One-loop electroweak Sudakov logarithms: automation and applications

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Joint Max-Planck & TUM seminar
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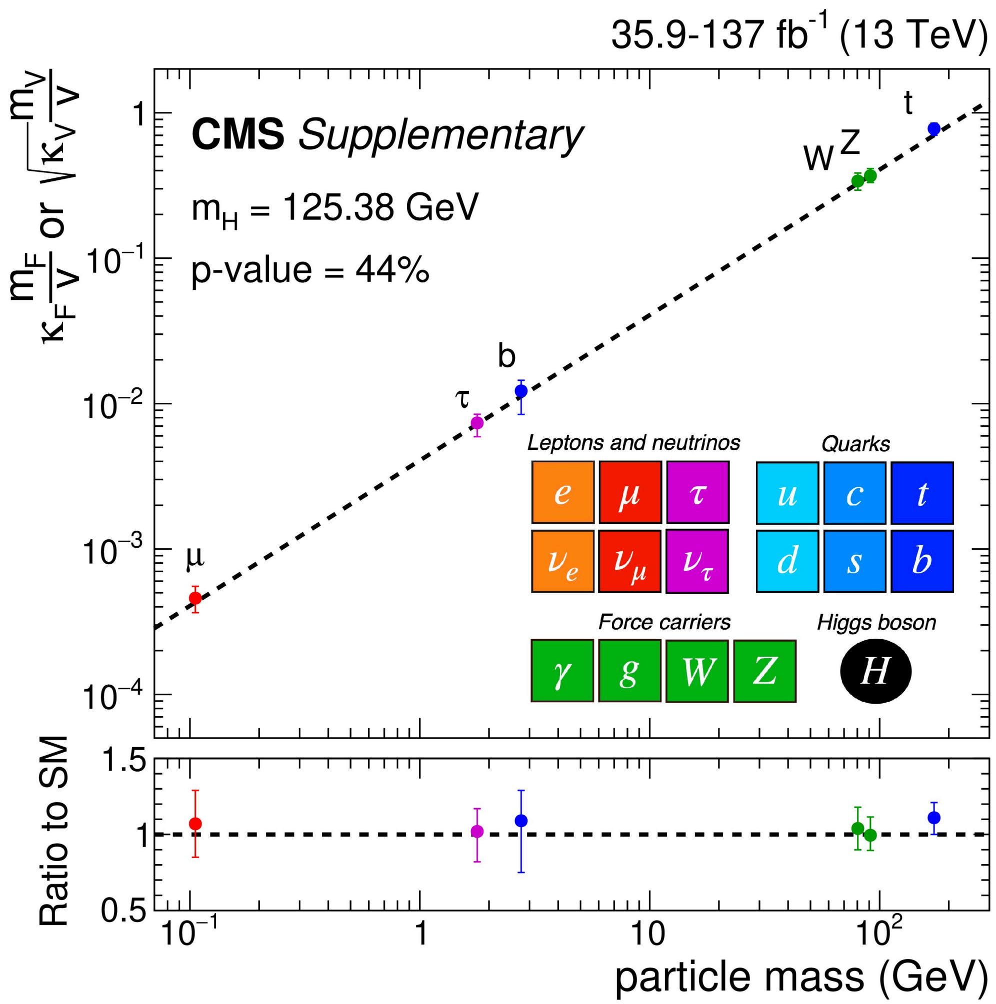
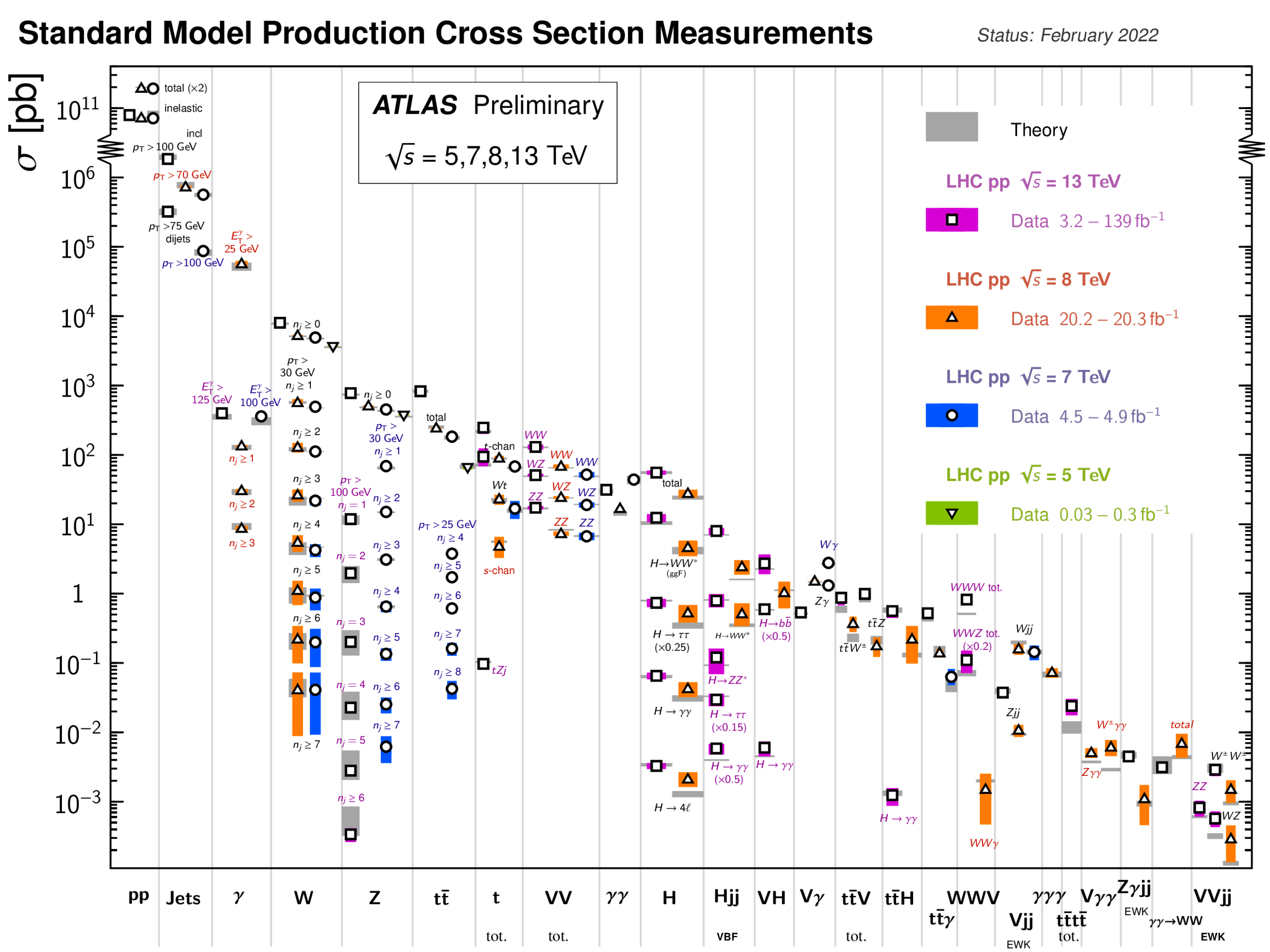
MAX-PLANCK-INSTITUT FÜR PHYSIK

Istituto Nazionale di Fisica Nucleare
Sezione di Milano

LHC is running (again)!





A beautiful theory

- The Standard Model encloses our current knowledge of fundamental interactions
- It is a complete theory, and successfully explain phenomena over a vast range of scales (from low-energy QED to the largest energy scales we can probe)

Electron g-2 ↓ 10^{-12}

$$g/2 = 1.001\ 159\ 652\ 180\ 73\ (28) \quad [0.28\ \text{ppt}]\ (\text{measured})$$
$$g(\alpha)/2 = 1.001\ 159\ 652\ 177\ 60\ (520) \quad [5.2\ \text{ppt}]\ (\text{predicted}).$$

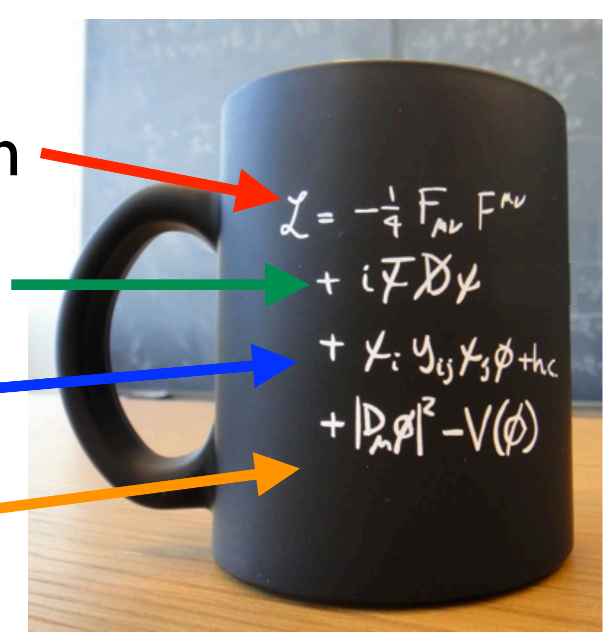
- Its Lagrangian can be cast in a very compact form

Gauge kinetic term

Matter kinetic term

Matter-Higgs interaction

Higgs kinetic term+potential



New Physics?

New Physics?

- We (still) believe that new physics must exist
  - What is Dark Matter made of?
  - Where is all the anti-matter in the universe?
  - Why do particles have such innatural masses?
  - …

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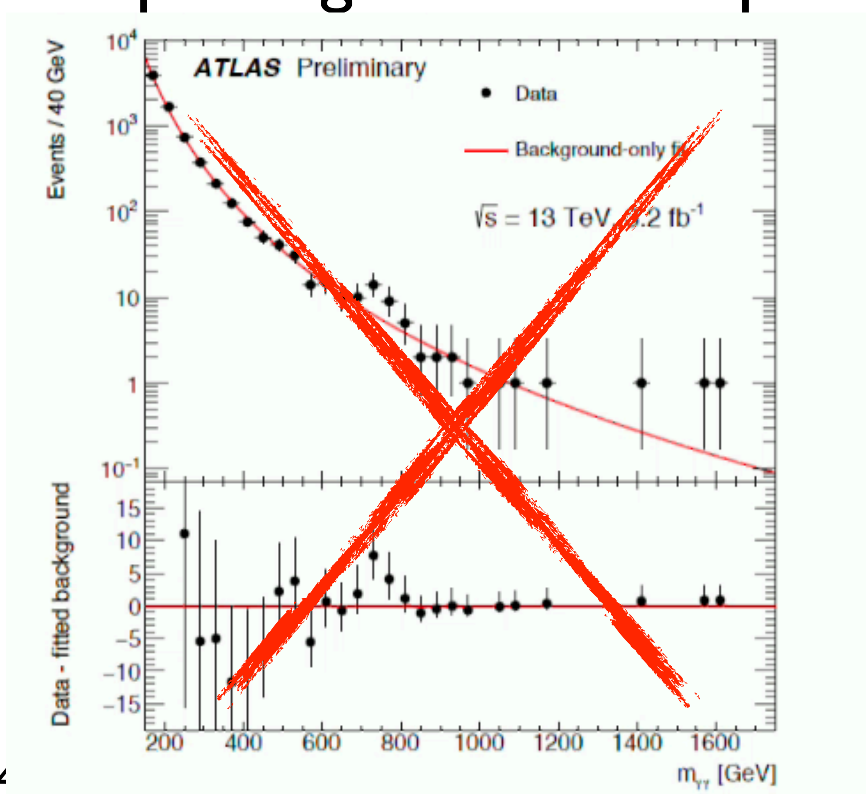
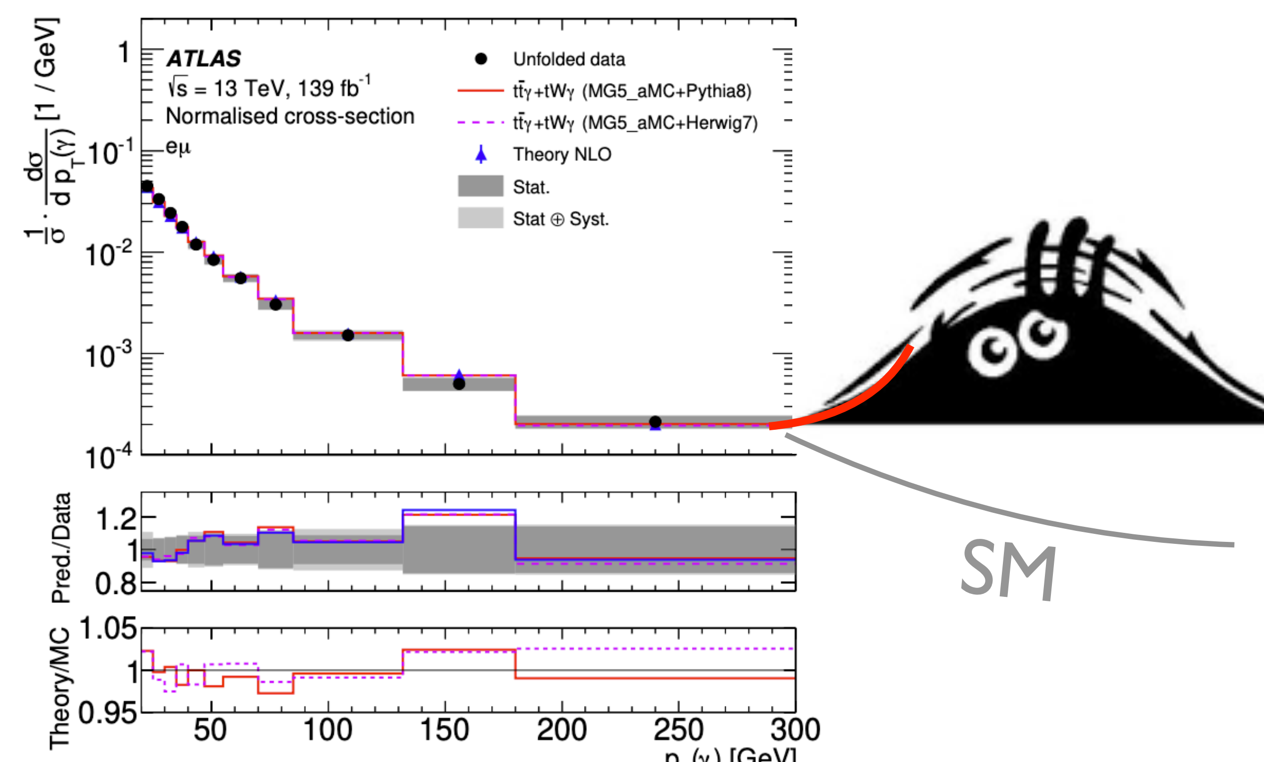
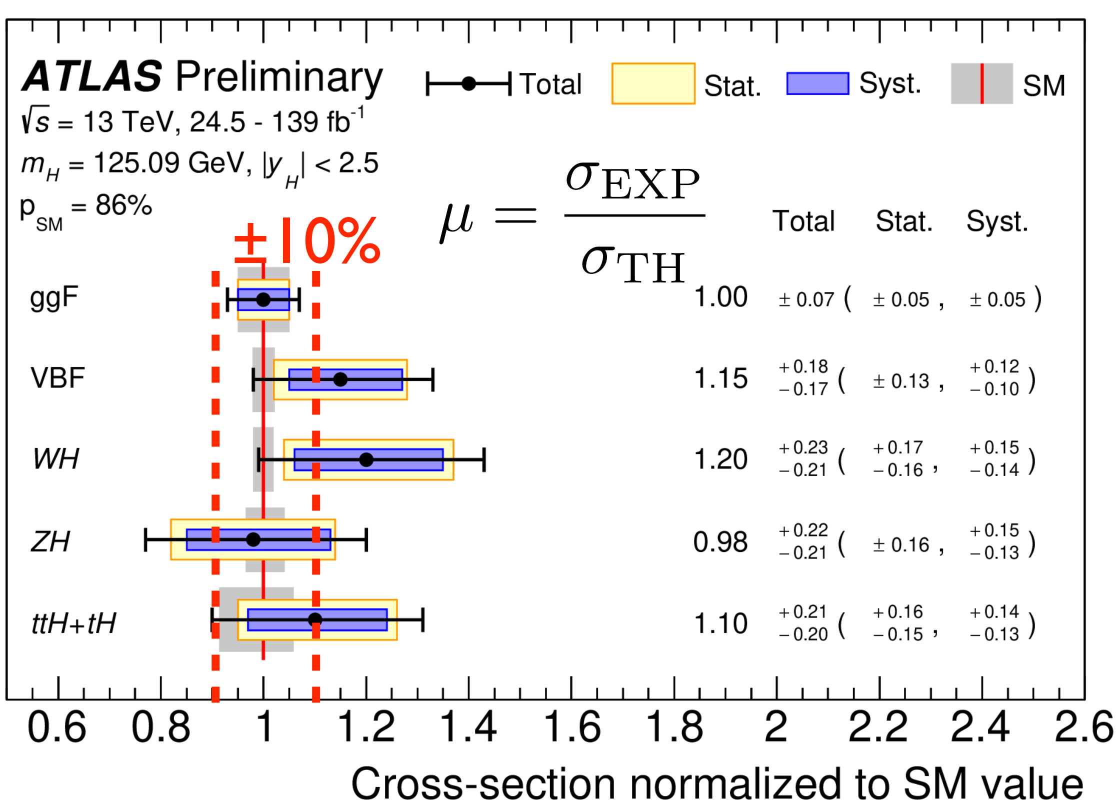
  - …
- New physics must be hiding very well!
  - Change of paradigm: from bump hunting to precision measurements

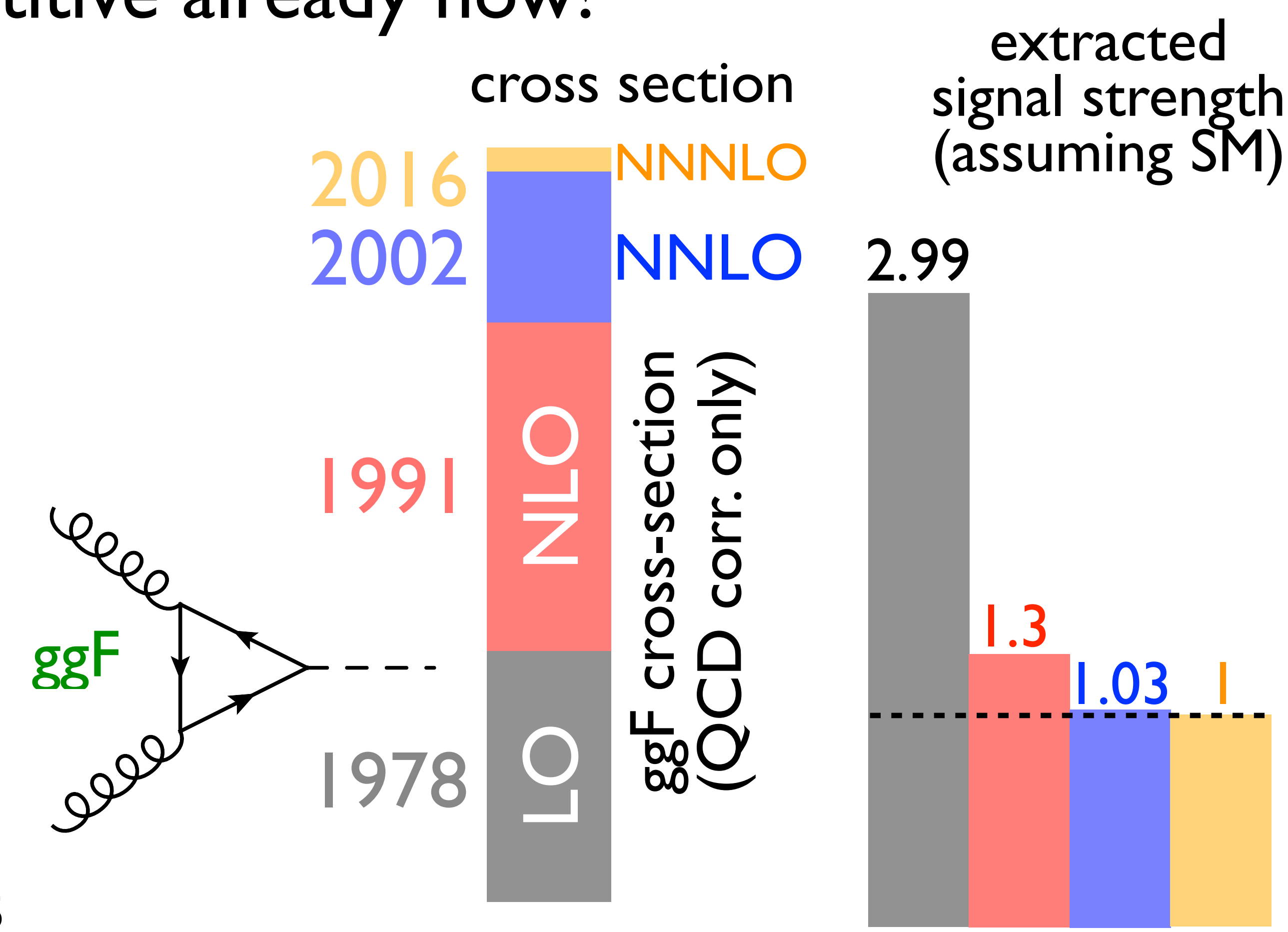




Precision for measurements

- Our ability to make measurements and discoveries is limited by the goodness of our theory predictions
- Higgs physics gives a clear example: the dominant production channel receives large perturbative corrections
- Without the inclusion of higher orders, ggF measured rate would be 3*SM
- Exp. measurements are very competitive already now!





How do we do precision calculations?

- We cannot solve exactly the SM Lagrangian: use perturbation theory
- QCD factorisation theorem

$$\sigma_{pp\to X}(s) = \sum_{ab} \int dx_1 dx_2 f_a(x_1) f_b(x_2) \hat{\sigma}_{ab\to X}(\hat{s} = x_1 x_2 s)$$

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Parton distribution functions: must be fit to data, process independent

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strong coupling, ~0.1

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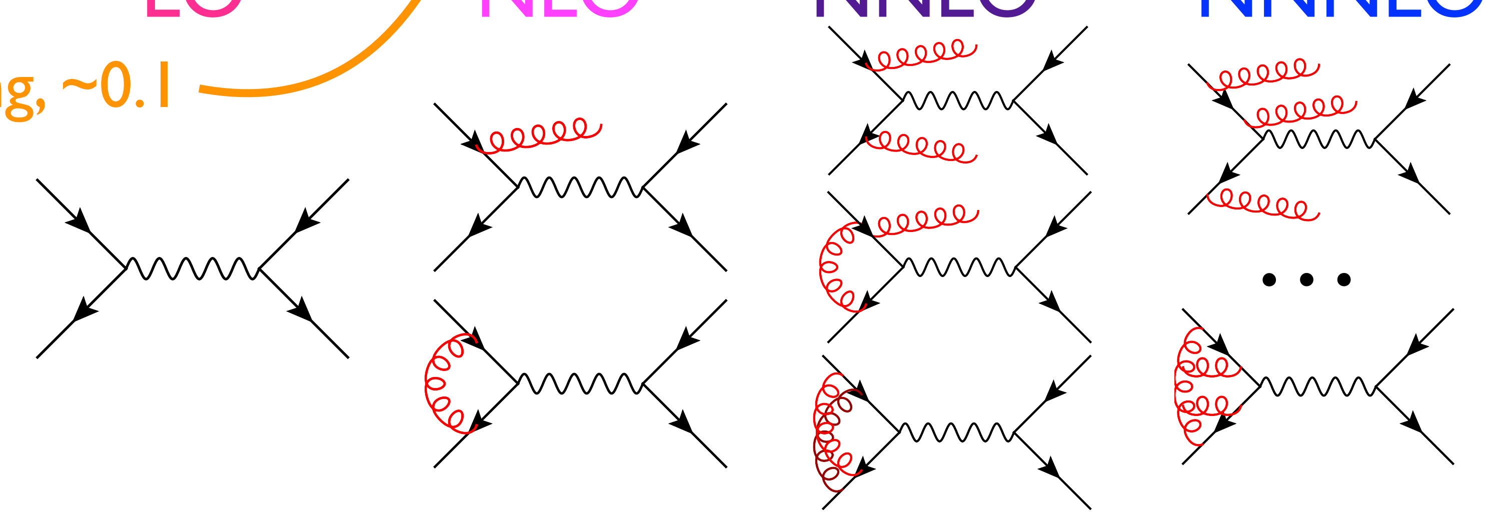
LO NLO NNLO NNNLO

strong coupling, ~0.1



- Going higher orders, the complexity of the computation explodes

SM ≠ QCD

- So far, we considered only QCD effects
- In the SM also electroweak effects must be accounted for
  →Multi-coupling expansion
- Since $\alpha \simeq \alpha_s^2$, EW effects cannot be neglected for precision
  - EW effects grow at large energies: Sudakov enhancement
  - Luckily, NLO EW corrections have been automated in the last years
    see e.g.: Kallweit et al,1412.5157 (Sherpa+OpenLoops), Biedermann et al, 1704.05783 (Sherpa+Recola+Collier), Frederix, Frixione, Hirschi, Pagani, Shao, MZ, 1804.10017 (MG5_aMC)
  - Relevance of EW corrections also beyond SM and LHC:
    - Can be O(1) at high-energy lepton colliders (specially muons)
    - Sizeable effects in Dark-Matter searches, e.g. indirect-detection with heavy DM particles see e.g. Ciafaloni et al, 1104.2996 …, Cavasonza et al, 1409.8226

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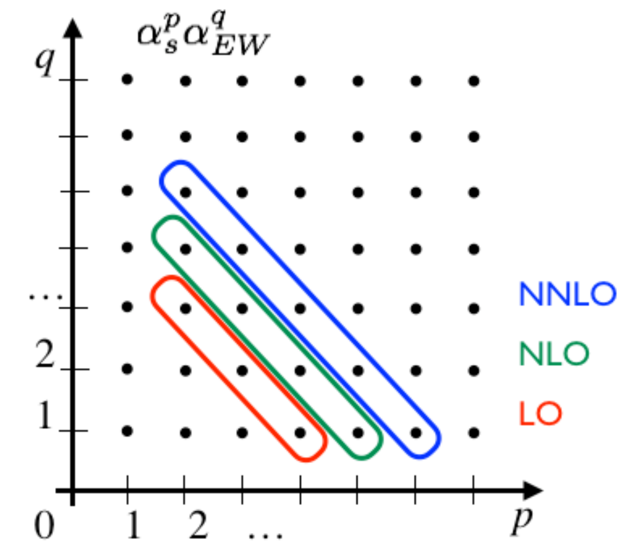

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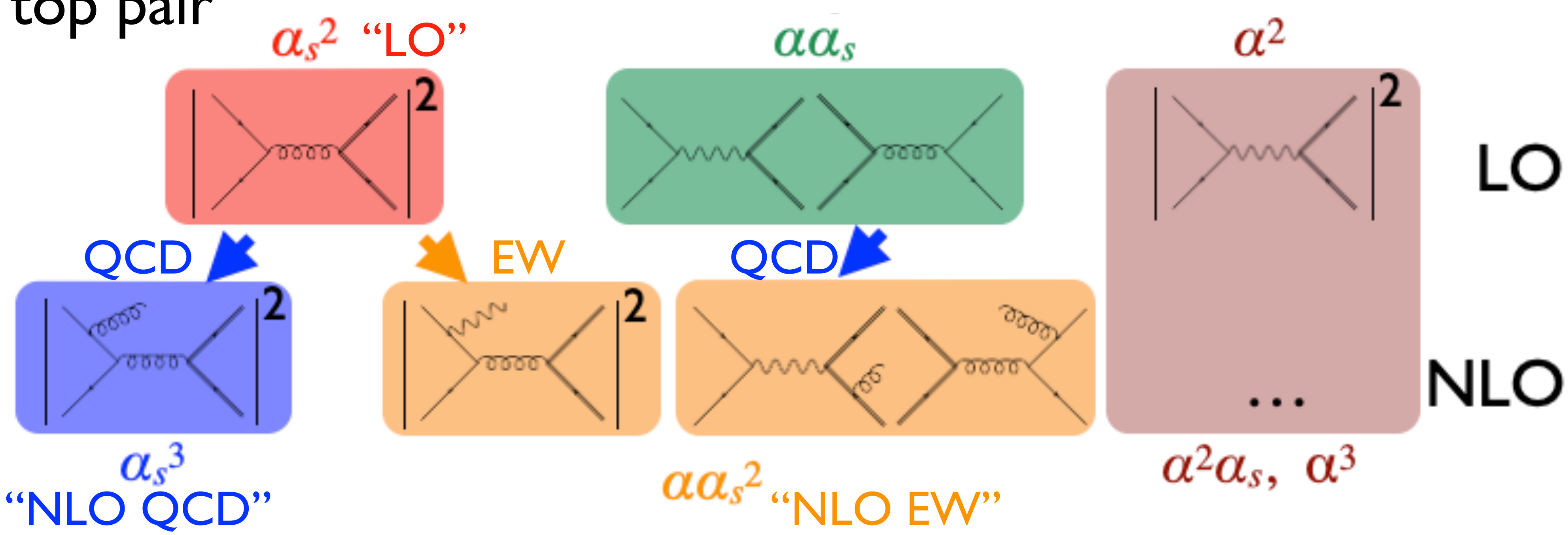
EW corrections vs EW effects

- A general process has several contributions at LO, NLO, …
- Example: top pair

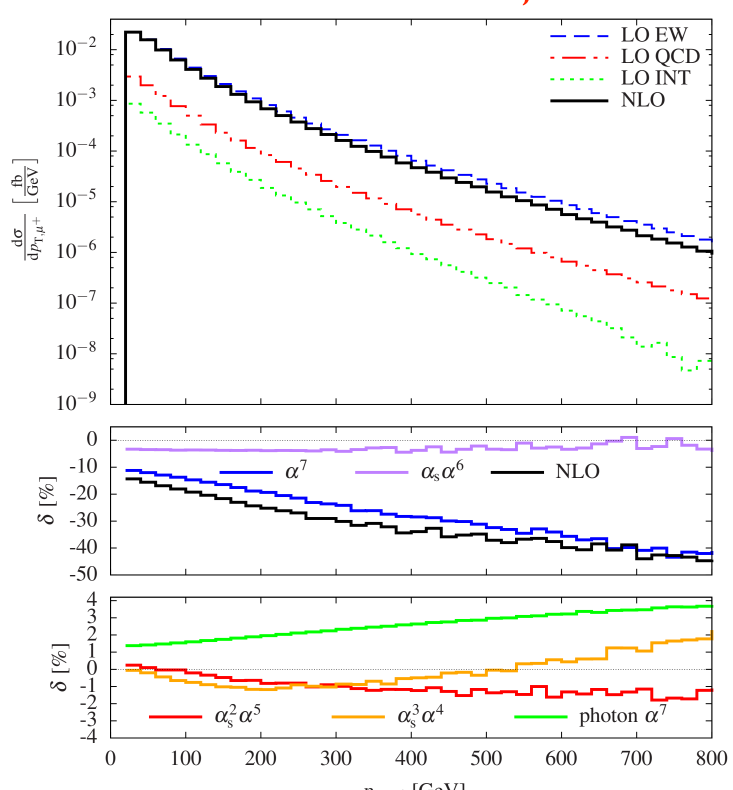


- The LO is often identified with the contribution with most α_s
- At NLO the first two contributions are identified with the NLO QCD and NLO EW corrections
- This structures induces mixed QCD-EW effects at NLO:
  $\mathrm{NLO}_i = \mathrm{LO}_{i-1} \otimes \mathrm{EW} + \mathrm{LO}_i \otimes \mathrm{QCD}$

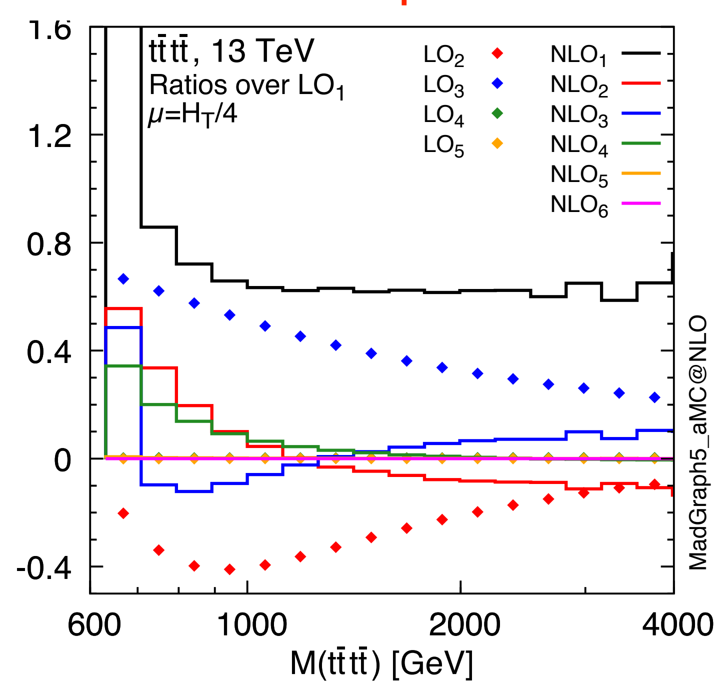
Large EW corrections

- Despite the naive estimate $\alpha \sim \alpha_s^2$, there are cases when EW corrections comparable to NLO QCD or larger. It happens when:
  - Large scales are probed (VBS)
  - Power counting is altered (4 top: y_t vs α)
  - New production mechanisms, different than those at the "dominant" LO, enter (ttW, bbH)

VBS: Biedermann et al, 1708.00268

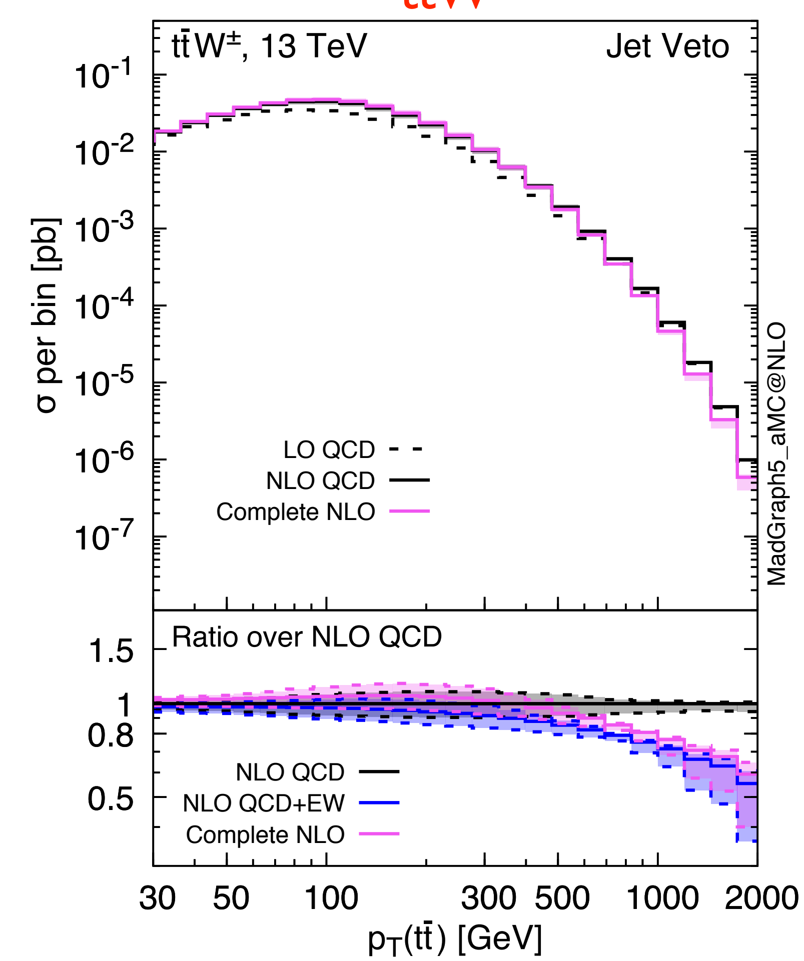


4 top

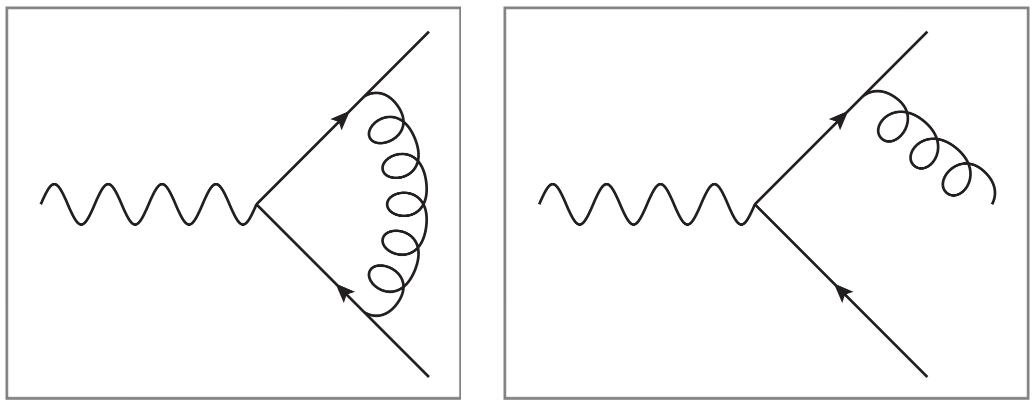


Frederix, Pagani, MZ 1711.02116

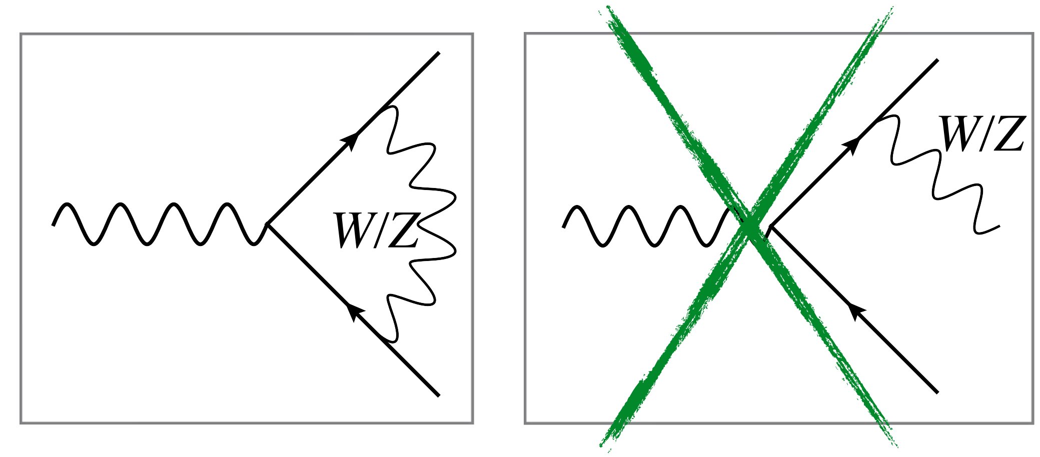
ttW



EW Sudakov Logarithms



QCD



EW

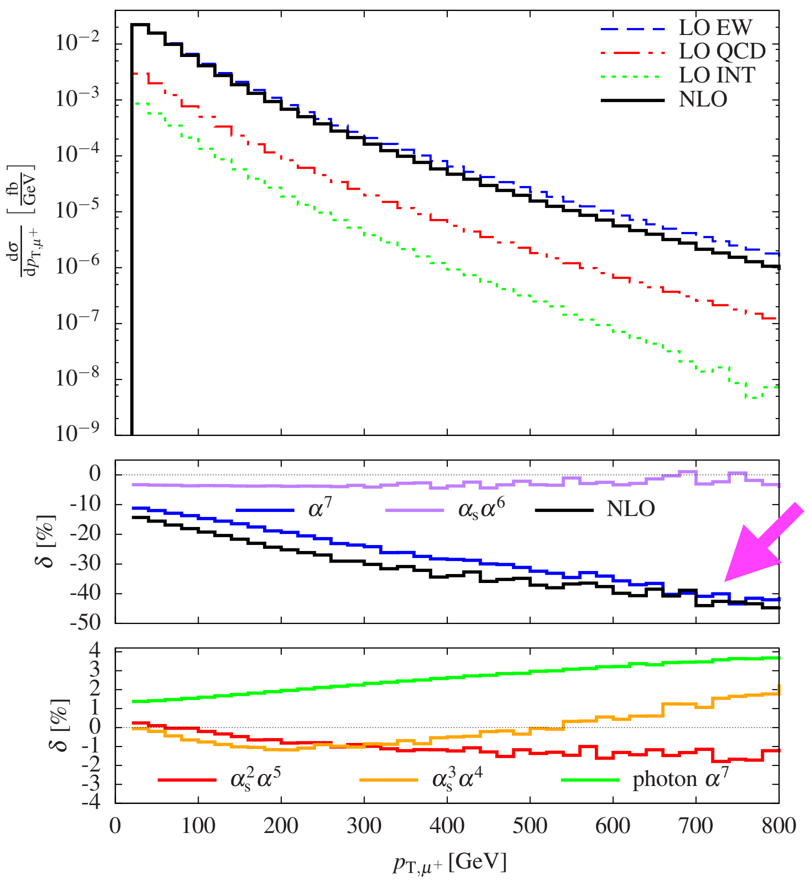
- Since gluons are massless, one must include virtual and real radiation in NLO QCD computations
- The W/Z/Higgs boson masses make EW corrections finite. No need to include heavy-boson radiation (distinguishable, in principle)
- Even if we included HBR, cancelation will only be partial Manohar et al, 1409.1918
- However, at high energies, the would-be IR divergence appears via logs:

$$\alpha^k \log^p \frac{s}{m_W^2}, \quad p \leq 2k$$

- EWSL are universal, enhance the cross section at high-energy, and can be resummed Denner, Rode, 2402.10503

Universality of EWSL

VBS: Biedermann et al, 1708.00268



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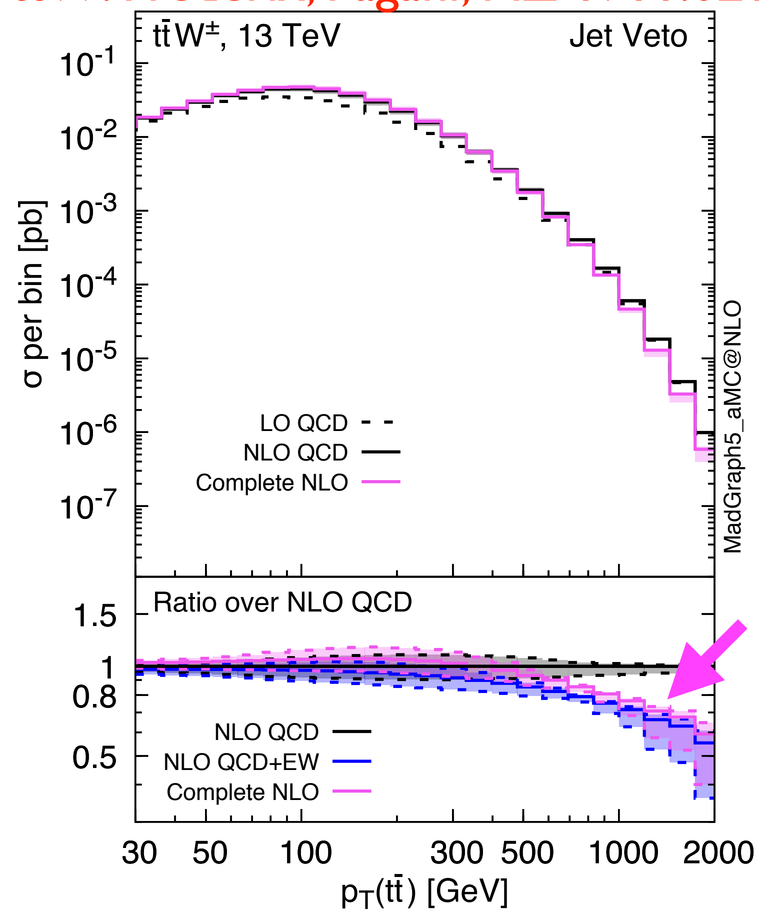

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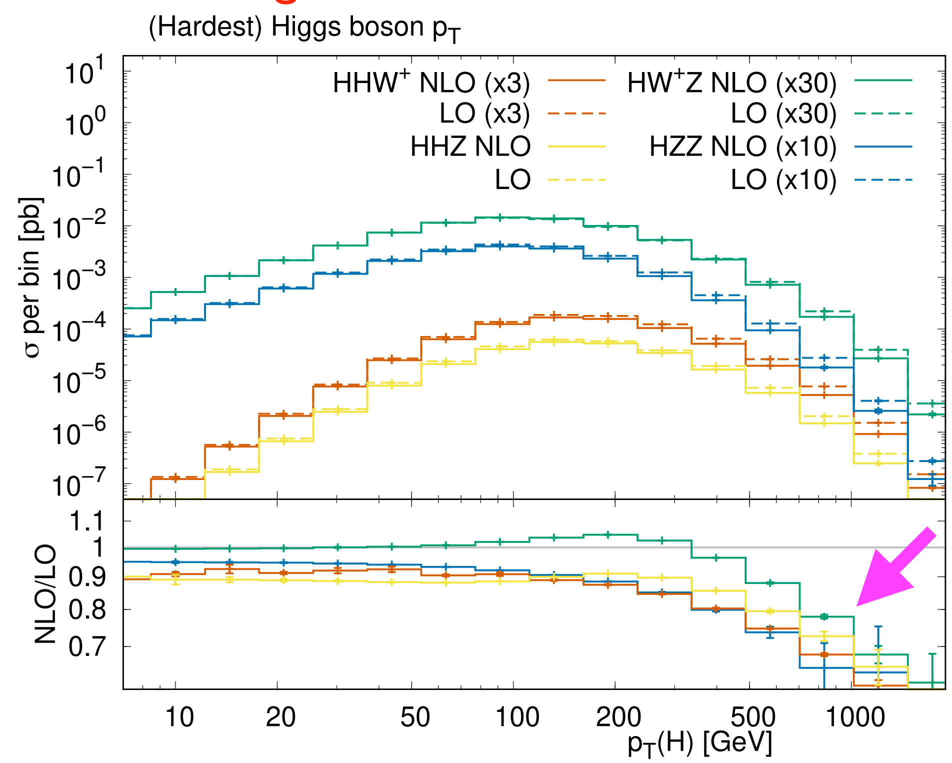
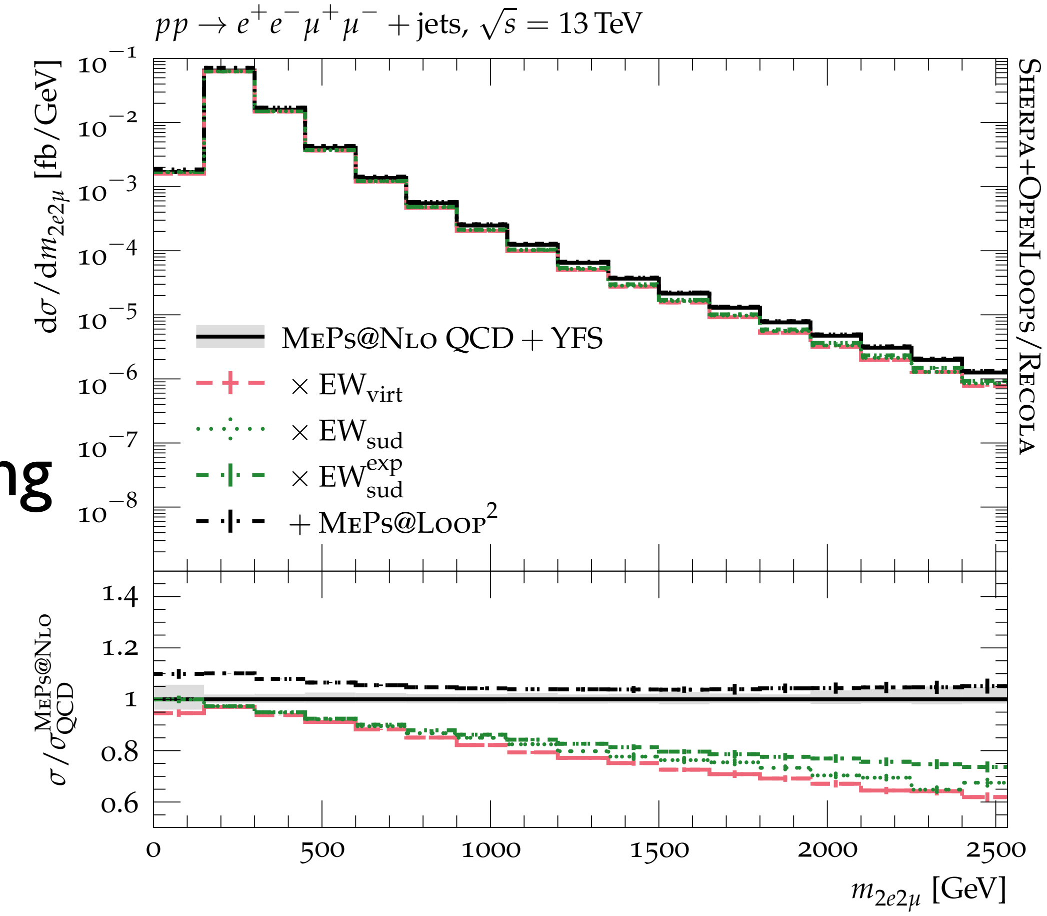


- EWSL enhancement is a feature of many scattering processes
- Still, other effects of different origin can appear in the same kinematic regime: photon PDFs, quasi-collinear enhancements, etc…

Don't we have the exact EW corrections?

- Despite the fact we have the exact EW corrections, EWSL have re-gained attention in the recent years:
  see e.g. the automation in Sherpa, Bothmann et al, 2006.14635
  or OpenLoops, Lindert et al, 2312.07927
  - Can be resummed, providing NLO+NLL EW accuracy
  - Much faster and more stable than exact NLO EW corrections
  - ★ Only Born-like kinematics: PS merging/matching simplified
    Chiesa et al, 1305.6837; Bothmann et al, 2111.13453
  - ★ Universal: can be computed also for BSM theories, where UV renormalisation is very complex or even impossible

Bothmann et al, 2111.13453



★ =In this talk

EWSL by Denner and Pozzorini

hep-ph/0010201 & hep-ph/0104127

- In their seminal works, D&P derived the structure of EWSL for one-loop matrix elements, *where at least one helicity configuration is not mass-suppressed*
- *All invariants* must satisfy the constraint $|r_{ij}| \simeq s \gg M_W^2$
- SM is chiral → EWSL must be computed helicity-by-helicity
  - Use GBET for longitudinal polarisations
- EWSL decomposed as sum of 4 terms

$$\delta = \delta^{\mathrm{LSC}} + \delta^{\mathrm{SSC}} + \delta^{\mathrm{C}} + \delta^{\mathrm{PR}}$$

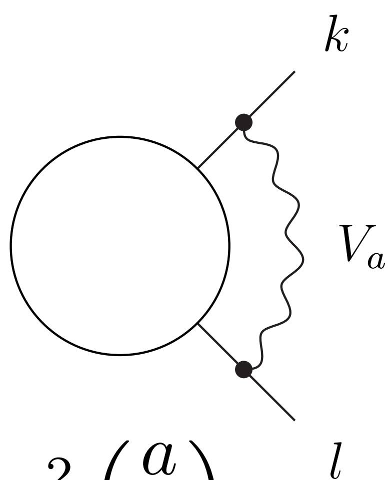
Subleading soft-collinear Parameter remormalisation

Leading soft-collinear Collinear single logs

- Photon and fermion masses to regulate IR divergences
- Analytic control of expressions (for simple processes): ability to single out only the dominant terms in the results

A glance at the anatomy of EWSL

$$\sum_{k=1}^{n}\sum_{l<k}\sum_{V_a=\mathrm{A,Z,W^\pm}}$$



$$\simeq C_0\left(p_k,p_l,M_V,M_k,M_l\right)\simeq \log^2\left(\frac{-(p_k+p_l)^2-i\epsilon}{M_V-i\epsilon}\right)$$

$$= L\left(|r_{kl}|,M_V\right)-2i\pi\,\theta(r_{kl})\,l\left(|r_{kl}|,M_V\right) \quad *$$

$$= L(s,M_V) + 2l(s,M_V)\left[\log\left(\frac{|r_{kl}|}{s}\right) - i\pi\,\theta(r_{kl})\right]$$

$$+\, L(|r_{kl}|,s) - 2i\pi\,\theta(r_{kl})l(|r_{kl}|,s)$$

LSC

SSC

Imaginary part and extra angular dependence ($\Delta^{s\to r_{kl}}$)

$$L(a,b)=\log^2\left(\frac{a}{b}\right)$$

$$l(a,b)=\log\left(\frac{a}{b}\right)$$

- Soft-collinear terms originate from vector-boson exchange between external legs (in the eikonal approx.)
  - In the strict high-energy approximation (as in D&P), terms with s/r_{kl} are neglected. Their inclusion can improve angular dependence
  - The imaginary part was not considered in D&P
- Other terms originate from purely-collinear configurations and field renormalisation

*M_V is further expressed in terms of M_W; constant terms are dropped

Implementation of EWSL in MG5_aMC

Pagani, MZ arXiv:2110.03714

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- Builds on the work by D&P, with some variations:
  - Automate the computation of EWSL for any process, in a fully-numerical framework: MG5_aMC Alwall, …, MZ, 1405.0301 & Frixione, …, MZ, 1804.10017
  - Translate expressions using the modern language of Dim.Reg.
  - Include a missing imaginary part in D&P (relevant for 2→n, n≥3)
  - Provide results for the squared amplitude, including the tree-loop interference, both due to EW and QCD effects
  - Improve angular dependence by retaining explicit r_{kl} dependence
  - Obtain approximations for physical cross sections (Virtual+Reals), with the possibility that photons are clustered with charged particles

The automation of EWSL

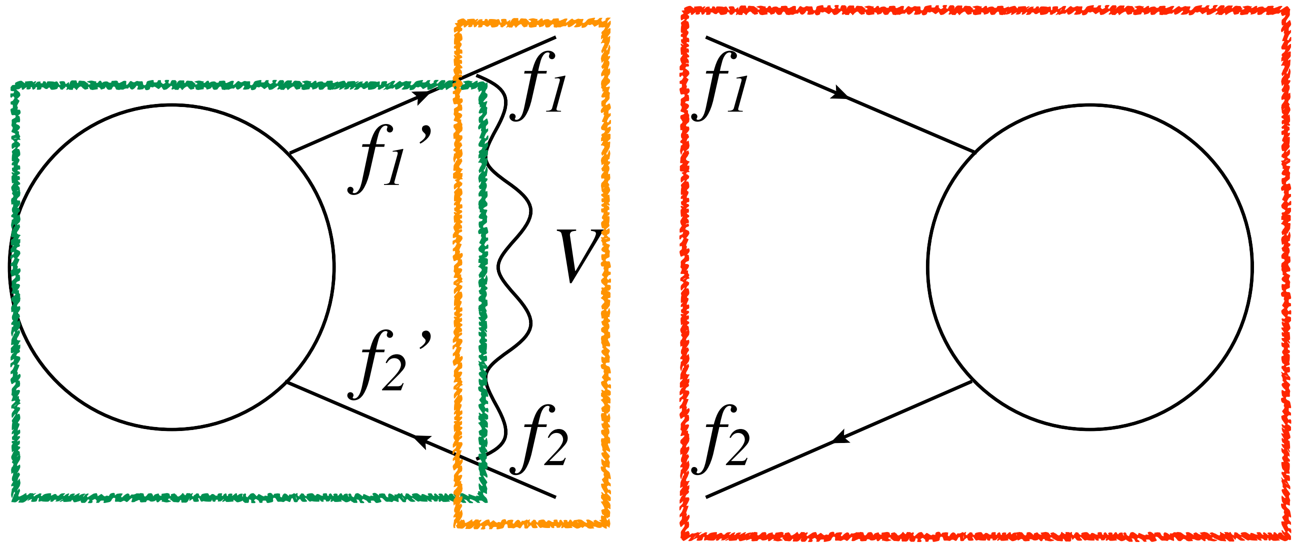
- Use MG5_aMC to generate all the needed matrix elements:
  - Born ME's B_i, including those where $V^{0,\pm} \to G^{0,\pm}$
  - Isospin-linked Borns $B_{i,j}$, and their interferences with B_i
    - Since external particles differ, momenta may need reshuffling to satisfy on-shell relations
  - Keep track of all terms needed for each EWSL contribution, helicity by helicity
  - Compute δ^{PR} with numerical derivatives

$$\delta^{\mathrm{PR}}\mathcal{M} = \frac{\delta\mathcal{M}_0}{\delta e}\delta e + \frac{\delta\mathcal{M}_0}{\delta c_{\mathrm{w}}}\delta c_{\mathrm{w}} + \frac{\delta\mathcal{M}_0}{\delta h_{\mathrm{t}}}\delta h_{\mathrm{t}} + \frac{\delta\mathcal{M}_0}{\delta h_{\mathrm{H}}}\delta h_{\mathrm{H}}^{\mathrm{eff}}\bigg|_{\mu^2=s}$$

    - No special Feynman rule needed by the model → easy to extend BSM
    - Formula adapted for both G_μ and $\alpha(M_Z)$ scheme

Isospin-linked borns

- EWSL originate from loops where EW vector bosons attach to one or two external legs
- This can change e.g. the flavour of a given fermion line (u→d, l→ν,…)
- In this case, the Born matrix element is interfered with an 'isospin-linked' term

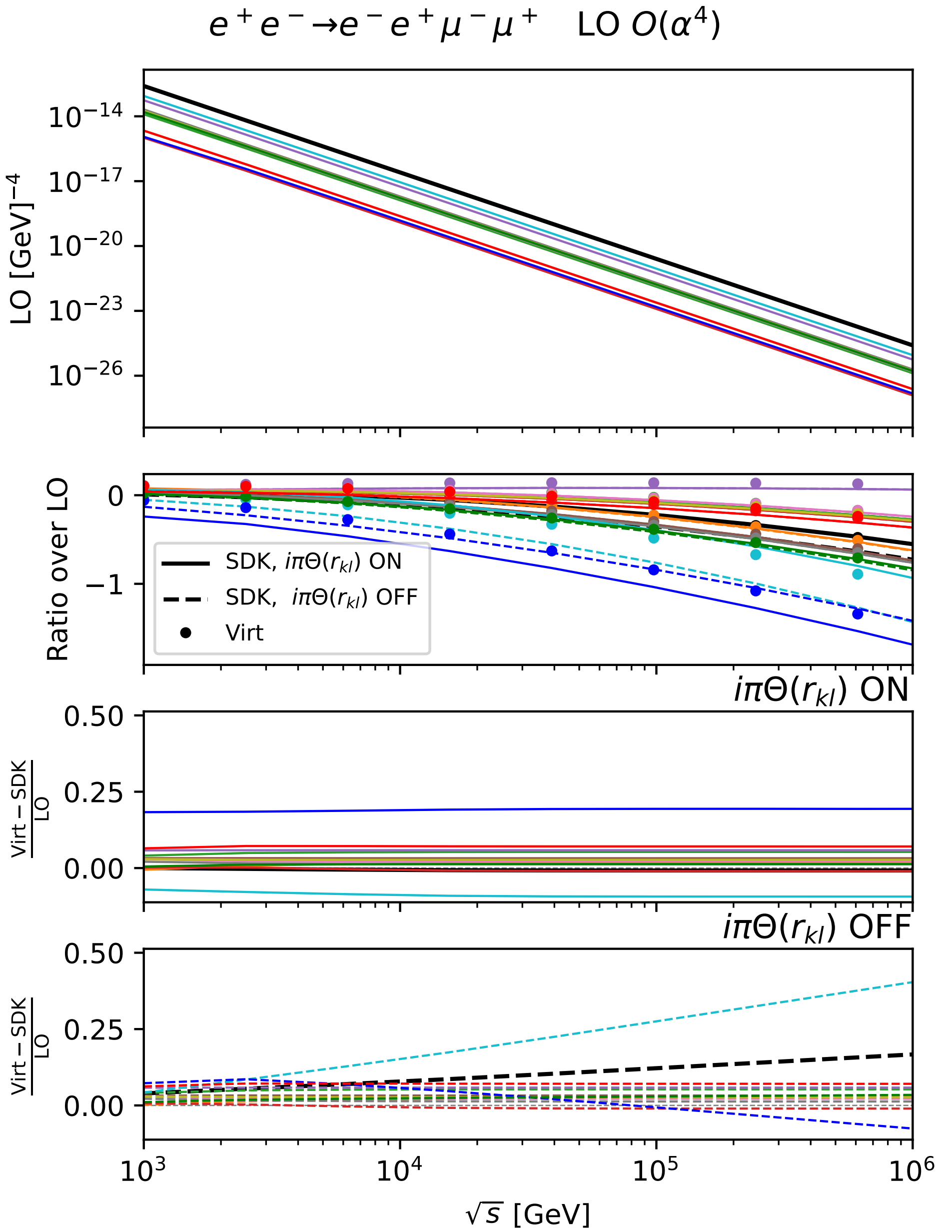


Born amp with $f_i \rightarrow f_i$'

(Original) Born amp.

Logarithmic kernel, couplings…

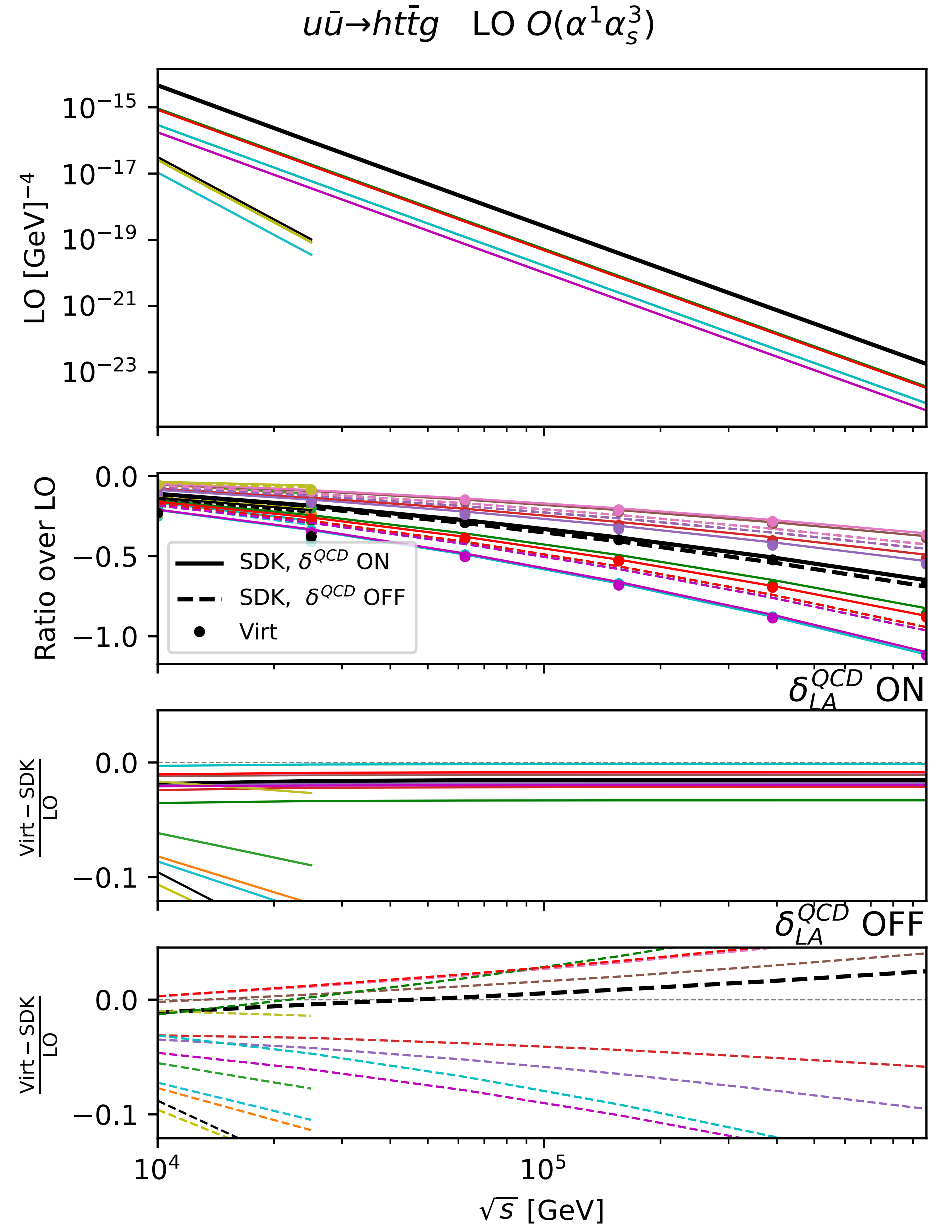
Validation: Approximated virtual amplitudes



LO amplitude, for each leading helicity

Loop or Sudakov / LO

(Loop-Sudakov)/LO must be a constant if logs are correct (checked with a fit)



Im. part ON/OFF

QCD contr. ON/OFF

From amplitudes to cross sections

- D&P approximate the contribution of virtual diagrams to the cross section
- Real emissions will partly compensate it, in particular the QED part

$$\delta^{\mathrm{LSC}}_{i'_k i_k}(k) = -\frac{1}{2}\left[\overbrace{C^{\mathrm{ew}}_{i'_k i_k}(k)}^{Q_k^2+(I_Z^2)_k+(I_W^2)_k}L(s) - 2(I^Z(k))^2_{i'_k i_k}\log\frac{M_Z^2}{M_W^2}\,l(s) + \delta_{i'_k i_k}Q_k^2 L^{\mathrm{em}}(s,\lambda^2,m_k^2)\right]$$

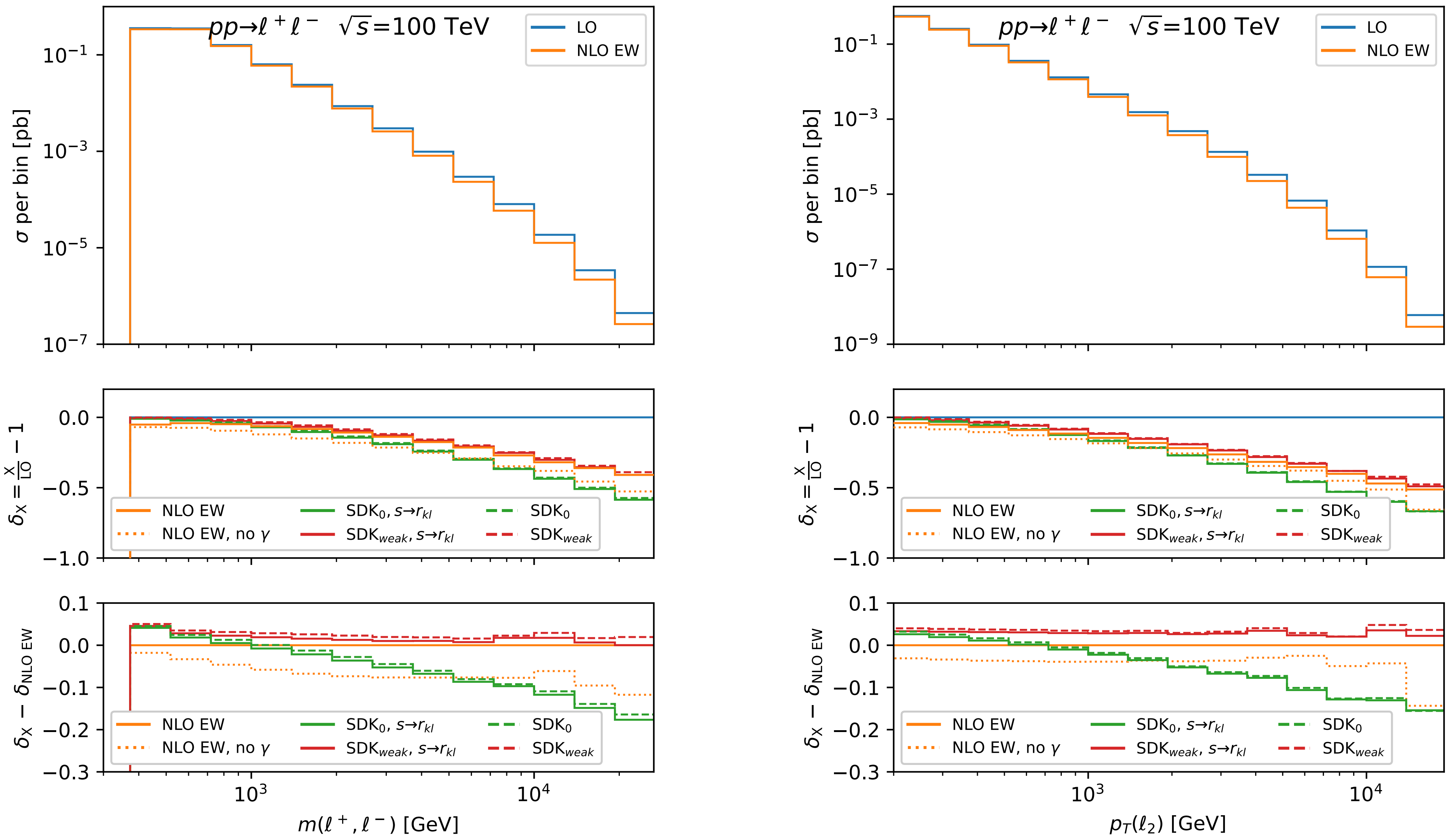
- We introduce a purely-weak Sudakov approximation: QED effects are removed everywhere, except for PR renormalisation
- This assumes that photons are always clustered with charged particles (also massive ones!)
- Other approaches drop the IR-divergent em terms. However:
  - This way QED is removed only up to M_W
  - But QED effects appear also elsewhere (SSC, Collinear)
- How does this compare with exact NLO corrections?

Predictions for cross sections

- Setup:
  - 100 TeV pp collider
  - Charged particles are always clustered with photons within $\Delta R=0.4$
  - Final-state particles required to be hard, central and separated (cuts are specific to each process considered)
- We compare exact NLO EW corrections (including and excluding initial-state photons) with
  - The Sudakov approximation as from D&P, excluding only the ^{em} terms (SDK^0)
  - Our approximation for the purely-weak Sudakov corrections (SDK_{weak})
  - Both cases are studied with or without the extra angular terms from $\Delta^{s\to rkl}$

Drell-Yan (pp→e$^+$e$^-$)

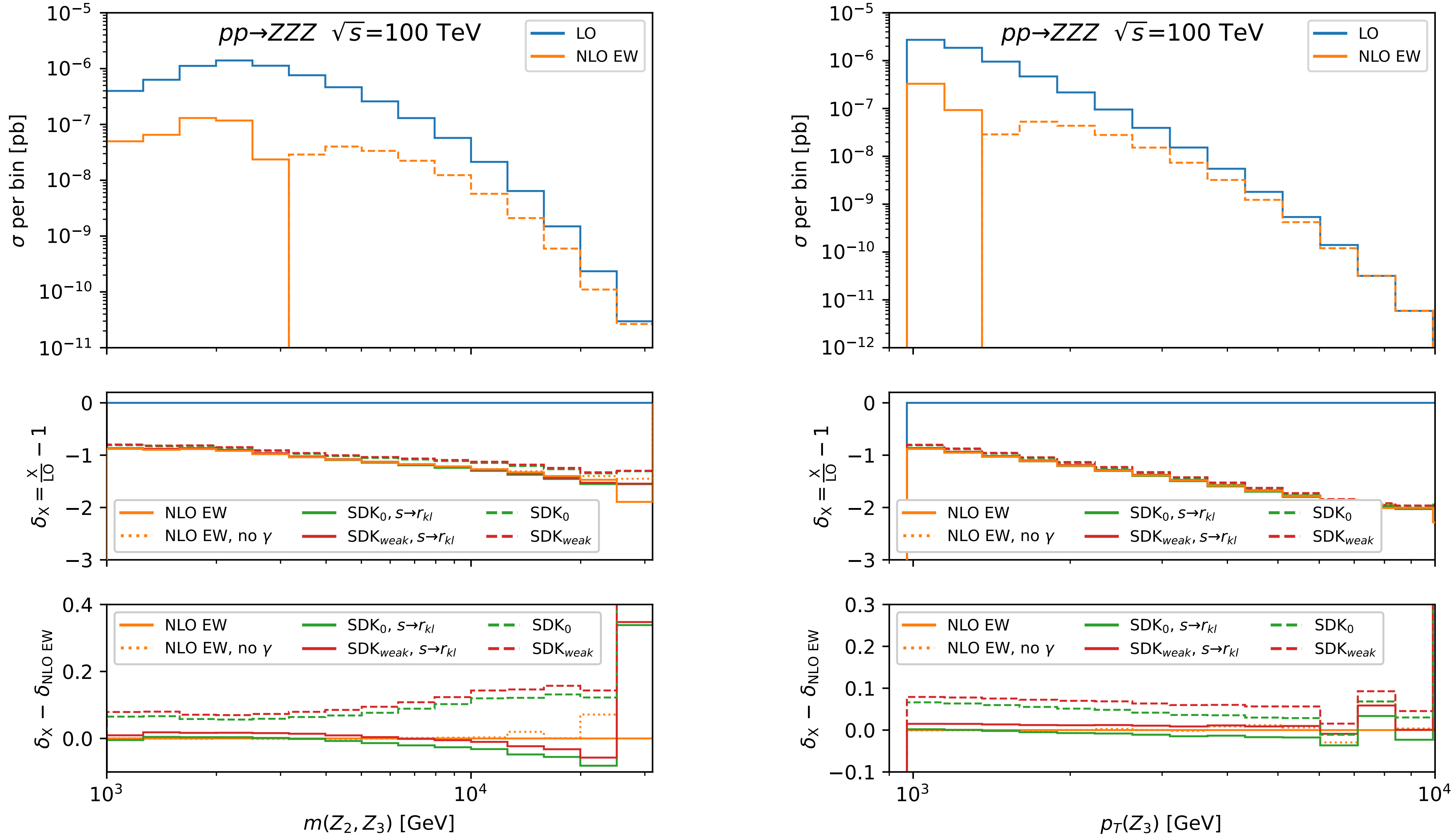
$$p_T(\ell^\pm) > 200\ \text{GeV}\,,\qquad |\eta(\ell^\pm)| < 2.5\,,\qquad m(\ell^+,\ell^-) > 400\ \text{GeV}\,,\qquad \Delta R(\ell^+,\ell^-) > 0.5$$



- Charged FS: SDK_{weak} much closer to EW corrections wrt SDK_0
- 2→2 process with hard cuts: small effects due to $\Delta^{s\to rkl}$

ZZZ production

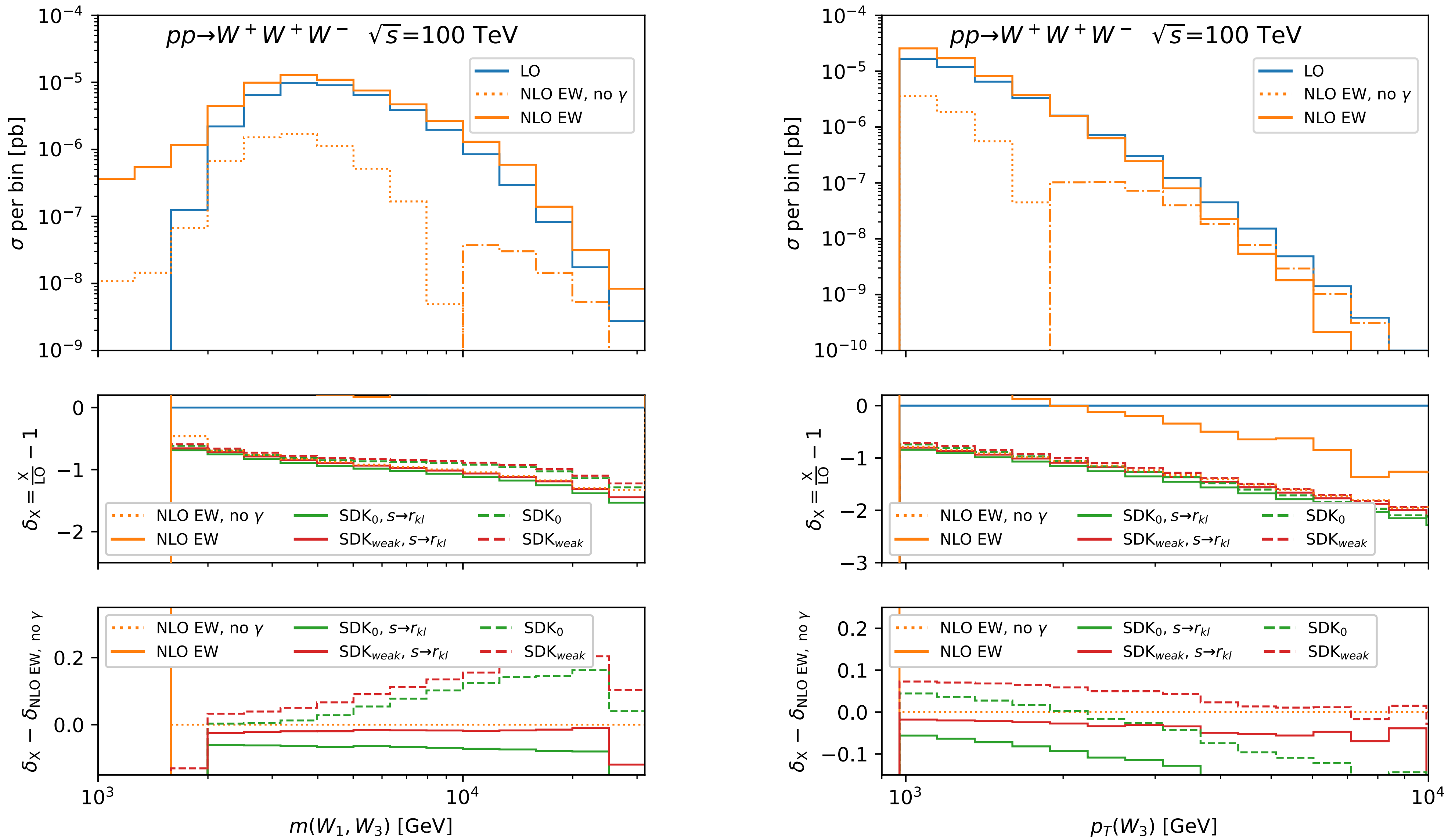
$$p_T(Z_i) > 1\ \text{TeV}\,, \quad |\eta(Z_i)| < 2.5\,, \quad m(Z_i, Z_j) > 1\ \text{TeV}\,, \quad \Delta R(Z_i, Z_j) > 0.5$$



- Neutral FS: small difference between SDK_{weak} and SDK_0
- 2→3 process: inclusion of $\Delta^{s\to rkl}$ improves approximation of EW corrections
- EW corrections exceed 100%: need for their resummation

WWW production

$$p_T(W_i) > 1 \ \text{TeV}, \quad |\eta(W_i)| < 2.5, \quad m(W_i, W_j) > 1 \ \text{TeV}, \quad \Delta R(W_i, W_j) > 0.5$$



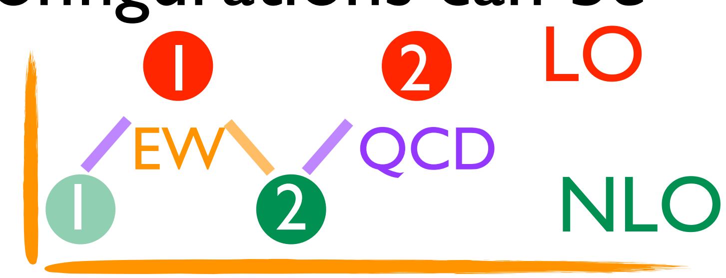
- 2→3 process with charged FS: SDK_{weak} with $\Delta^{s\rightarrow rkl}$ closest to exact EW corrections (without initial photons)
- Initial photons (from real radiation) have huge effects: not accounted for by Sudakov approx.

Including EWSL in NLO+PS simulations

Pagani, Vitos, MZ, 2309.00452

The problem

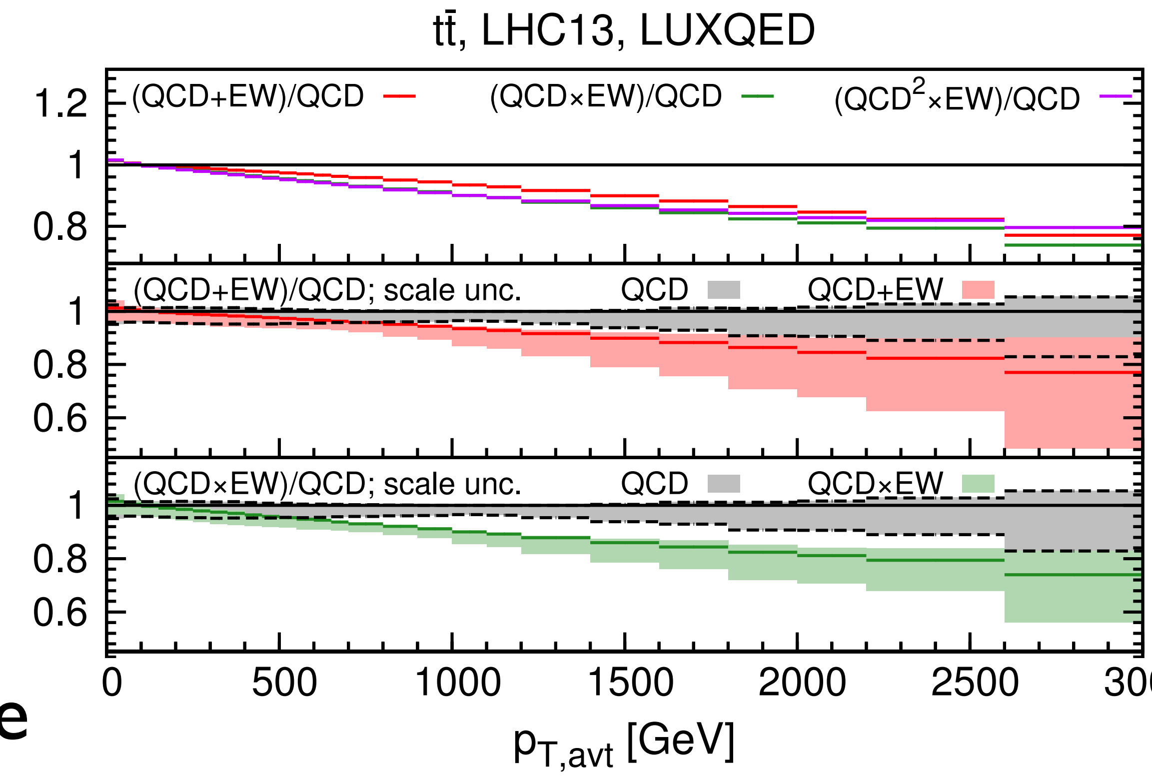
- Matching NLO EW to QED PS is not yet solved in general
  - Exact matching available only for processes with a single LO contribution
    DY: Barzè et al,1302.4606; HV(J): Granata et al, 1706.03522;
    VBS: Chiesa et al, 1906.01863,VV: Chiesa et al, 2005.12146;
    WZ@NNLO+PS: Lindert et al, 2208.12660
  - Approximate solutions exist, not formally NLO-accurate, but with a decent phenomenological description (when target accuracy is ~10%)
    VV(J): Brauer et al, 2005.12128; top: Gutschov et al, 1803.00950;
    V+jets: Kallweit et al, 1511.08692, …
- Main issue: how to assign colour-flows to interferences (LO_2 is mostly an interference contribution)
  - However, quite often, $LO_2/LO_1 \ll \alpha/\alpha_s$ so that these configurations can be somehow neglected
- EWSL are an excellent compromise for this problem:



  - They provide the bulk of the cross section, in a fast and stable manner
  - In the SDK_{weak} scheme, they can be supplemented by QED PS without double counting

Including approximate EW corrections beyond NLO

- When combining NLO QCD EW corrections, one can approximate the mixed NNLO₂ term by the so-called multiplicative approach, if both are due to universal effects (soft emissions for QCD, EWSL for EW)
- This stabilises the scale-dependence of EW corrections, which is now NLO-like



Czakon et al, 1705.04105

- In the context of event-generation, EWSL can improve the multiplicative approach:
  - Each kind of events, Born-like (S) or Real-like (H), can be corrected by the EWSL corresponding to the event's multiplicity
  - Approach can be extended to multijet-merging Bothmann et al, 2111.13453
  - A smooth transition in the soft/collinear limit of H events must be ensured

Including EWSL in NLO+PS samples

- in MG5_aMC, S and H events are defined as follows:

$$d\sigma^{(\mathbb{S})} = d\phi_{n+1}\left[\left(\mathcal{B}+\mathcal{V}+\mathcal{C}^{\rm int}\right)\frac{d\phi_n}{d\phi_{n+1}} + \left(\mathcal{C}_{\rm MC}-\mathcal{C}\right)\right]$$

$$d\sigma^{(\mathbb{H})} = d\phi_{n+1}\left(\mathcal{R}-\mathcal{C}_{\rm MC}\right),$$

- Events from each class can be corrected by the corresponding EWSL

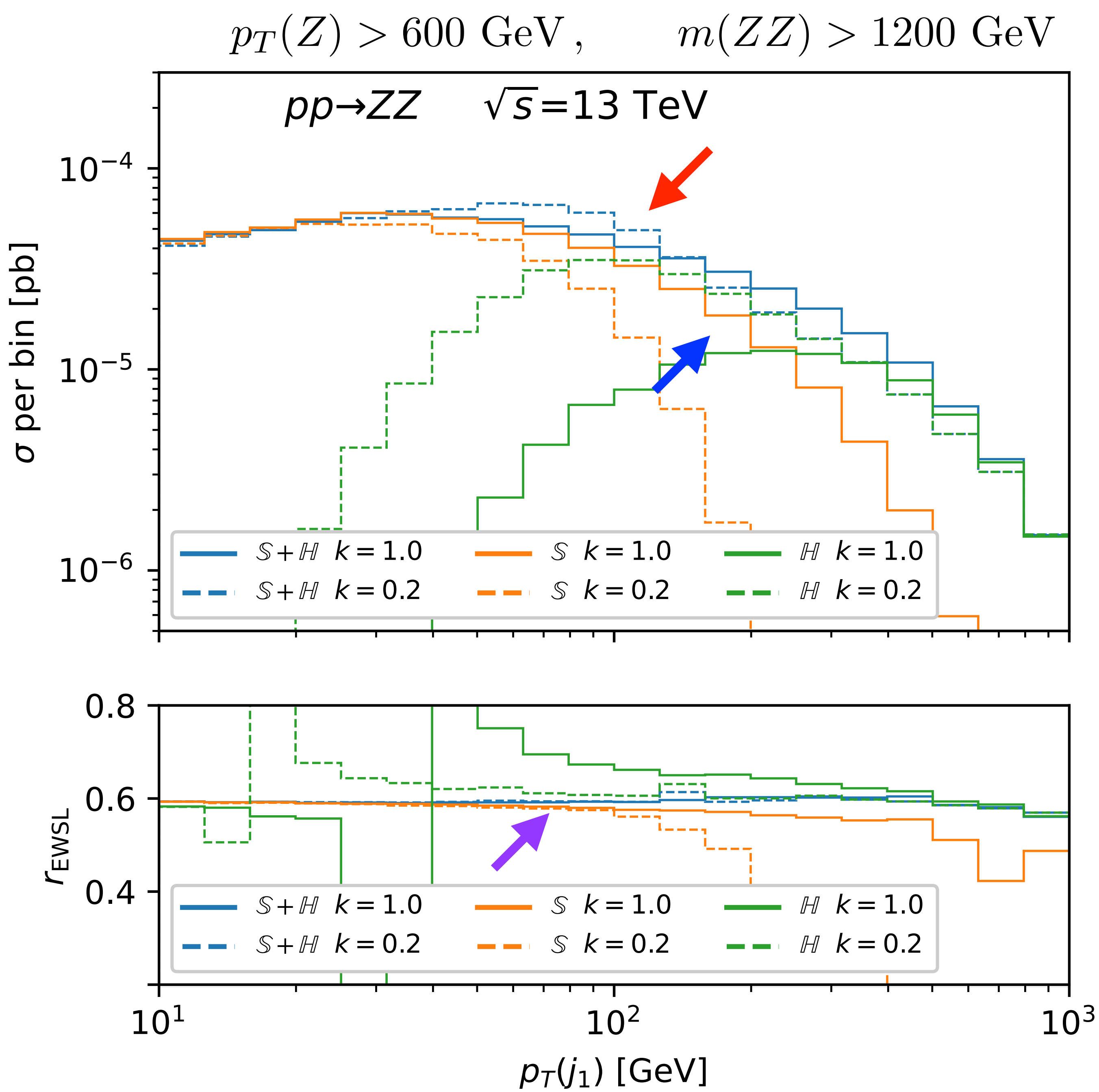
$$w_{\mathbb{S}} \Longrightarrow (1+\delta^{\rm EWSL}_{(\mathbb{S})})w_{\mathbb{S}} \qquad w_{\mathbb{H}} \Longrightarrow (1+\delta^{\rm EWSL}_{(\mathbb{H})})w_{\mathbb{H}}$$

with $\delta^{\rm EWSL}_{(\mathbb{S})} = \delta^{\rm EW}_{\rm LA}\Big|_{\rm SDK_{weak}}(e_{\mathbb{S}})$ $\qquad$ $\delta^{\rm EWSL}_{(\mathbb{H})} \equiv \delta^{\rm EW}_{\rm LA}\Big|_{\rm SDK_{weak}}(e_{\mathbb{H}})$ if $\forall\ |r_{kl}|/m_W > C$

$\delta^{\rm EWSL}_{(\mathbb{H})} \equiv \delta^{\rm EW}_{\rm LA}\Big|_{\rm SDK_{weak}}(e_{\mathbb{S}}^{(\hat{k},\hat{l})})$ else

- This enforces the proper IR behaviour of H events
- In principle, there is also an interplay between C and the shower scale μ_s. In practice, relative impact of EWSL is independent on μ_s variations even by large factors

Shower-scale independence of relative corrections



k=1 (default μ_s) ———

vs

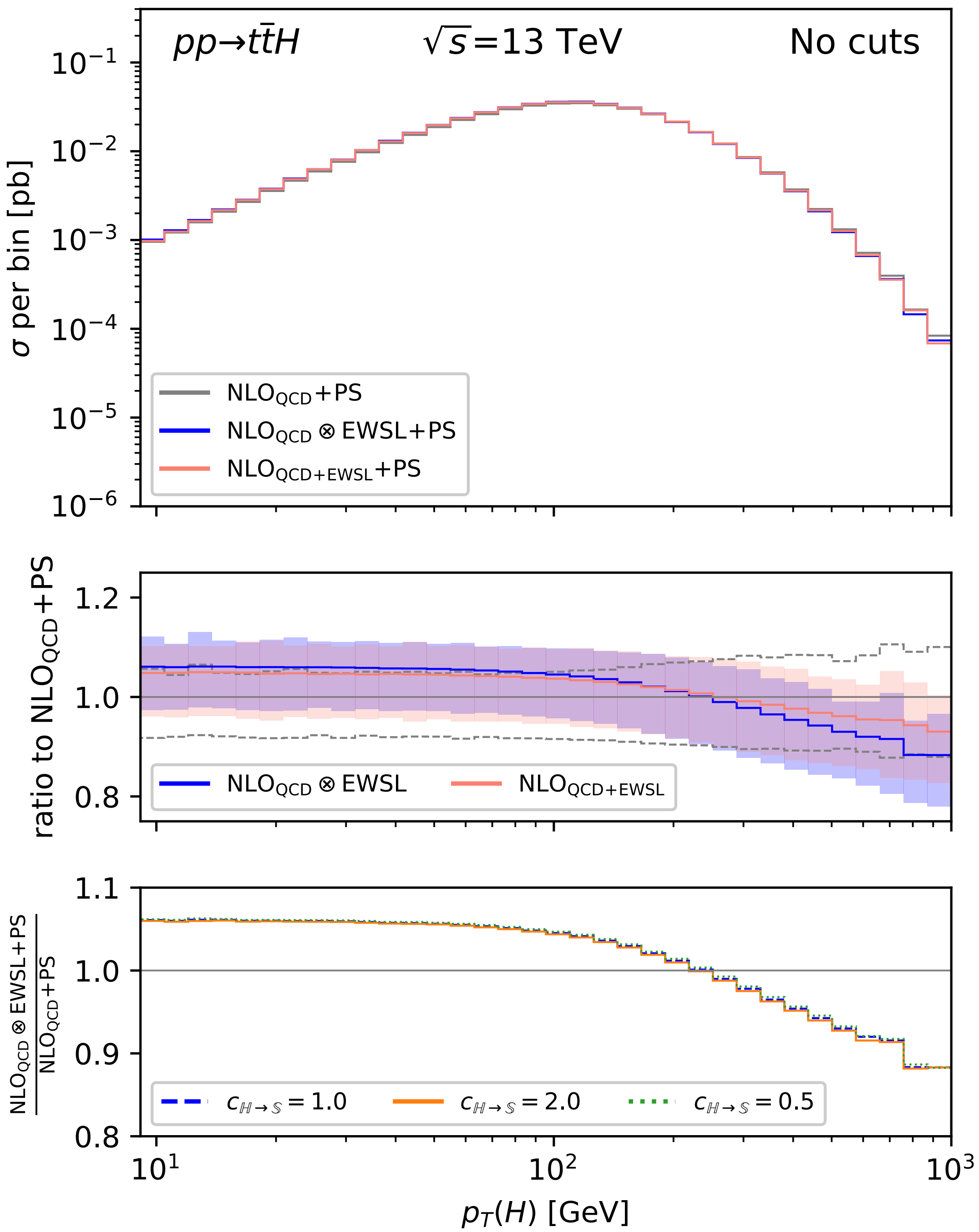
k=0.2 (1/5 reduction) - - - - - - -

Shower-scale variations have effect on rates

Huge effects on interplay between S and H events

Relative effect of EWSL stays the same for S+H

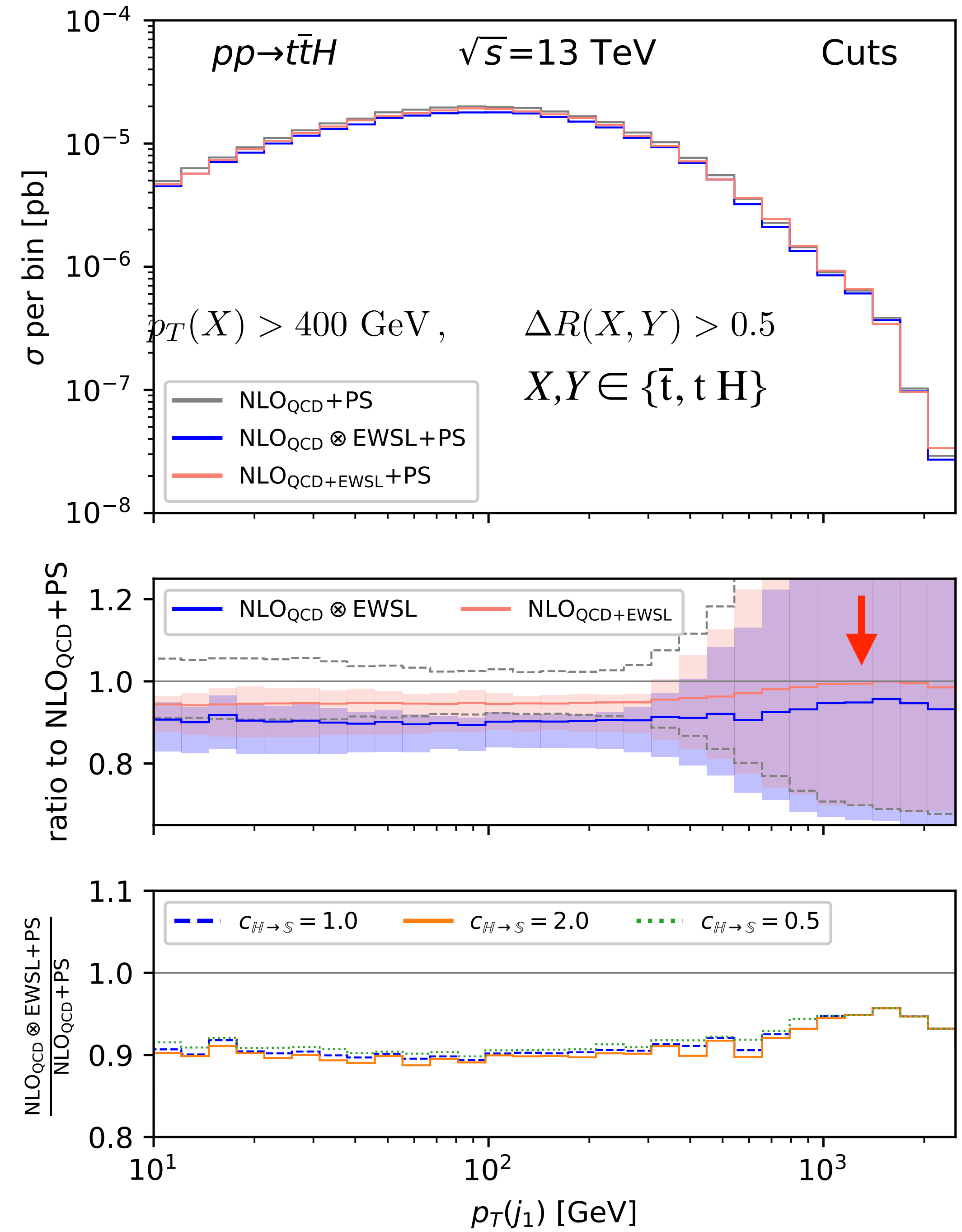
Results: ttH



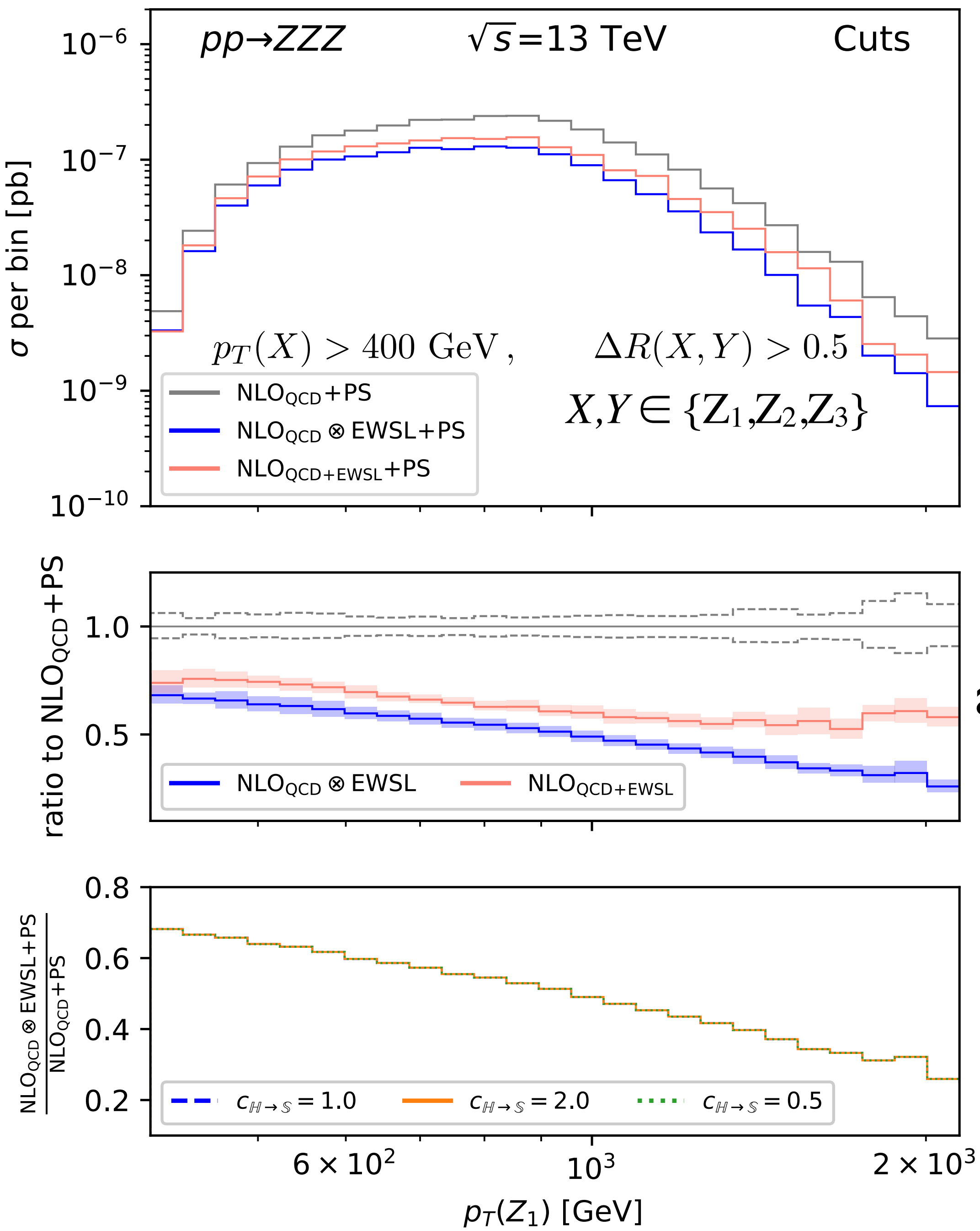
Effect of EW corr. rather mild for ttH

Difference between mult. and add. approach visible in regions dominated by hard radiation

Effect of EWSL independent on C



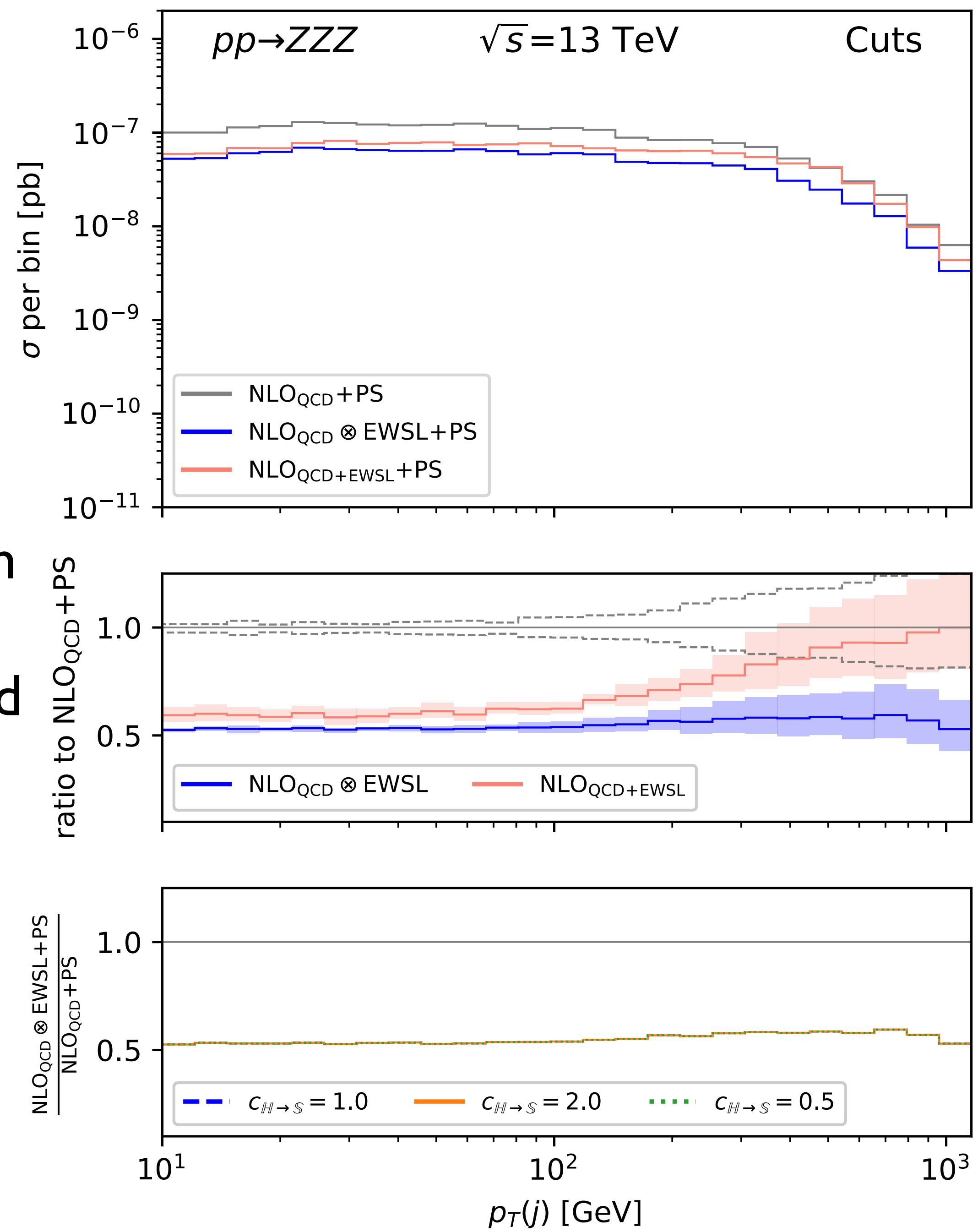
Results: ZZZ



Effect of EW corr. (very) large for 3Z

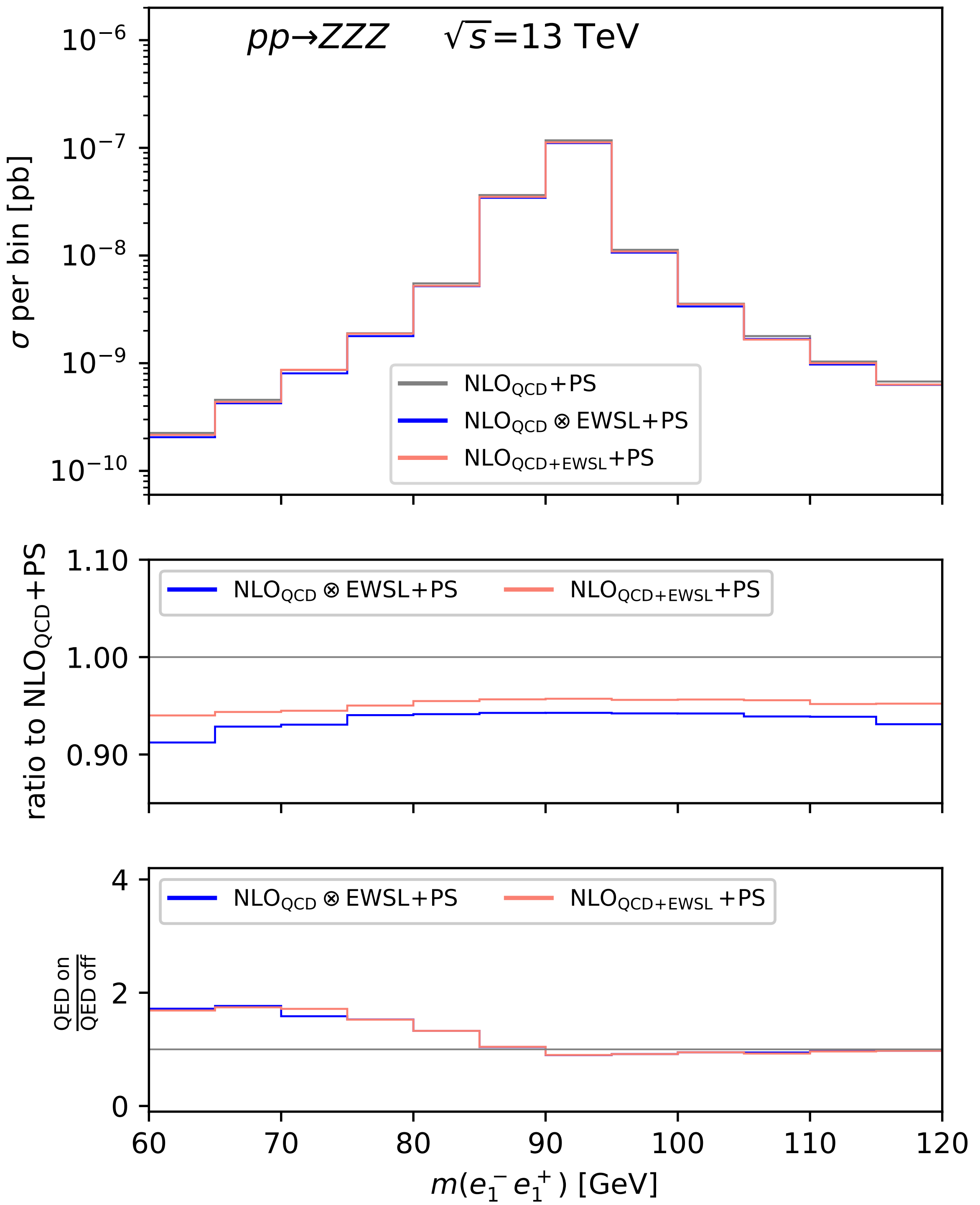
Difference between mult. and add. approach visible and larger than QCD scale unc.

Effect of EWSL independent on C



Results: ZZZ (decayed)

- Events reweighed with the EWSL can be further processed with other tools, e.g. MadSpin Artoisenet et al, 1212.3460
- Decays are included keeping tree-level spin correlations (neglects non-resonant and virtual/EWSL-induced effects)
- The weak-only version of EWSL can be combined with QED PS without double counting



EWSL for BSM simulations: top-pair production in the SMEFT

El-Faham, Mimasu, Pagani, Severi, Vryonidou, MZ, 24XX.YYYYY

EW corrections in the SMEFT

- Typical searches for BSM effects look at tails of distributions, where the high-energy behaviour may be different from the SM
- A comprehensive approach for BSM searches is the usage of Effective Theories, such as the SMEFT
- Currently, SMEFT is simulated without EW corrections
- Computing EW corrections in the SMEFT is a very challenging: so far, only available for very simple processes
  μ decay: Pruna et al, 1408.3565
  H decay: Hartmann et al, 1505.02646 & 1507.03568; Ghezzi et al, 1505.03706; Gauld et al, 1512.02508; Dawson et al, 1801.01136 & 1807.11504; Dedes et al, 1805.00302 & 1903.12046; Cullen et al, 1904.06358 & 2007.15238;
  Z/W pole obs.: Hartmann et al, 1611.09879; Dawson et al, 1808.05948 & 1909.02000;
  Drell-Yan: Dawson et al, 2105.05852
- Can we use EWSL in the SMEFT?

Mass suppressed amplitudes in the SMEFT

- While in the SM processes with a mass-suppressed amplitude are very rare, they are quite common in the SMEFT

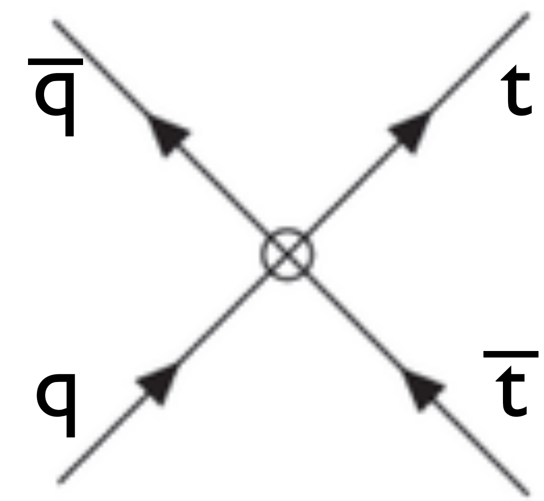
mass-supp. non mass-supp.

$$O_{tG} = \frac{g_S C_{tG}}{\Lambda^2} \bar{Q}_L \tilde{\phi} \sigma^{\mu\nu} G_{\mu\nu} t_R = \frac{g_S C_{tG} v}{\Lambda^2} \bar{t}_L \sigma^{\mu\nu} G_{\mu\nu} t_R + \frac{g_S C_{tG}}{\Lambda^2} h \bar{t}_L \sigma^{\mu\nu} G_{\mu\nu} t_R$$

- The D&P algorithm works only for non-mass suppressed amplitudes
  - One cannot use EWSL in general for SMEFT processes
- However, for those operators which are not mass suppressed, EWSL can give us the bulk of EW corrections at high energy

A class of non-mass-suppressed contributions: four fermion operators

- 4f operators are a class of non mass-suppressed operators
- They are relevant for Drell-Yan, top pair production, …
- We can use them to validate D&P in a non-trivial BSM case, and to estimate, for the first time, the impact of EW corrections on these processes in the SMEFT. Are EW corrections the same as in the SM?
- If we restrict ourselves to 4f operators, the 3-coupling expansion of the amplitudes (QCD, EW, 1/Λ) greatly simplifies
- In the case of $q\bar{q} \to t\bar{t}$



$$\begin{aligned}
\mathcal{O}^8_{tu} &= \textstyle\sum_{\mathrm{f}=1}^2 (\bar{t}\gamma_\mu T^A t)(\bar{u}_\mathrm{f}\gamma^\mu T_A u_\mathrm{f}),\\
\mathcal{O}^8_{td} &= \textstyle\sum_{\mathrm{f}=1}^3 (\bar{t}\gamma_\mu T_A t)(\bar{d}_\mathrm{f}\gamma^\mu T^A d_\mathrm{f}),\\
\mathcal{O}^8_{tq} &= \textstyle\sum_{\mathrm{f}=1}^2 (\bar{t}\gamma^\mu T^A t)(\bar{q}_\mathrm{f}\gamma_\mu T_A q_\mathrm{f}),\\
\mathcal{O}^8_{Qu} &= \textstyle\sum_{\mathrm{f}=1}^2 (\bar{Q}\gamma_\mu T_A Q)(\bar{u}_\mathrm{f}\gamma^\mu T^A u_\mathrm{f}),\\
\mathcal{O}^8_{Qd} &= \textstyle\sum_{\mathrm{f}=1}^3 (\bar{Q}\gamma_\mu T_A Q)(\bar{d}_\mathrm{f}\gamma^\mu T^A d_\mathrm{f}),\\
\mathcal{O}^{1,8}_{Qq} &= \textstyle\sum_{\mathrm{f}=1}^2 (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_\mathrm{f}\gamma^\mu T_A q_\mathrm{f}),\\
\mathcal{O}^{3,8}_{Qq} &= \textstyle\sum_{\mathrm{f}=1}^2 (\bar{Q}\gamma_\mu T^A \sigma_I Q)(\bar{q}_\mathrm{f}\gamma^\mu T_A \sigma^I q_\mathrm{f})
\end{aligned}$$

=0 for 4F op.

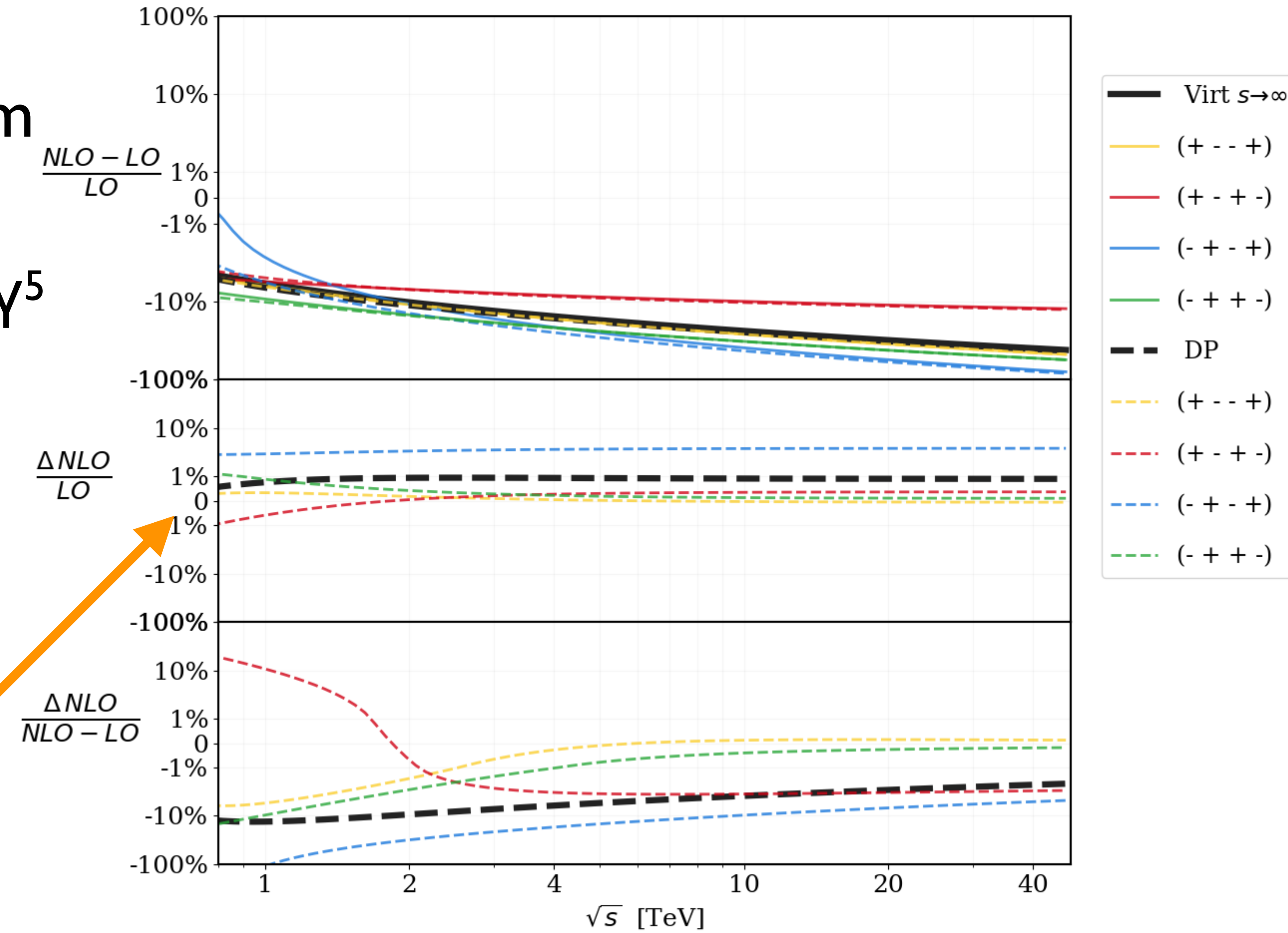
$$\lim_{M_W^2/s \to 0} \mathcal{M}_1^{\mathrm{NP}} = \delta\mathcal{M}^{\mathrm{NP}} = \mathcal{M}_0^{\mathrm{NP}}\delta_{\mathrm{SM}}^{\mathrm{EW}} + \cancel{\mathcal{M}_0^{\mathrm{NP}'}}\delta_{\mathrm{SM}}^{\mathrm{QCD}} + \mathcal{M}_0^{\mathrm{SM}}\cancel{\delta_{\mathrm{NP}}^{\mathrm{EW}}} + \cancel{\mathcal{M}_0^{\mathrm{SM}'}}\delta_{\mathrm{NP}}^{\mathrm{QCD}}$$

=0 for color octets

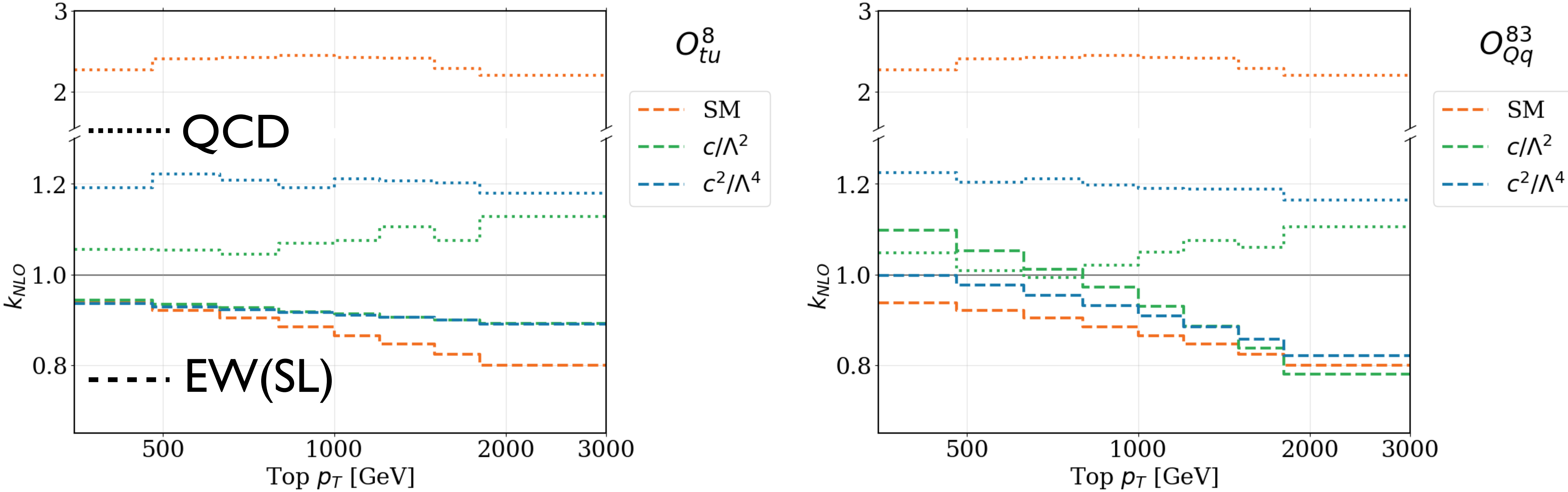
=0 for q≠b

Validation of one-loop results

- We compute 1-loop EW corrections to $u\bar{u} \to t\bar{t}$ and we compare with the D&P algorithm
  - Loops are computed with FeynCalc+Feynarts+PackageX. γ^5 is treated in the BHMV scheme
  - EWSL are computed with MG5_aMC, on top of the $1/\Lambda^4$ Born
- Difference between EWSL and exact virtual approaches a constant



EW Corrections to top-pair production

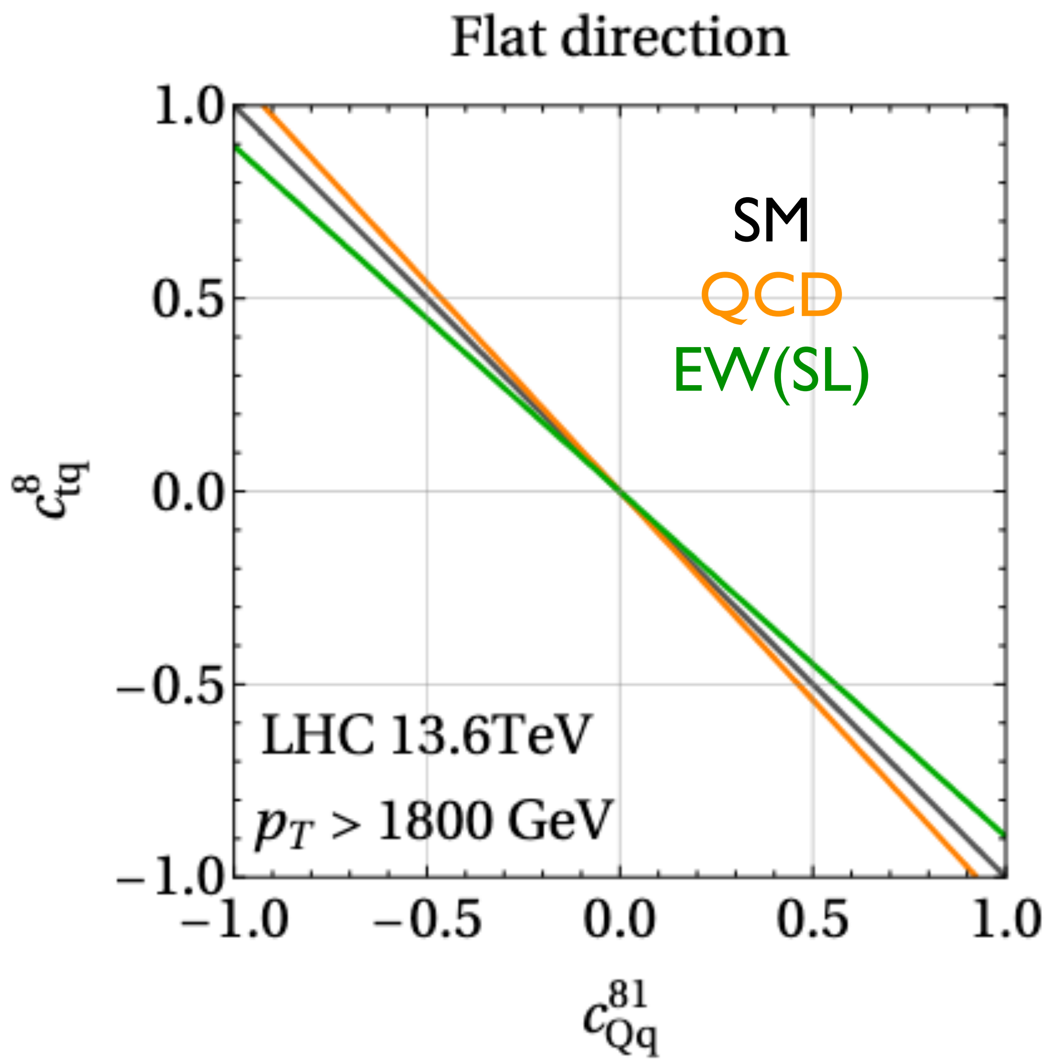


- Relative impact of EWSL is different between SM, $1/\Lambda^2$, $1/\Lambda^4$ terms. Pattern of corrections depend on operator
  - Difference related to isospin-linked contributions (single-logaritmic)
  - EFT contributions show cancelations between QCD and EW
- It is inaccurate to propagate SM K-factors to SMEFT contributions
- Impact of EW corrections about 10% at 1 TeV

Lifting degeneracy between operators

Cross-section [pb]
Top $p_T > 1.8$ TeV

	LO	EWSL		
SM	$2.01 \cdot 10^{-4}$	$1.61 \cdot 10^{-4}$		
	Linear		Quadratic	
	LO	SUD	LO	SUD
$c_{Qq}^{1,8}$	$3.78 \cdot 10^{-4}$	$2.56 \cdot 10^{-4}$	$9.04 \cdot 10^{-4}$	$6.06 \cdot 10^{-4}$
$c_{Qq}^{3,8}$	$2.20 \cdot 10^{-4}$	$1.72 \cdot 10^{-4}$	$9.04 \cdot 10^{-4}$	$7.41 \cdot 10^{-4}$
c_{tq}^{8}	$3.78 \cdot 10^{-4}$	$2.86 \cdot 10^{-4}$	$9.04 \cdot 10^{-4}$	$6.80 \cdot 10^{-4}$
c_{tu}^{8}	$3.00 \cdot 10^{-4}$	$2.68 \cdot 10^{-4}$	$7.30 \cdot 10^{-4}$	$6.50 \cdot 10^{-4}$
c_{Qu}^{8}	$2.99 \cdot 10^{-4}$	$2.43 \cdot 10^{-4}$	$7.30 \cdot 10^{-4}$	$5.88 \cdot 10^{-4}$
c_{td}^{8}	$7.95 \cdot 10^{-5}$	$7.12 \cdot 10^{-5}$	$1.74 \cdot 10^{-4}$	$1.56 \cdot 10^{-4}$
c_{Qd}^{8}	$7.92 \cdot 10^{-5}$	$6.45 \cdot 10^{-5}$	$1.74 \cdot 10^{-4}$	$1.41 \cdot 10^{-4}$



- EW corrections lift degeneracy of different operators, removing flat directions in global fits

Wrapping up…

- LHC is restarting: a challenging physics programme is awaiting us!
- Search for new physics relies on accurate knowledge of SM processes
  → Inclusion of QCD and EW corrections crucial
- EW corrections dominated by Sudakov logarithms at high energies
- EWSL provide a fast and stable approximation for EW corrections, with some practical advantages
  - Possibility to deliver predictions at NLO+NLL EW
  - Easy matching/merging
  - Straightforward extension to BSM scenarios
- However, large EW effects can also come via other mechanisms (photon PDF, quasi-collinear configurations, etc)
  → the validity of the EWSL approximation should be assessed process by process and observable by observable

Conclusion & Outlook

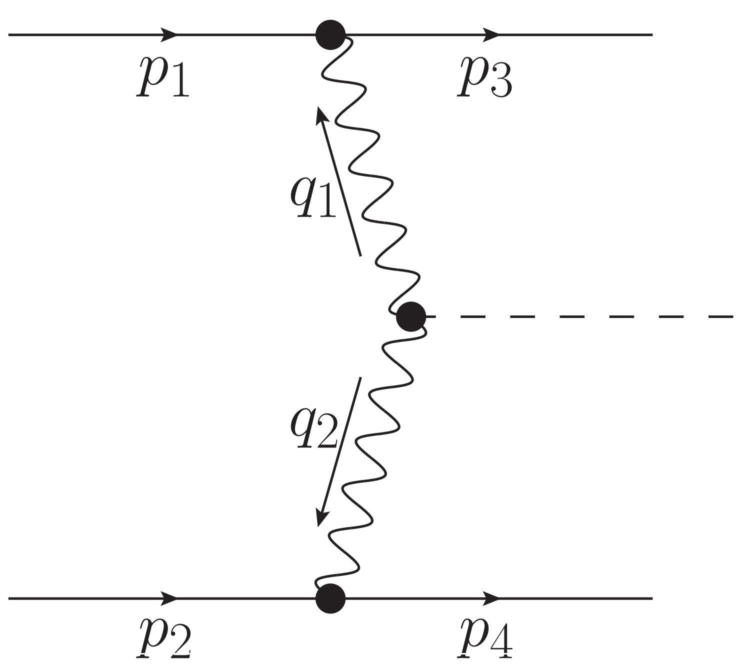
- We have automated EWSL in MG5_aMC, based on the work of Denner&Pozzorini, with a couple of extensions
- EWSL thoroughly validated vs exact virtual amplitude
- For physical cross-sections, we have devised a weak-only version of EWSL
- EWSL contributions can be included in NLO+PS samples via reweighting
  - For the moment, our method neglects terms originating from LO_2, therefore it can be applied only for processes where $LO_2/LO_1 \ll \alpha/\alpha_s$
  - EWSL in the SDK_{weak} approach can be combined with QED PS
- WIP for the application of EWSL in the SMEFT
  - Care should be used to avoid mass-suppressed terms
  - Results for 4 fermion operators: simplest case
    - Relative impact is different on $1/\Lambda^4$, $1/\Lambda^2$, and SM. Important for EFT fits
    - EW corrections lift degeneracy between operators

Thank You!

Backup

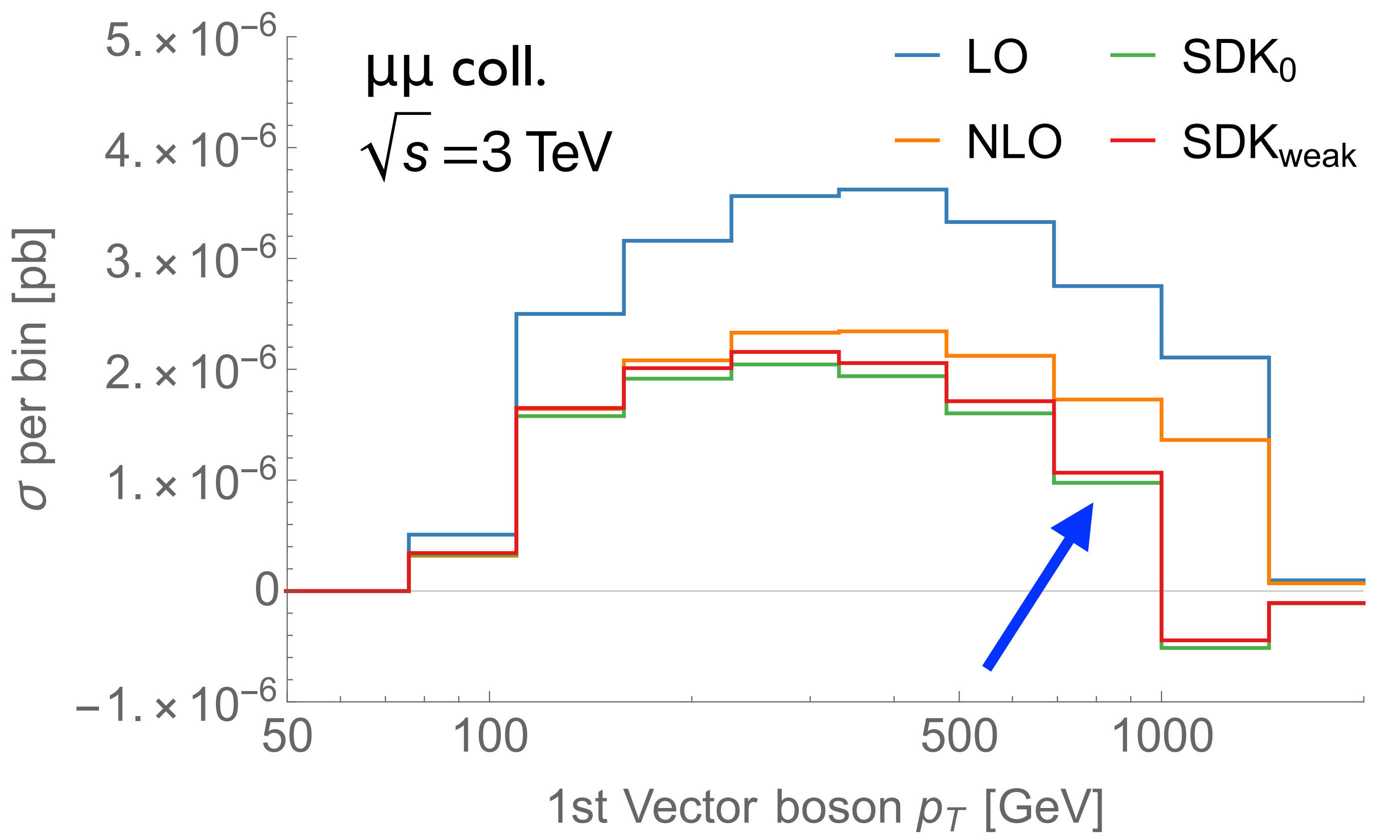
Dominant helicities

- The derivation of D&P crucially relies on the amplitude not being mass-suppressed
- If d is the dimensionality of a squared matrix element (for $2\to n$, $d=2-n$), the D&P algorithm applies only if $|M|^2$ scales with s as s^d
- A notable exception: Higgs VBF, for which $|M|^2 \sim M_W^2/s^2$



Don't buy everything they sell

- In ZHH production, at *large* $p_T(Z)$, EWSLs fail to reproduce EW corrections



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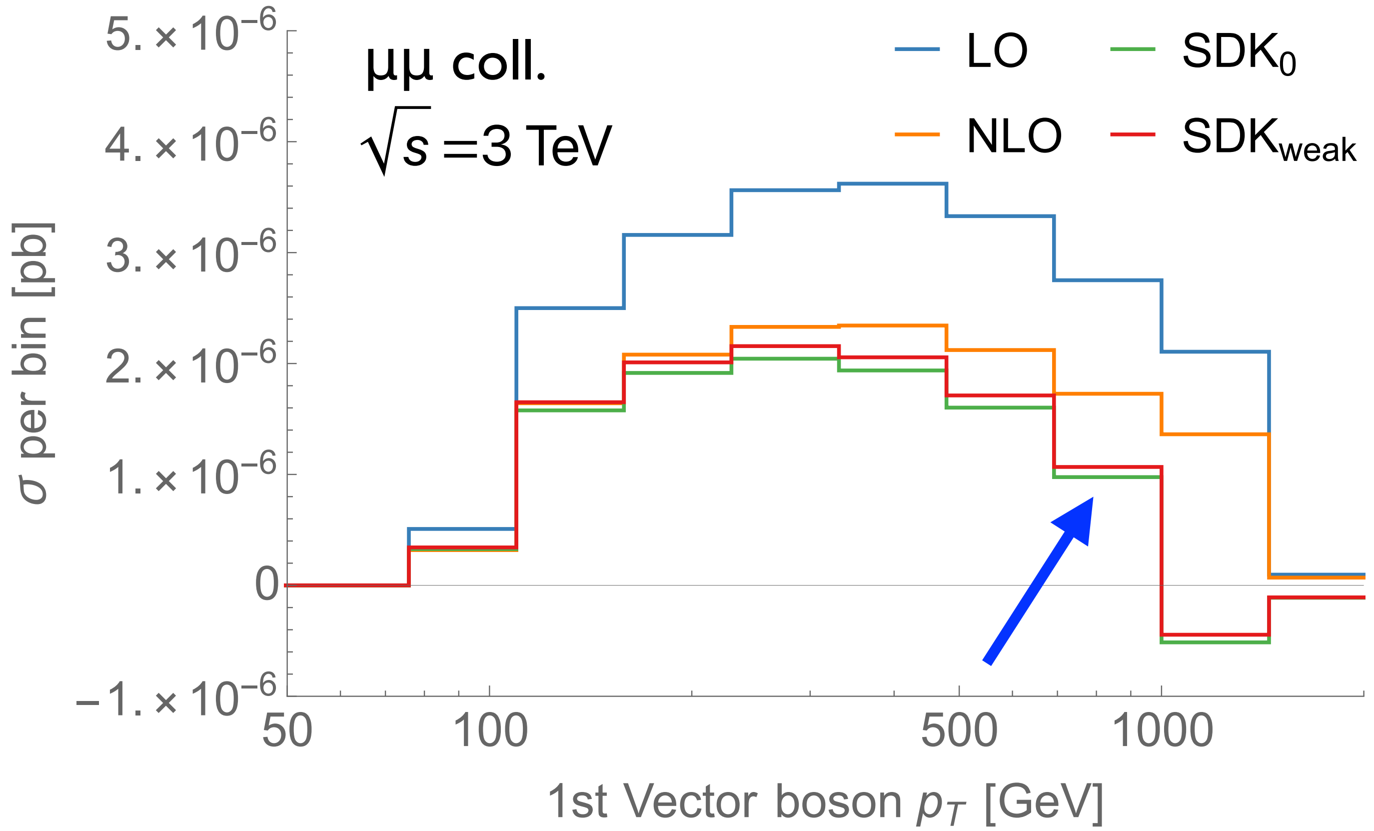

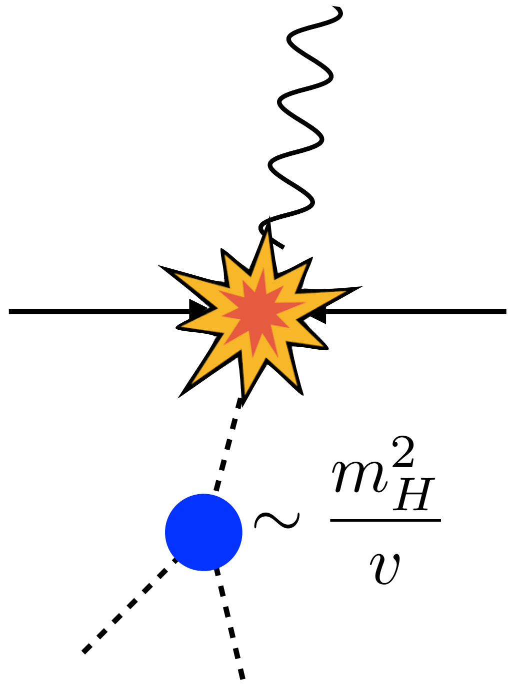

- These configurations are dominated by low M(HH) and are mass-suppressed (dominated by the trilinear diagram)

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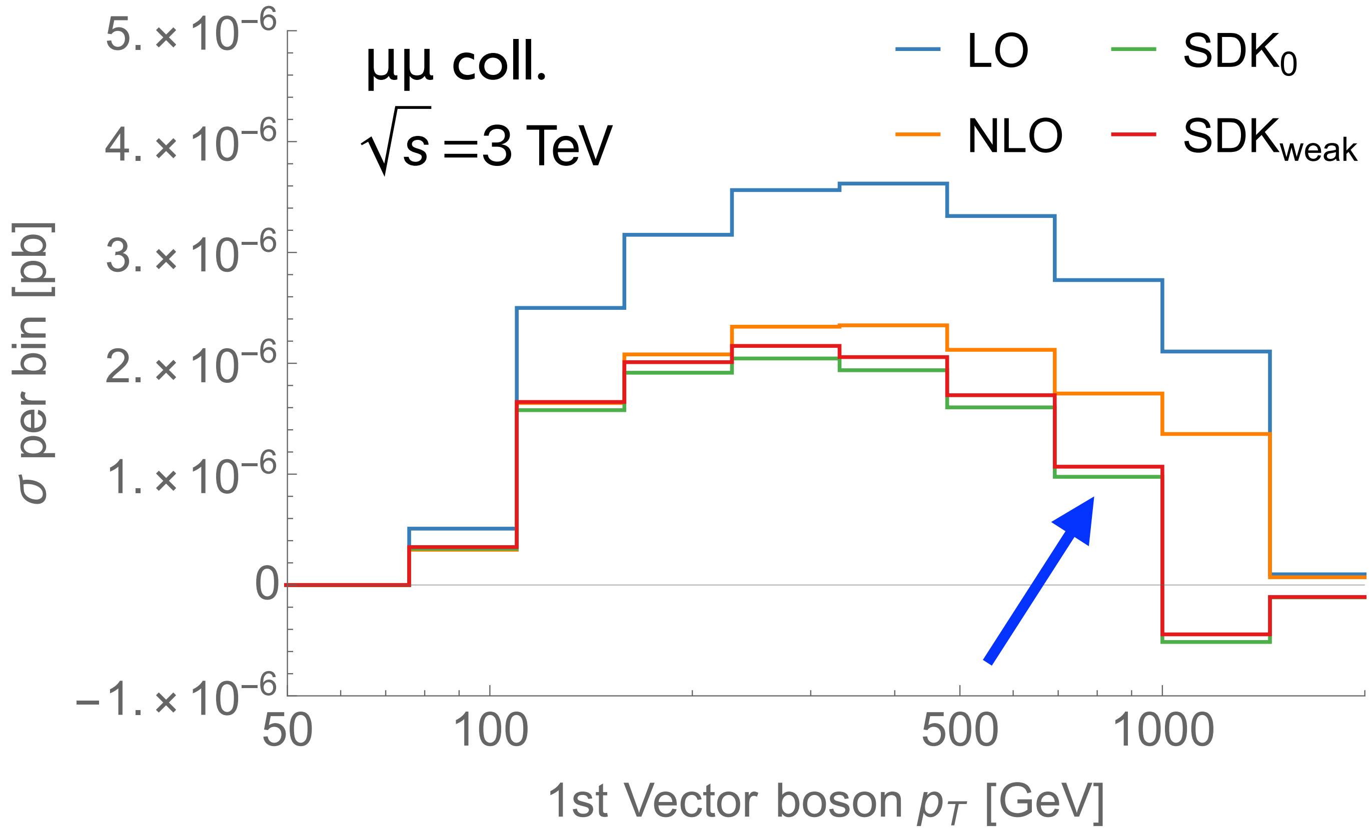

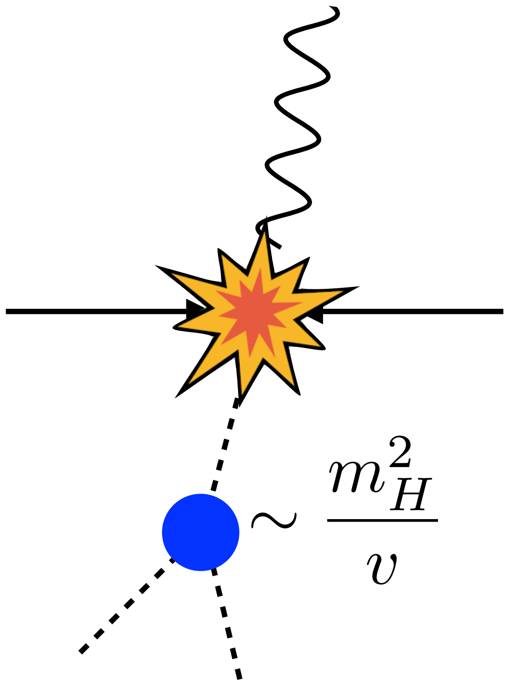

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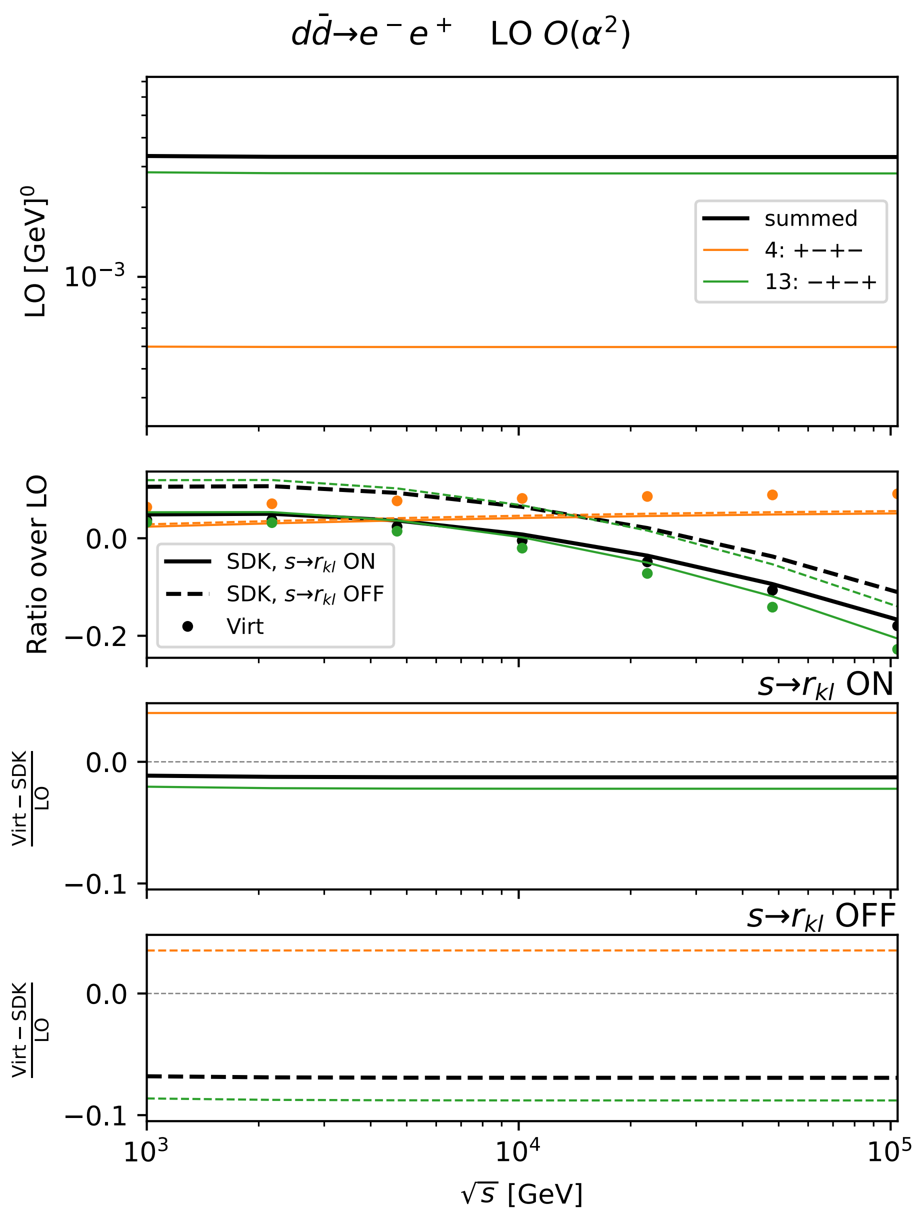
WIP with Y. Ma, D. Pagani

Some first results, 2→2

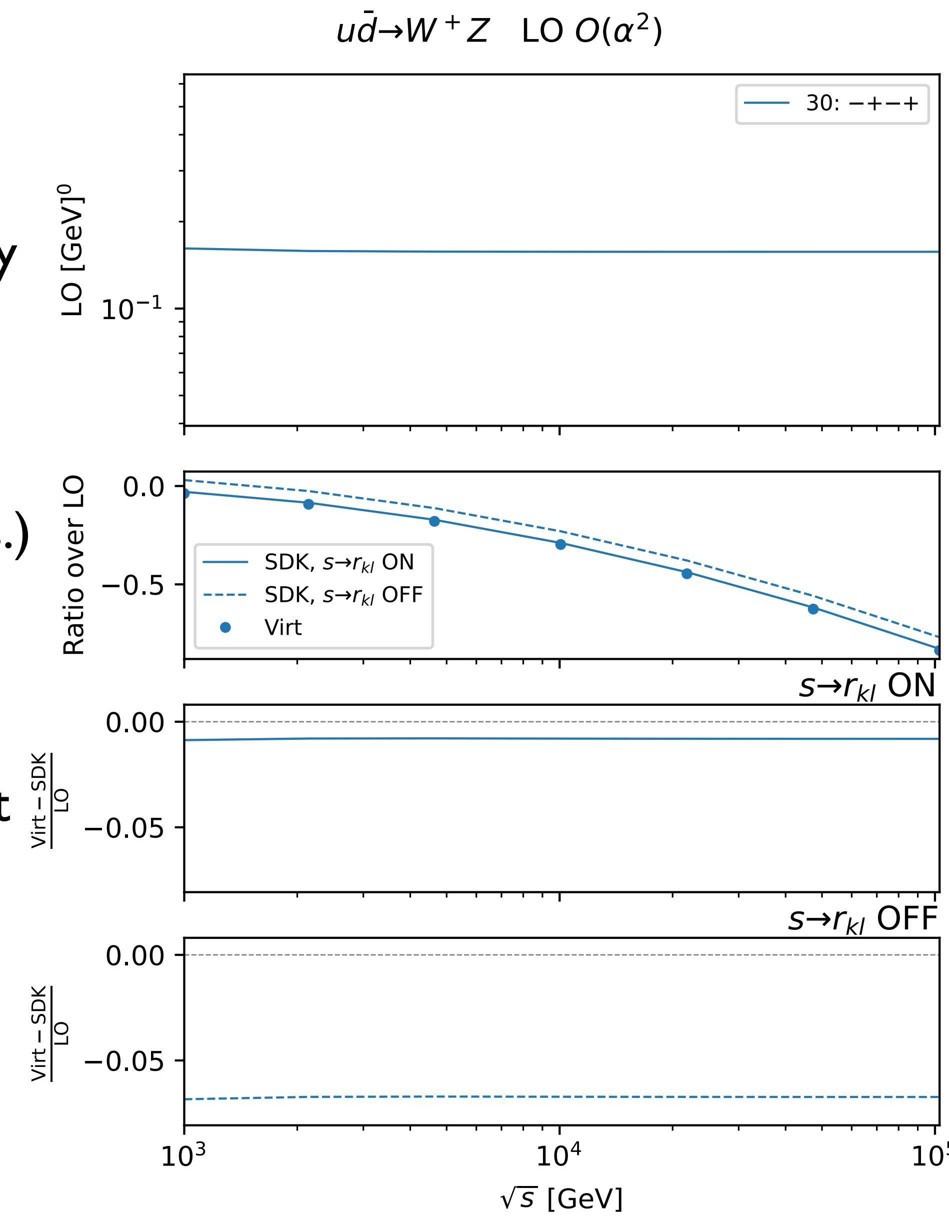


LO amplitude, for each leading helicity

Loop or Sudakov (in different approxs.) over LO

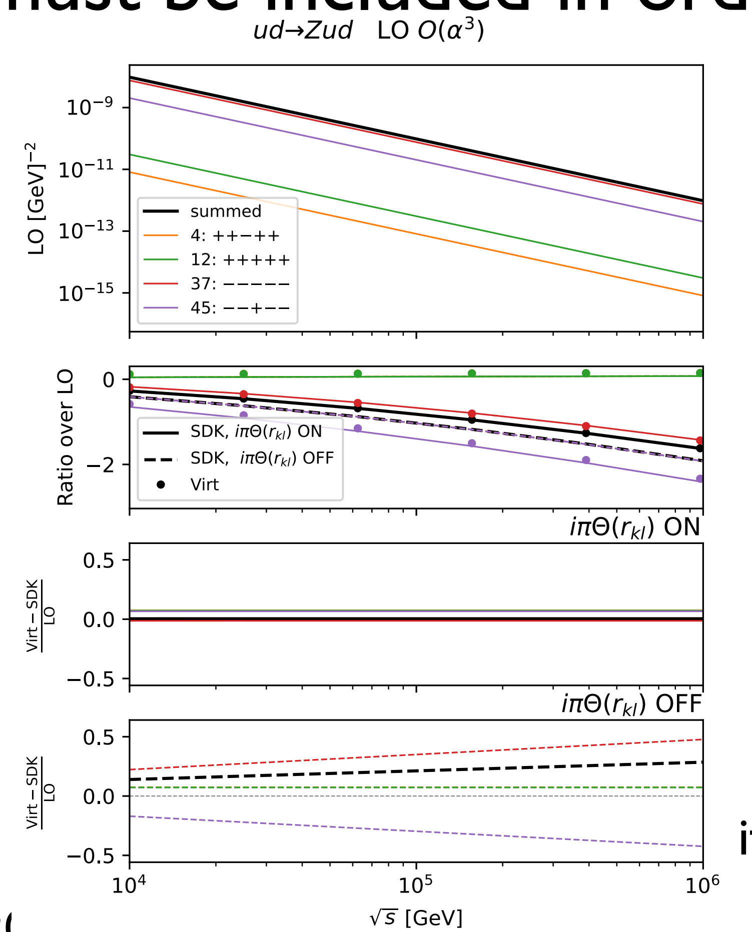
(Loop-Sudakov)/LO must be a constant if logs are correct (this is verified also with a fit)

We see that the inclusion of the angular dependent $\Delta^{s\to rkl}$ term in general reduces the constant



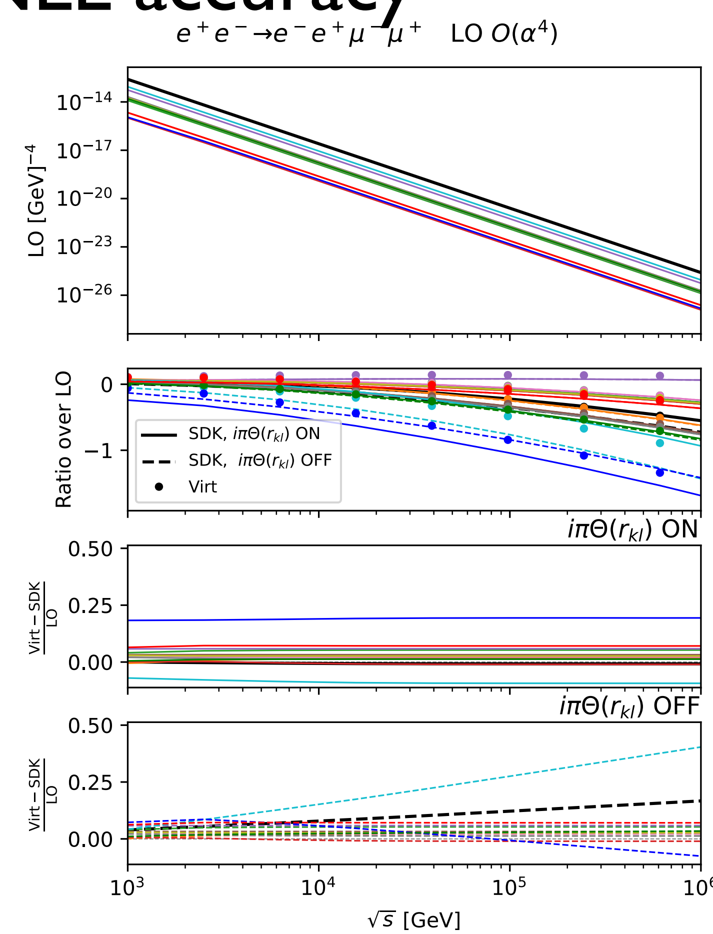
The missing $i\pi\theta(r_{kl})$ factor

- 2→2 amplitudes (as those considered by D&P) are always real (optical theorem). Any missing imaginary part in the logs drops out when considering $2\Re(BV^*) \simeq 2\Re(BB'^*\delta)$
- For 2→n, n≥3, imaginary parts from the logs can combine with those of BB'*, giving rise to single-logarithmic terms
- They must be included in order to claim NLL accuracy



constant V-SDK helicity by helicity

V-SDK ~log(s) if $i\pi\theta(r_{kl})$ neglected



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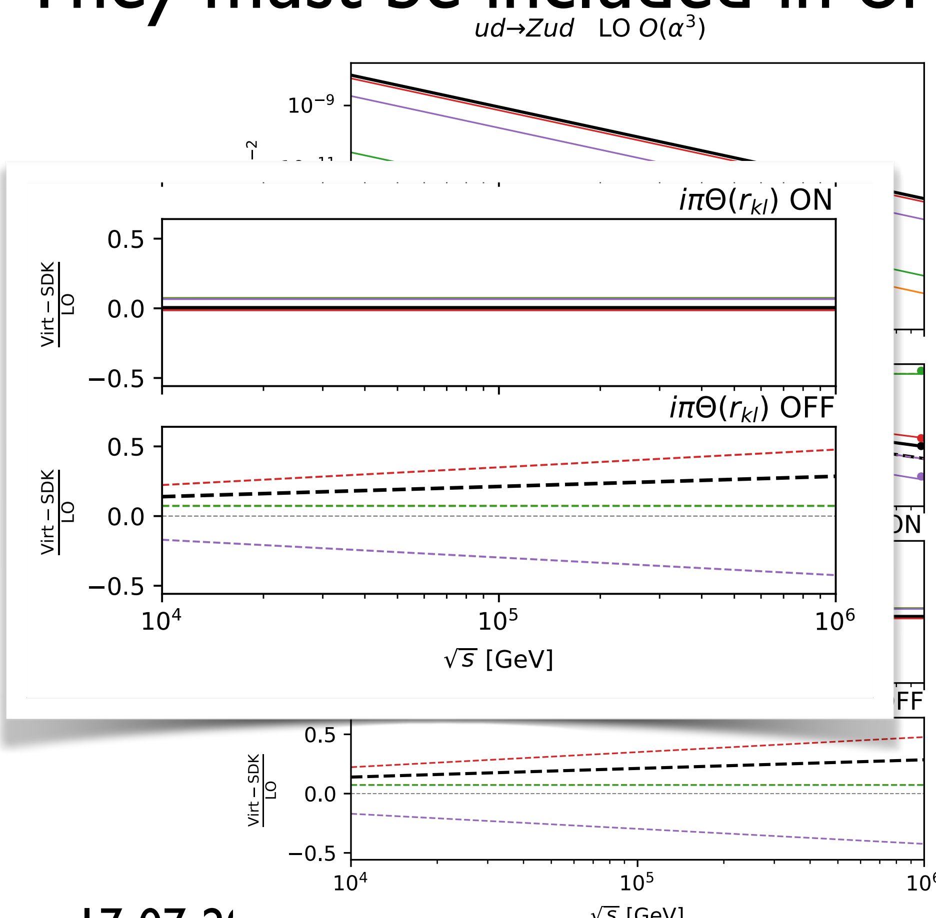

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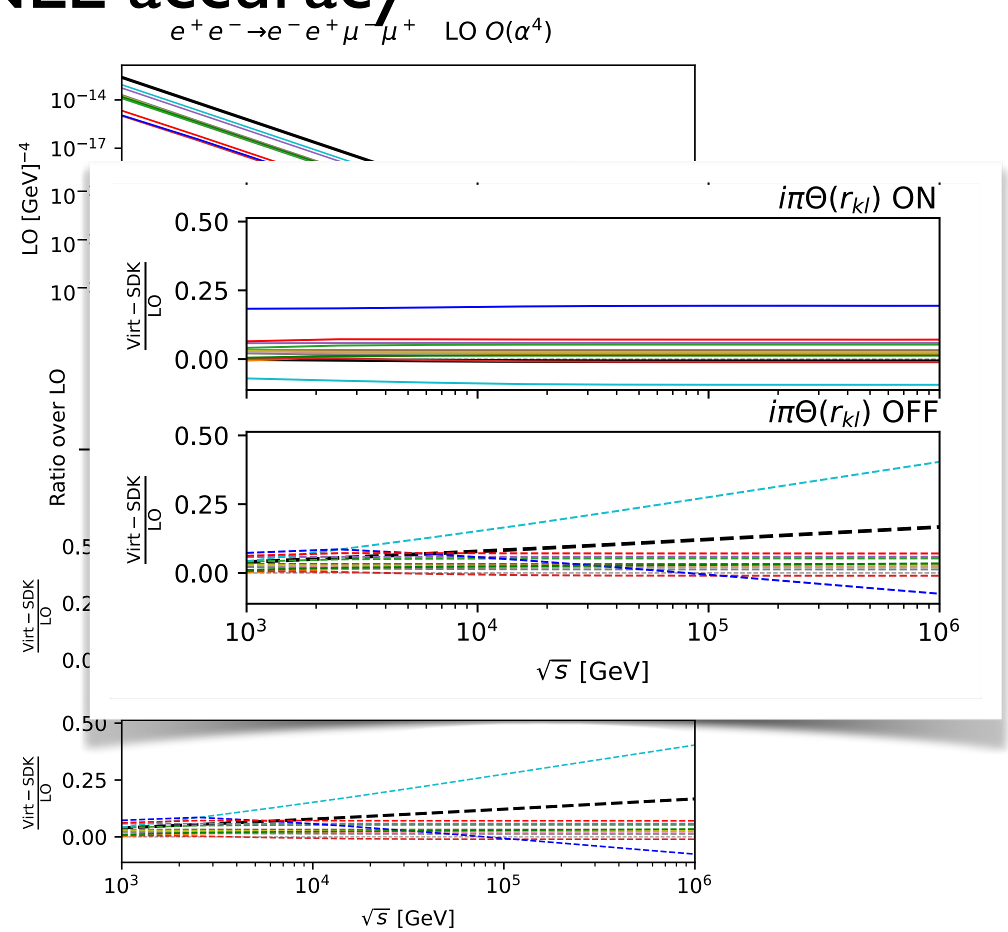


From IR masses to Dim.Reg. (and the treatment of QED effects)

- Consider e.g. the LSC term, in the D&P formalism. A photon mass appears

$$\delta^{\mathrm{LSC}}_{i'_k i_k}(k) = -\frac{1}{2}\Big[\underbrace{C^{\mathrm{ew}}_{i'_k i_k}(k)}_{Q_k^2+(I_Z^2)_k+(I_W^2)_k} L(s) - 2(I^Z(k))^2_{i'_k i_k}\log\frac{M_Z^2}{M_W^2}\, l(s) + \delta_{i'_k i_k} Q_k^2 L^{\mathrm{em}}(s,\lambda^2,m_k^2)\Big]$$

- The QED contribution is split in two parts:
  - from to M_W in L^{em} $\quad L^{\mathrm{em}}(s,\lambda^2,m_k^2) := 2l(s)\log\left(\frac{M_W^2}{\lambda^2}\right) + L(M_W^2,\lambda^2) - L(m_k^2,\lambda^2)$
  - from M_W to s in L(s)
- Consider the divergent part: λ (and m_k) acts as a regularisation scale for the IR divergences
- We can promote λ to Q, the IR regularisation scale of Dim.Reg., without losing any logarithmic term
- We can then set $Q^2=\mu^2_R$, and compare the Sudakov approximation with the exact virtuals

From IR masses to Dim.Reg. (and the treatment of QED effects)

- In the SSC terms, this leads to a vanishing contribution if the r_{ij}/s part is dropped

$$\delta^{A,\mathrm{SSC}}_{i'_k i_k i'_l i_l}(k,l) = \left[2\left(l(s) + l(M_W^2, Q^2)\right)\left(\log\frac{|r_{kl}|}{s} - i\pi\Theta(r_{kl})\right) + \Delta^{s\to r_{kl}}(r_{kl}, M_W^2)\right] I^A_{i'_k i_k}(k) I^A_{i'_l i_l}(l)$$

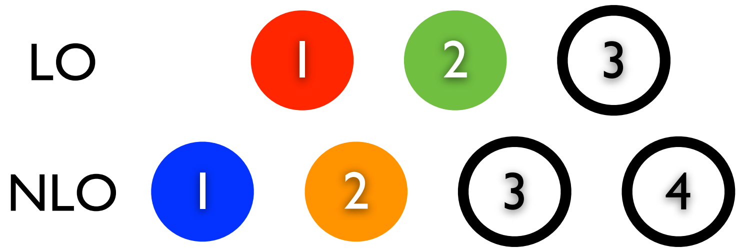
More on the QED contribution (towards the extension to QCD)

$$\delta^{\mathrm{LSC}}_{i'_k i_k}(k) = -\frac{1}{2}\Big[\underbrace{C^{\mathrm{ew}}_{i'_k i_k}(k)}_{Q_k^2 + (I_Z^2)_k + (I_W^2)_k} L(s) - 2(I^Z(k))^2_{i'_k i_k} \log\frac{M_Z^2}{M_W^2}\, l(s) + \delta_{i'_k i_k} Q_k^2 L^{\mathrm{em}}(s, Q^2, m_k^2)\Big],$$

$$L^{\mathrm{em}}(s,\lambda^2,m_k^2) := 2l(s)\log\left(\frac{M_{\mathrm{W}}^2}{\lambda^2}\right) + L(M_{\mathrm{W}}^2,\lambda^2) - L(m_k^2,\lambda^2)$$ remember: $\lambda^2 \to Q^2 = s$

- In LSC, QED enters in L^{em} and in the term ~L(s)
- In the D&P formulation, M_W acts as a separator from the low-energy ($\lambda^2 \to M_W^2$) to the high-energy regime ($M_W^2 \to s$)
- If $Q^2=s$, the QED contribution vanishes in LSC (also in SSC) for massless particles
  - Warning! This is not equivalent to just saying that L^{em} can be dropped
  - For massive particles (e.g. top), a term ~ $L(s, m_t)$ remains
- QED contributions appear also in the C and PR terms
- QCD terms are analogous to those from QED (only top is massive)

The inclusion of QCD effects



- Remember: $\mathrm{NLO}_i = \mathrm{LO}_{i-1} \otimes \mathrm{EW} + \mathrm{LO}_i \otimes \mathrm{QCD}$
- So far, we have focused on approximating EW corrections
- The corrections of QCD origin stemming on top of LO_2 are analogous to the QED-type corrections
- Since in QCD we always cluster massless patrons into jets, a remarkably-simple structure appears

$$\delta\tilde{\mathcal{M}} \equiv \tilde{\mathcal{M}}_0 \left[\left(\underbrace{n_t\, L^t(s)}_{\text{LSC}} + \underbrace{n_{\alpha_S}\, l^{\alpha_S}(\mu_R^2)}_{\text{PR, } \alpha_s} - \underbrace{n_g\, l^{\alpha_S}(s)}_{\text{C, } g\to t\bar{t}} \right) + \underbrace{\frac{\delta\tilde{\mathcal{M}}_0}{\delta m_t}(\delta m_t)^{\mathrm{QCD}}}_{\text{PR, } m_t} \right]$$

with

$$L^t(s) \equiv \frac{C_F}{2}\frac{\alpha_S}{4\pi}\left(\log^2\frac{s}{m_t^2} + \log\frac{s}{m_t^2}\right) \qquad l^{\alpha_S}(\mu^2) \equiv \frac{1}{3}\frac{\alpha_S}{4\pi}\log\frac{\mu^2}{m_t^2} \qquad (\delta m_t)^{\mathrm{QCD}} \equiv -3C_F\frac{\alpha_S}{4\pi}\log\frac{s}{m_t^2}$$

The inclusion of QCD effects: some results