{UE}^2\right)\alpha_1^2 + U_{QL}^2\left(\alpha_1 + 3\alpha_2\right)^2}{54}$$

$$\hat{\sigma}^{\mathrm{LL}}_{u\bar{u}\to \nu\bar{\nu}} = N\,\frac{16\,U_{UL}^2\alpha_1^2 + U_{QL}^2\left(\alpha_1 - 3\alpha_2\right)^2}{54}$$

$$\hat{\sigma}^{\mathrm{LL}}_{d\bar{d}\to e^- e^+} = N\,\frac{4\left(U_{DL}^2 + U_{QE}^2 + 4\,U_{DE}^2\right)\alpha_1^2 + U_{QL}^2\left(\alpha_1 - 3\alpha_2\right)^2}{54}$$

$$\hat{\sigma}^{\mathrm{LL}}_{d\bar{d}\to \nu\bar{\nu}} = N\,\frac{4\,U_{DL}^2\alpha_1^2 + U_{QL}^2\left(\alpha_1 + 3\alpha_2\right)^2}{54}$$

$$\hat{\sigma}^{\mathrm{LL}}_{u\bar{d}\to \nu e^+} = N\,\frac{2\,U_{QL}^2\alpha_2^2}{3}$$

$$\hat{\sigma}^{\mathrm{LL}}_{d\bar{u}\to e^- \nu} = N\,\frac{2\,U_{QL}^2\alpha_2^2}{3}\,.$$

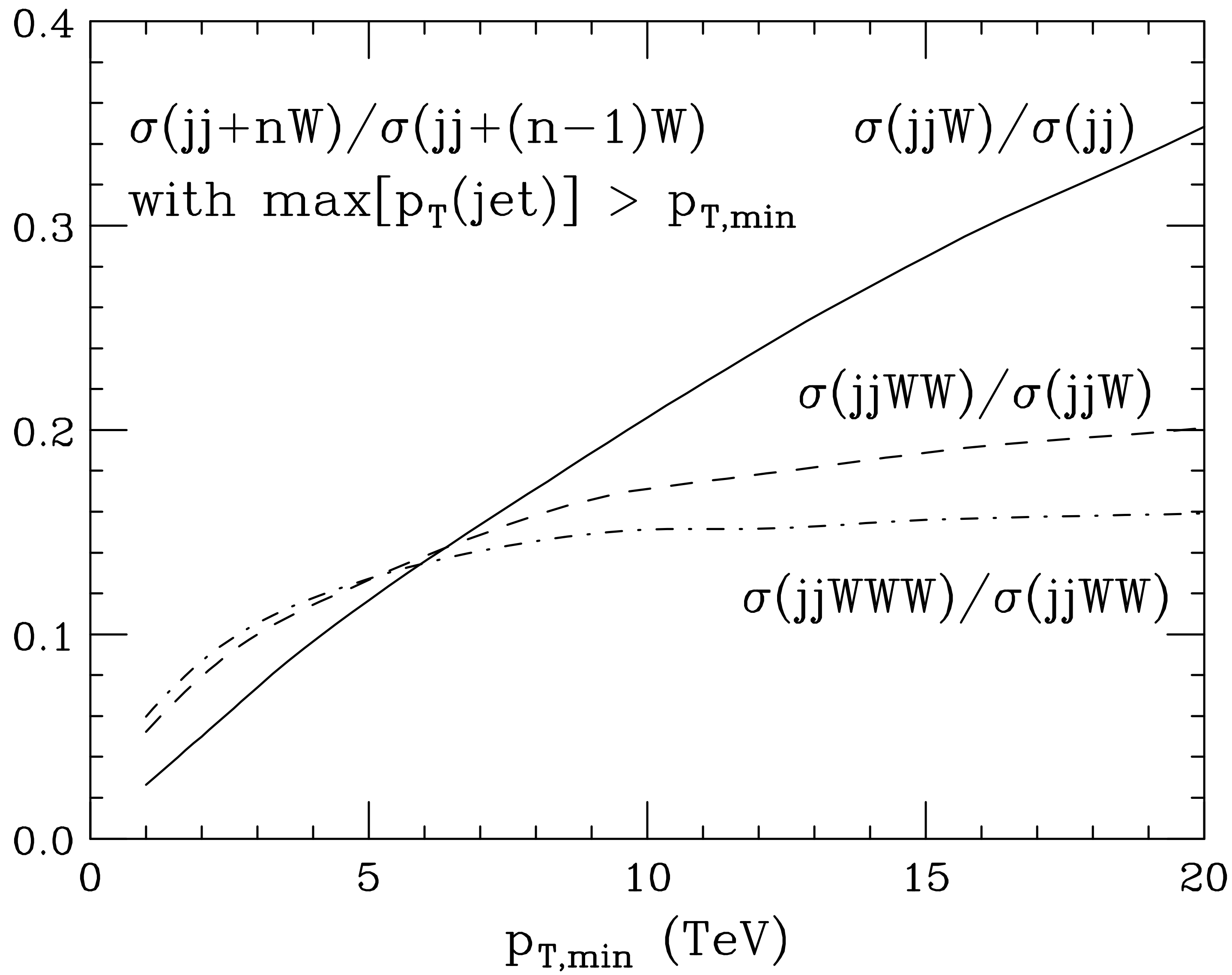
$$N = \frac{\pi}{8N_C\hat{s}}$$

Fadin, Lipton, Martin, Melles ('00)
Baur ('06)

There are good arguments that the resummation of the real is not as important as that of the virtual

W emission rates from jets

Slide from M. Mangano
at CERN workshop on 100 TeV



Conclusion: substantial increase of W production at large energy, but W-emission probability small enough that fixed-order PT is likely the most reliable way to model rates and kinematics

But real radiation of W and Z bosons has double logarithmic sensitivity, just as the virtual corrections

For completely SU(2) symmetric observables (for example production with gg in initial state) the sum over all real emissions has the same logarithms as virtual corrections

A priori no reason why real double logarithmic sensitivity should be less for real than for virtual

But real radiation of W and Z bosons has double logarithmic sensitivity, just as the virtual corrections

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Very important to understand EW Sudakov logarithms for real radiation

Resumming the LL dependence in real radiation possible by using analogy with parton shower

Let's first rewrite the virtual corrections for a pure SU(2) theory

$$\hat{\sigma}^{\mathrm{LL}}_{q_1^H q_2^H \to \ell_1^H \ell_2^H} = \hat{\sigma}^{B}_{q_1^H q_2^H \to \ell_1^H \ell_2^H} \Delta^{\mathrm{SU(2)}}_{q_1^H q_2^H \ell_1^H \ell_2^H} \left(m_V^2, s; s\right)$$

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Born cross-section

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no-branching of 4f system between s and m_V^2

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Born cross-section

no-branching of 4f system between s and m_V^2

The expressions can easily be written down explicitly

$$\hat{\sigma}^{B}_{q^H q^H \to \ell^H \ell^H} = N \frac{8\,\alpha_2^2 \left(T^3_{q^H} T^3_{\ell^H}\right)^2}{3} \qquad \hat{\sigma}^{B}_{q_1^L q_2^L \to \ell_1^L \ell_2^L} = N \frac{2\alpha_2^2}{3}$$

$$\Delta^{\mathrm{SU(2)}}_{q_1^H q_2^H \ell_1^H \ell_2^H}\left(m_V^2, s; s\right) = \exp\left[-\frac{A^{\mathrm{SU(2)}}_{q_1^H q_1^H \ell_1^H \ell_2^H}}{2} \ln^2 \frac{m_V^2}{s}\right] \qquad A^{\mathrm{SU(2)}}_{q_1^H q_1^H \ell_1^H \ell_2^H} = \frac{\alpha_2}{2\pi} \sum_i T_i^2$$

Resumming the LL dependence in real radiation possible by using analogy with parton shower

$$\hat{\sigma}^{\mathrm{LL}}_{q_1^H q_2^H \to \ell_1^H \ell_2^H} = \hat{\sigma}^{B}_{q_1^H q_2^H \to \ell_1^H \ell_2^H} \Delta^{\mathrm{SU(2)}}_{q_1^H q_2^H \ell_1^H \ell_2^H} \left(m_V^2, s; s\right)$$

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This is precisely the result how a parton shower would predict an exclusive (no extra V radiation) DY cross-section

Resumming the LL dependence in real radiation possible by using analogy with parton shower

$$\hat{\sigma}^{\mathrm{LL}}_{q_1^H q_2^H \to \ell_1^H \ell_2^H} = \hat{\sigma}^{B}_{q_1^H q_2^H \to \ell_1^H \ell_2^H} \Delta^{\mathrm{SU}(2)}_{q_1^H q_2^H \ell_1^H \ell_2^H} \left(m_V^2, s; s\right)$$

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Exclusive = Born x (no-branching Prob)

Resumming the LL dependence in real radiation possible by using analogy with parton shower

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Exclusive = Born x (no-branching Prob)

Since emission of massive V has resolution $t > m_V^2$ no branching probability (Sudakov) is from $s=Q^2$ to m_V^2

Resumming the LL dependence in real radiation possible by using analogy with parton shower

From a no-branching probability one can of course derive a branching probability

$$P_{\rm br}(m_V^2, s) = 1 - P_{\rm no-br}(m_V^2, s)$$

from which one can write

$$\hat{\sigma}^{\rm LL}_{q_1^H q_2^H \to \ell_1^H \ell_2^H + nV} = \hat{\sigma}^{B}_{q_1^H q_2^H \to \ell_1^H \ell_2^H} \left[1 - \Delta^{\rm SU(2)}_{q_1^H q_2^H \ell_1^H \ell_2^H} \left(m_V^2, s; s\right)\right]$$

The probability to emit a gauge boson with resolution t is

$$\hat{\sigma}^{\rm LL}_{q_1^H q_2^H \to \ell_1^H \ell_2^H + nV} = \hat{\sigma}^{B}_{q_1^H q_2^H \to \ell_1^H \ell_2^H} \int_{m_V^2}^{s} {\rm d}k_T^2 \, \frac{\rm d}{{\rm d}k_T^2} \Delta^{\rm SU(2)}_{q_1^H q_2^H \ell_1^H \ell_2^H} \left(k_T^2, s; s\right)$$

Resumming the LL dependence in real radiation possible by using analogy with parton shower

$$\hat{\sigma}^{\mathrm{LL}}_{q_1^H q_2^H \to \ell_1^H \ell_2^H + nV} = \hat{\sigma}^{B}_{q_1^H q_2^H \to \ell_1^H \ell_2^H} \int_{m_V^2}^{s} \mathrm{d}k_T^2 \, \frac{\mathrm{d}}{\mathrm{d}k_T^2} \Delta^{\mathrm{SU(2)}}_{q_1^H q_2^H \ell_1^H \ell_2^H} \left(k_T^2, s; s\right)$$

Inclusive σ only sensible if measurement not SU(2) violating

If specifying the flavors, have to define an exclusive real cross-section, with fixed number of emission

Resumming the LL dependence in real radiation possible by using analogy with parton shower

This requires an extra no-branching probability

$$\Delta^{\mathrm{SU}(2)}_{q_1^H q_2^H \ell_1^H \ell_2^H V}\left(m_V^2, k_T^2; s\right) \equiv \Delta_V\left(m_V^2, k_T^2; \hat{k}_T^2\right) \Delta^{\mathrm{SU}(2)}_{q_1^H q_2^H \ell_1^H \ell_2^H}\left(m_V^2, k_T^2; s\right)$$

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no-branching of extra
V from k_T to m_V

Resumming the LL dependence in real radiation possible by using analogy with parton shower

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no-branching of extra V from k_T to m_V

no-branching of 4-fermion system from k_T to m_V

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no-branching of extra V from k_T to m_V

no-branching of 4-fermion system from k_T to m_V

Putting this together one gets the final exclusive real radiation result

$$\hat{\sigma}^{\mathrm{LL}}_{q_1^H q_2^H \to \ell_1^H \ell_2^H + V}$$
$$= \hat{\sigma}^{B}_{q_1^H q_2^H \to \ell_1^H \ell_2^H} \int_{m_V^2}^{s} \mathrm{d}k_T^2 \frac{\mathrm{d}}{\mathrm{d}k_T^2}\left[\Delta^{\mathrm{SU}(2)}_{q_1^H q_2^H \ell_1^H \ell_2^H}\left(k_T^2, s; s\right)\right] \Delta^{\mathrm{SU}(2)}_{q_1^H q_2^H \ell_1^H \ell_2^H V}\left(m_V^2, k_T^2; s\right)$$

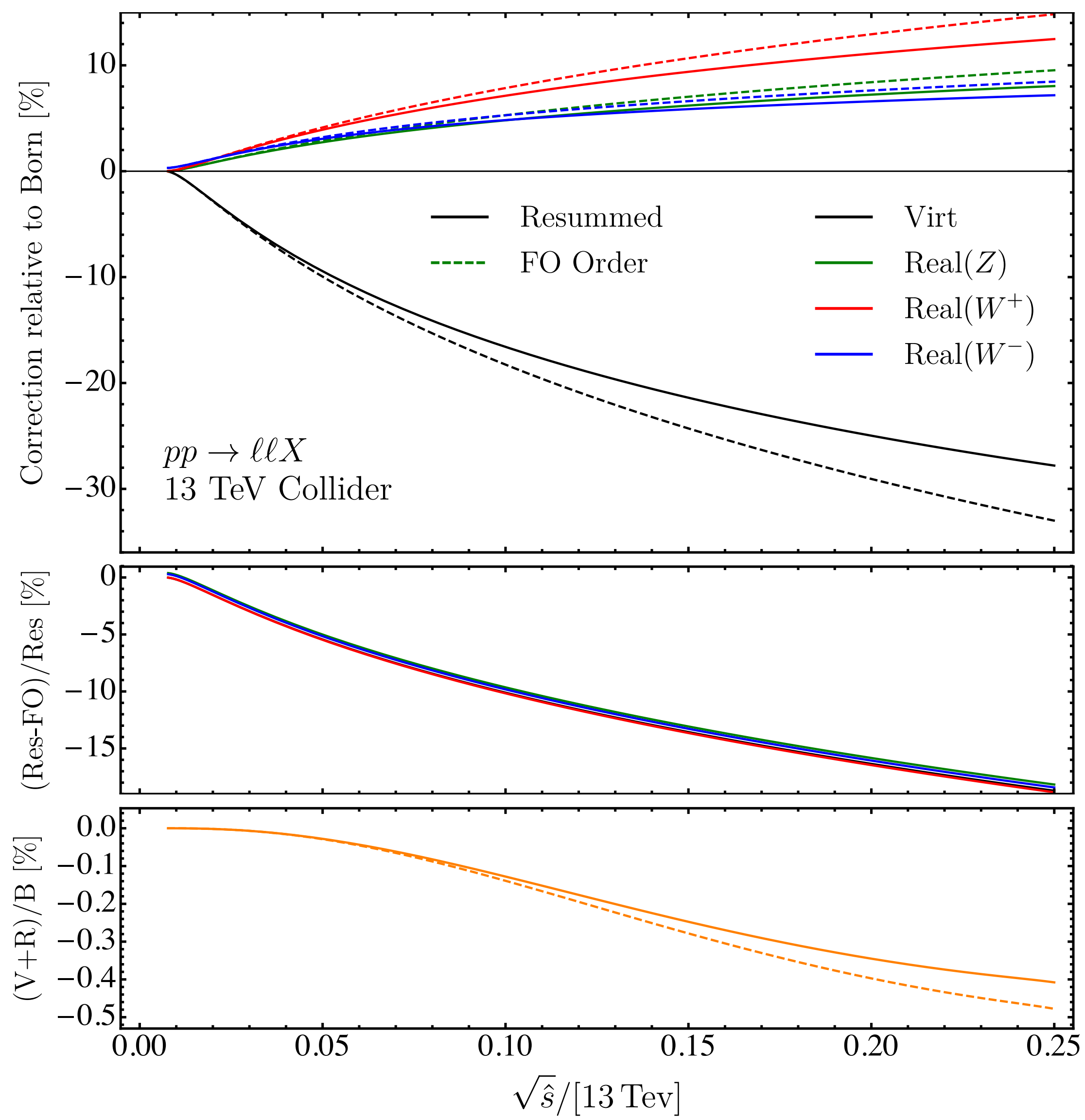
Taking into account the full SU(2) x U(1) structure and writing the result in terms of W, Z, one finds

W boson

$$\hat{\sigma}^{\mathrm{LL}}_{q_1^H q_2^H \to \ell_1^H \ell_2^H + W^\pm}$$
$$= \left[\Delta_{q_1^H q_2^H \ell_1^H \ell_2^H}\left(m_V^2, s; s\right)\ \Delta^{\mathrm{em}}_{q_1^H q_2^H \ell_1^H \ell_2^H W^\pm}\left(\Lambda^2, m_V^2; s\right) \int_{m_V^2}^{s} \frac{\mathrm{d}k_T^2}{k_T^2} \ln \frac{s}{k_T^2} \Delta_V\left(m_V^2, k_T^2; k_T^2\right)\right]$$
$$\times \left(\hat{\sigma}^B_{q'^H_1 q_2^H \to \ell_1^H \ell_2^H} A^{W^\pm}_{q_1^H} + \hat{\sigma}^B_{q_1^H q'^H_2 \to \ell_1^H \ell_2^H} A^{W^\pm}_{q_2^H} + \hat{\sigma}^B_{q_1^H q_2^H \to \ell'^H_1 \ell_2^H} A^{W^\pm}_{\ell_1^H} + \hat{\sigma}^B_{q_1^H q_2^H \to \ell_1^H \ell'^H_2} A^{W^\pm}_{\ell_2^H}\right)$$

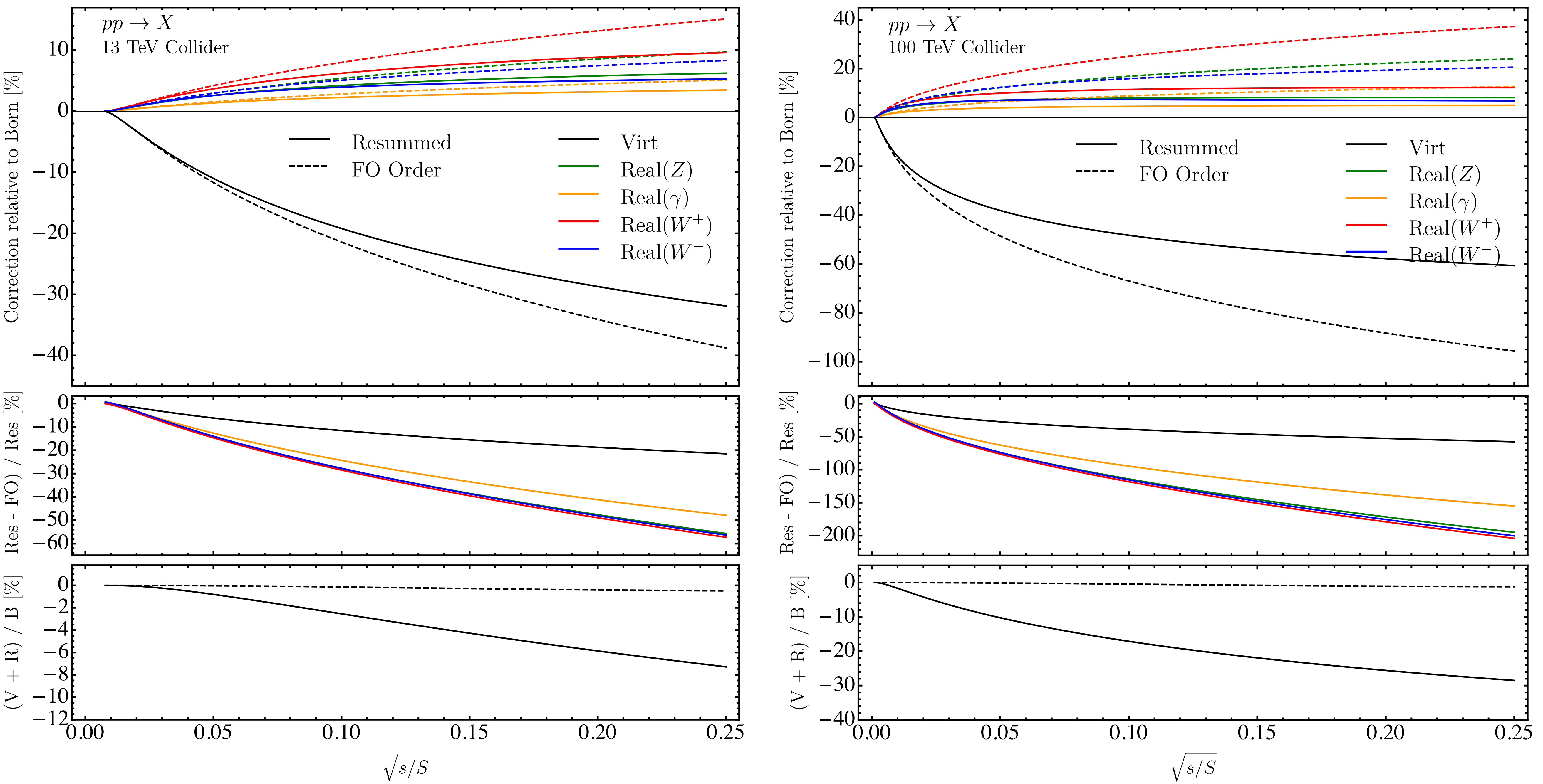
Z boson

$$\hat{\sigma}^{\mathrm{LL}}_{q_1^H q_2^H \to \ell_1^H \ell_2^H + Z} = \hat{\sigma}^B_{q_1^H q_2^H \to \ell_1^H \ell_2^H}\ \Delta_{q_1^H q_2^H \ell_1^H \ell_2^H}\left(m_V^2, s; s\right)\ \Delta^{\mathrm{em}}_{q_1^H q_2^H \ell_1^H \ell_2^H}\left(\Lambda^2, m_V^2; s\right) \tag{4.42}$$
$$\times \int_{m_V^2}^{s} \frac{\mathrm{d}k_T^2}{k_T^2} \ln \frac{s}{k_T^2} \Bigg(s_W^2 A^{\mathrm{U}(1)}_{q_1^H q_2^H \ell_1^H \ell_2^H} - A^{\mathrm{mixing}}_{q_1^H q_2^H \ell_1^H \ell_2^H} \sqrt{\Delta_W\left(m_V^2, k_T^2; k_T^2\right)}$$
$$+ c_W^2 A^{W^3}_{q_1^H q_2^H \ell_1^H \ell_2^H} \Delta_W\left(m_V^2, k_T^2; k_T^2\right) \Bigg)$$

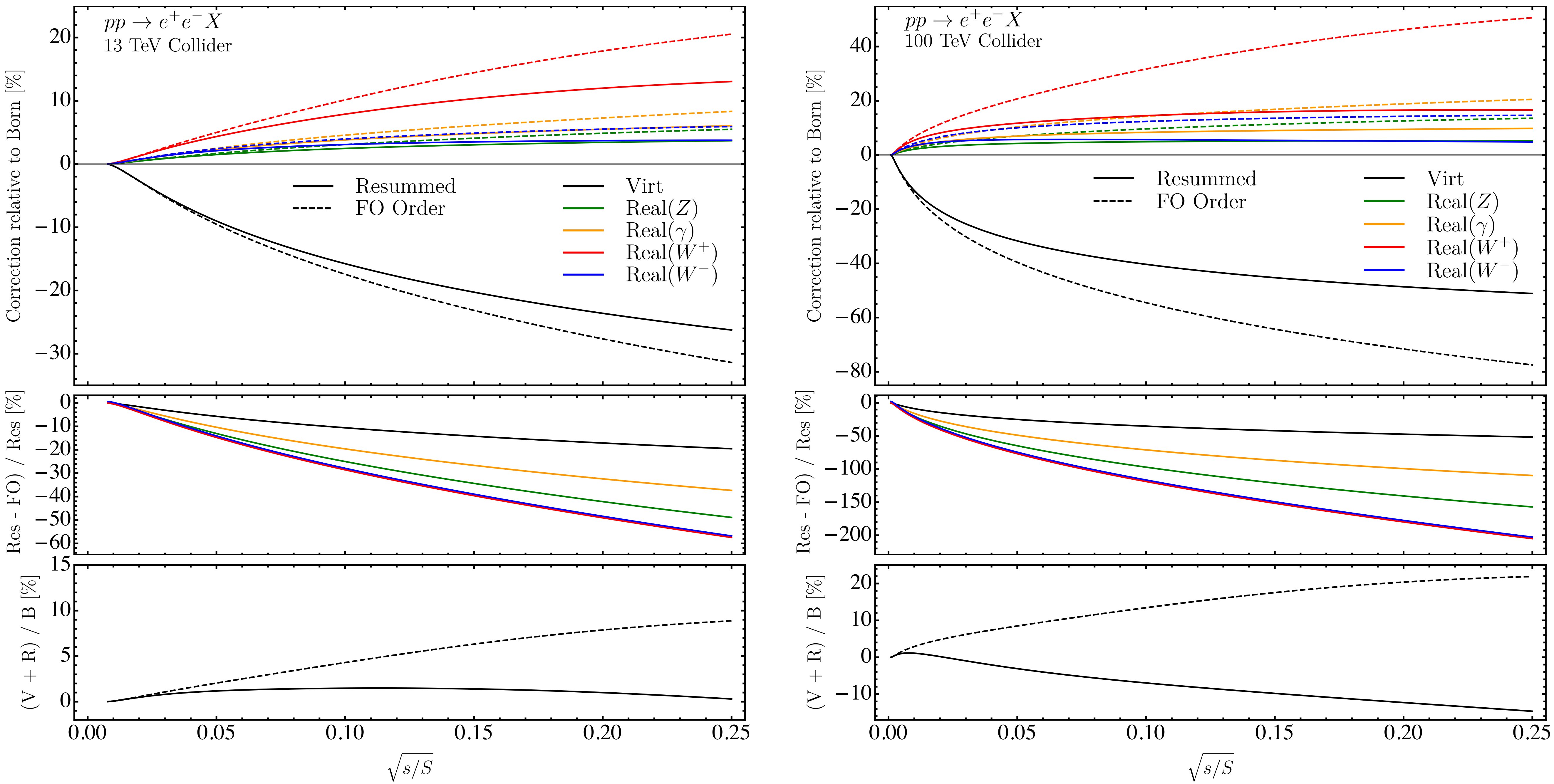


Correction relative to Born [%]
Resummed
FO Order
Virt
Real(Z)
Real(W^+)
Real(W^-)
$pp \to \ell\ell X$
13 TeV Collider
(Res-FO)/Res [%]
(V+R)/B [%]
$\sqrt{\hat{s}}/[13\,\text{Tev}]$

The results clearly indicate that resummation for the real is at least as important as for the virtual



The results clearly indicate that resummation for the real is at least as important as for the virtual



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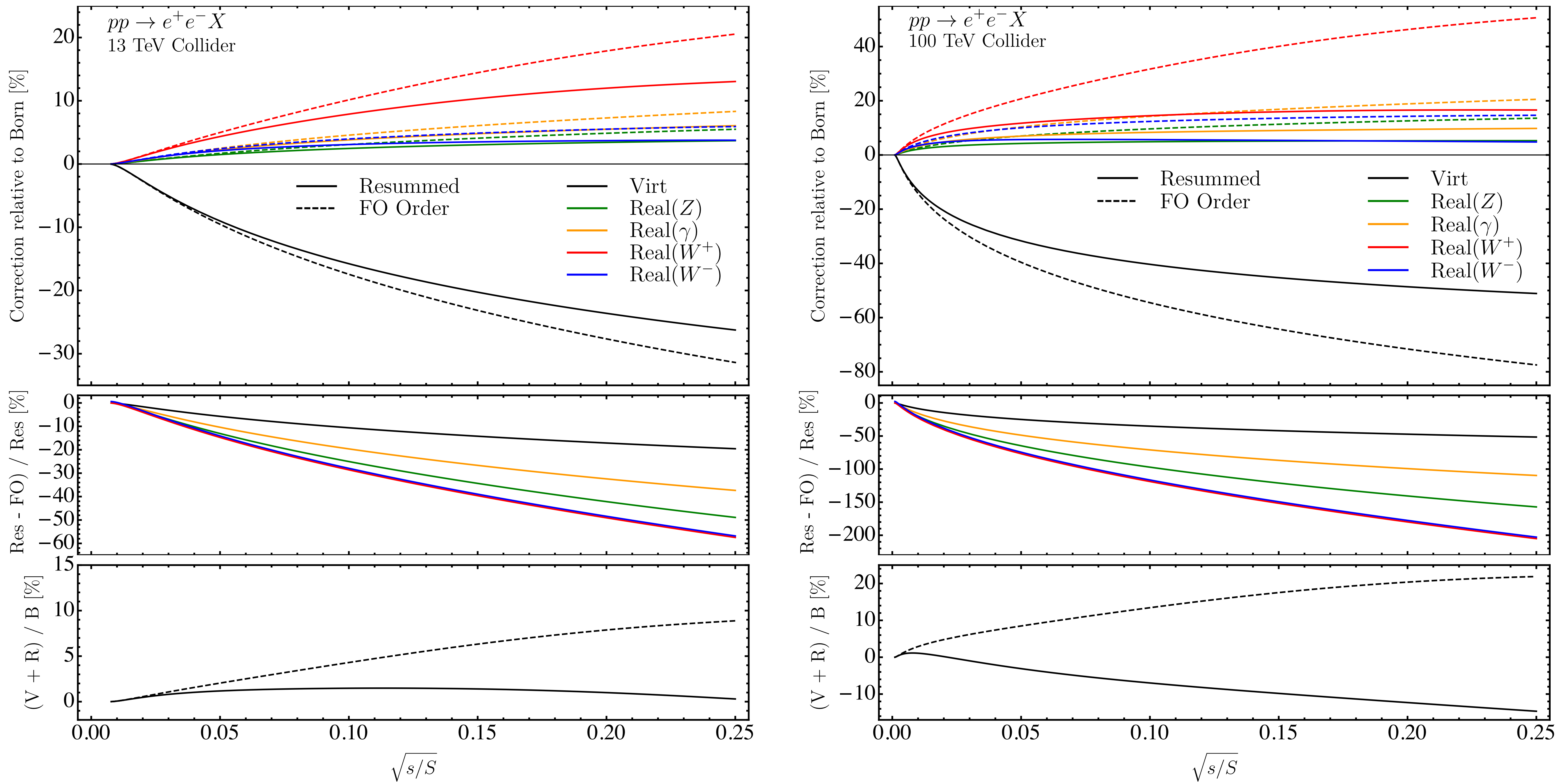

We have results for all possible leptonic final states in paper

We have first results on the LL resummation for real radiation, working on making these results fully differential

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Can obtain analytical results for the resummation of the real radiation

EW Sudakov logarithms are as important for real as for virtual

Currently working on fully exclusive implementation of above results

Also working on parton shower like approach, which can take into account arbitrary number of emissions

Absolutely crucial to do this for 100 TeV machine

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QUESTIONS?

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