Monte-Carlo developments and Electroweak/mixed QCD-EW corrections

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Outline

- Recent progress in the computation of EW corrections
  - Introduction on EW and mixed QCD-EW corrections
  - EW corrections in the high-energy limit
  - The problem of PS matching
  - Mixed QCD/EW corrections to Drell-Yan at NNLO
- Recent and future developments in MC tools
  - NNLO+PS predictions
  - Techniques for the reduction of negative weights in MC@NLO-type matching
  - GPU/AI related developments

2/3 of time

1/3 of time

Part I

EW corrections and mixed-coupling expansion

Precision physics and higher-order corrections

- The way we do precise predictions: perturbation theory

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strong coupling, ~0.1

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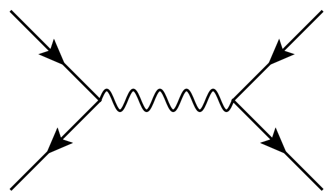

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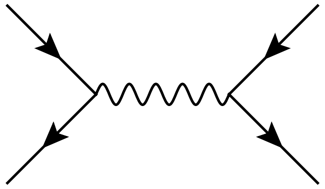

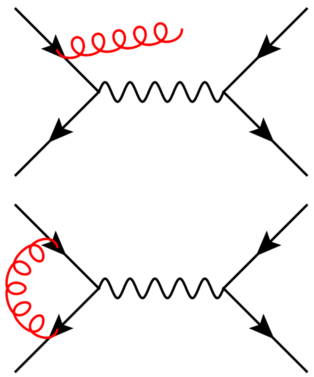

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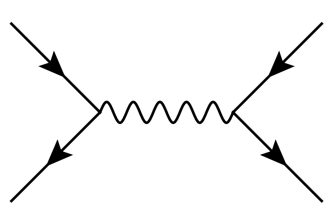

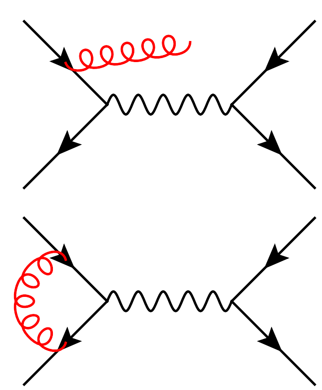

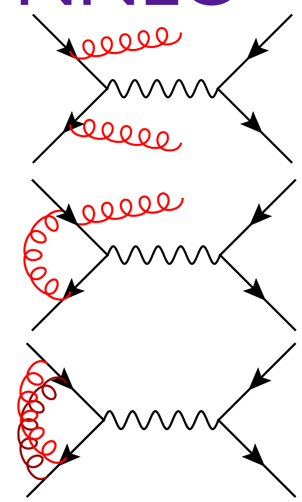

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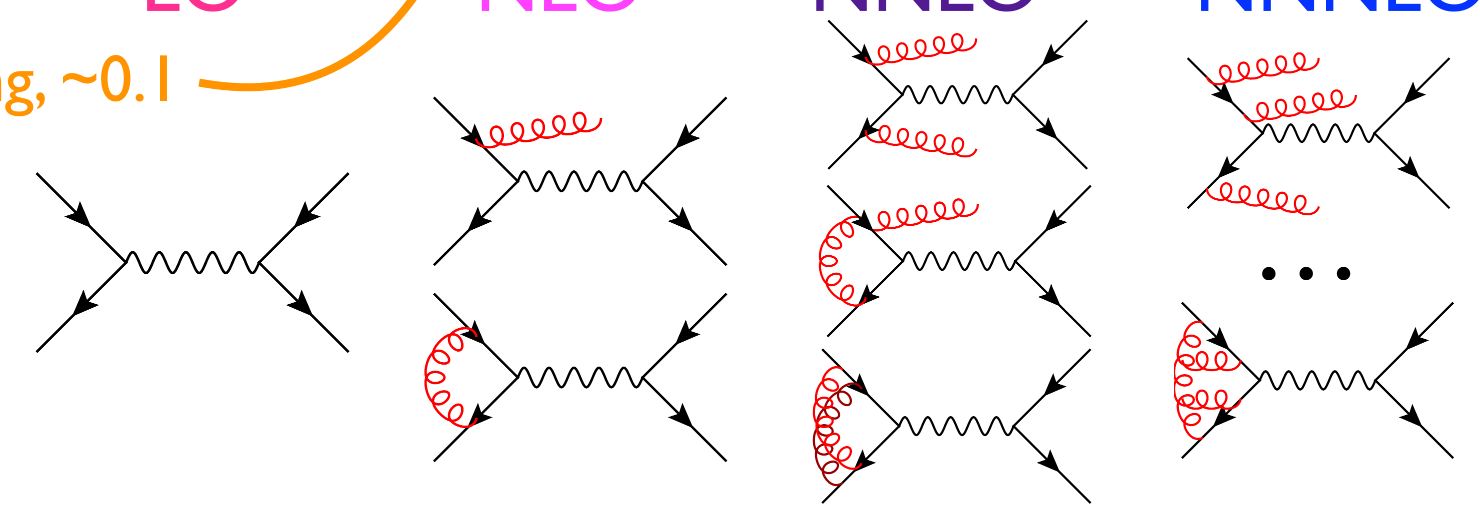

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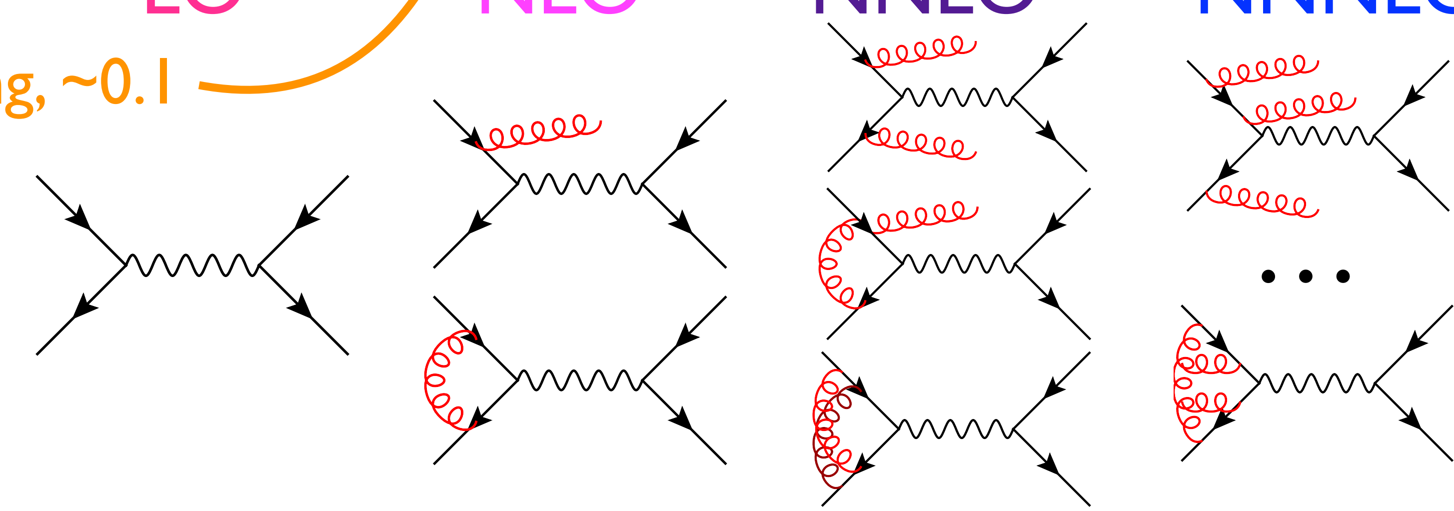
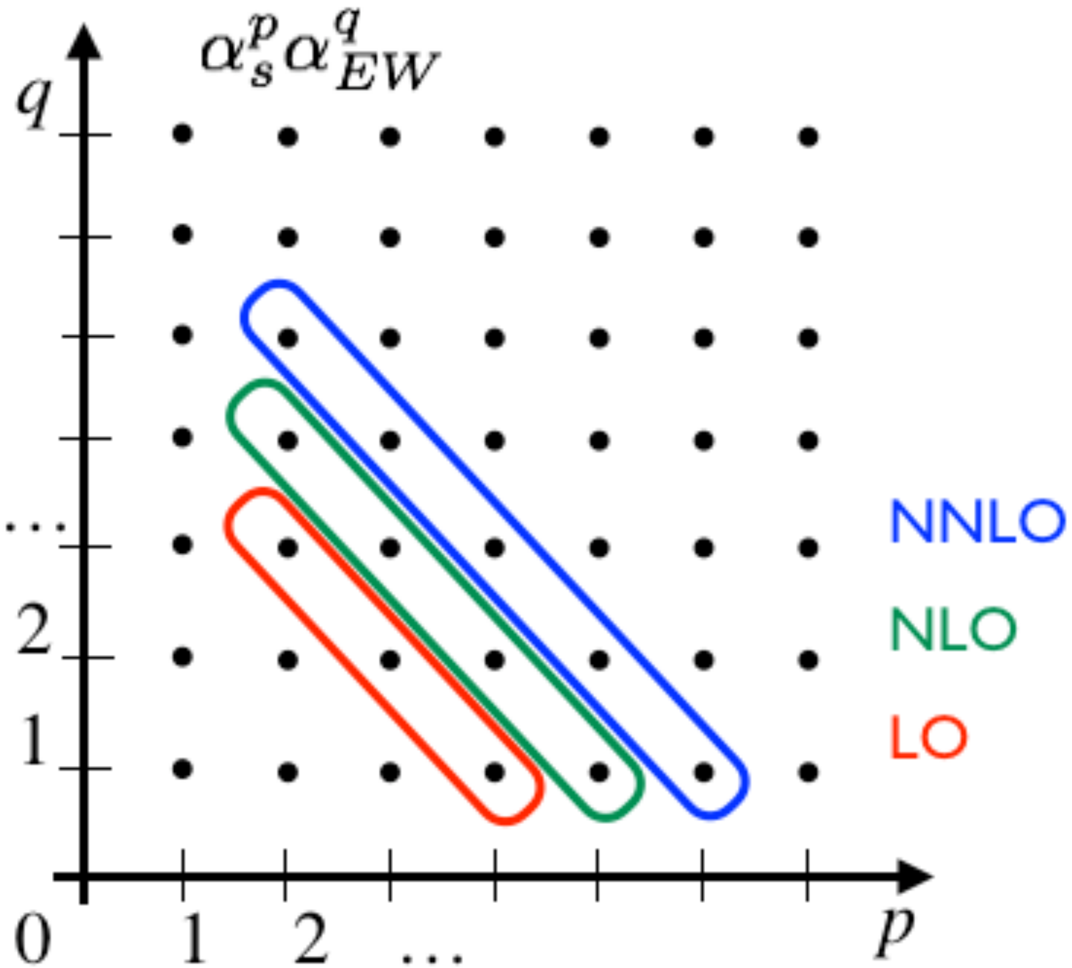
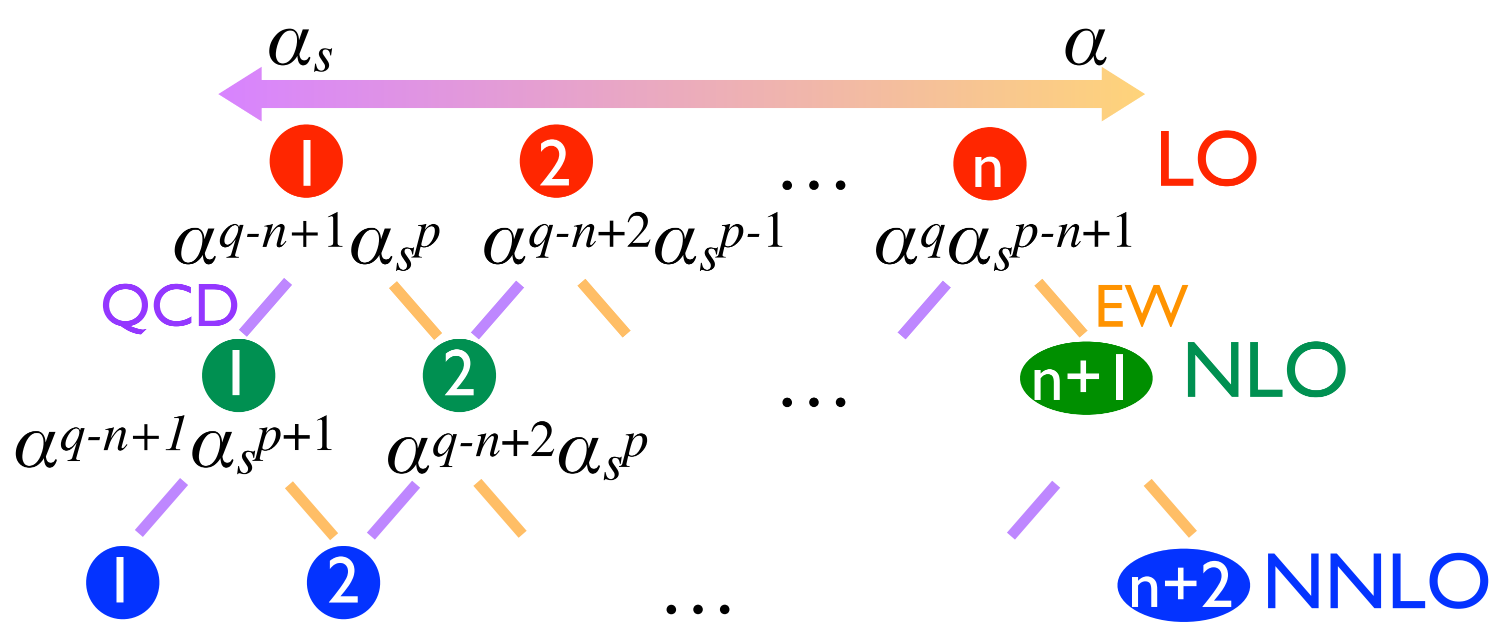


- Going higher orders, the complexity of the computation explodes

Electroweak corrections: a multi-coupling expansion

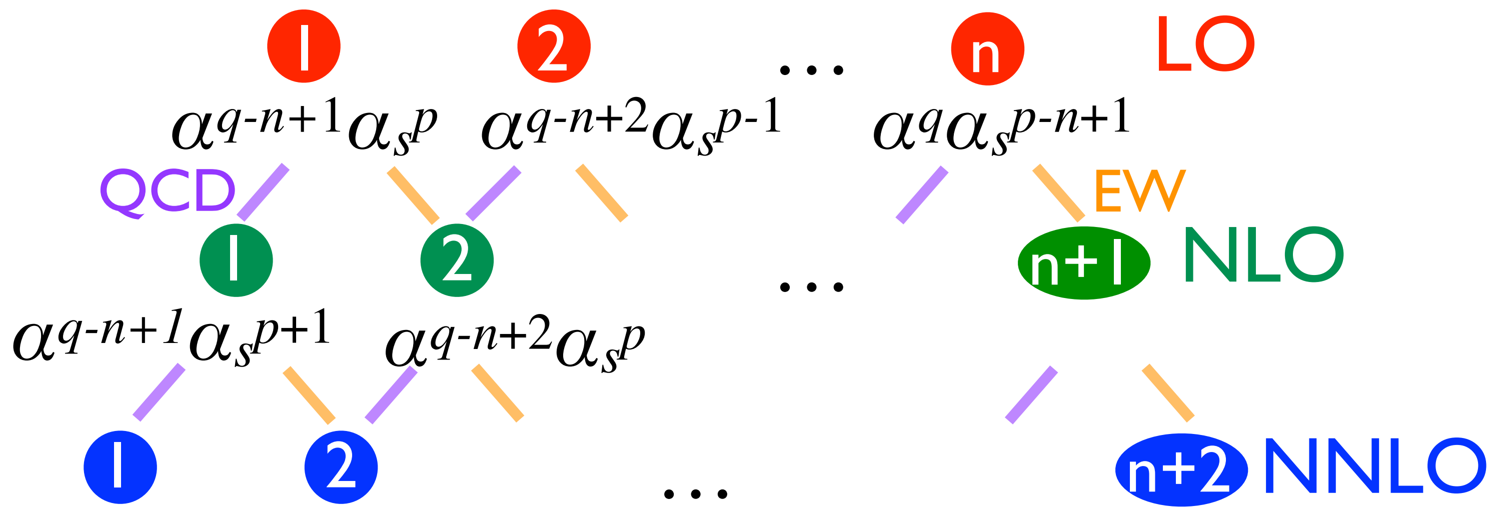
- If EW corrections come into play, one must carry the expansion both in α and α_s
- The structure of a given process are something like





n, p, q are process-dependent integers.
For $t\bar{t}$ production: n=3, p=q=2
For lepton-pair production, n=1, p=0, q=2

Some comments



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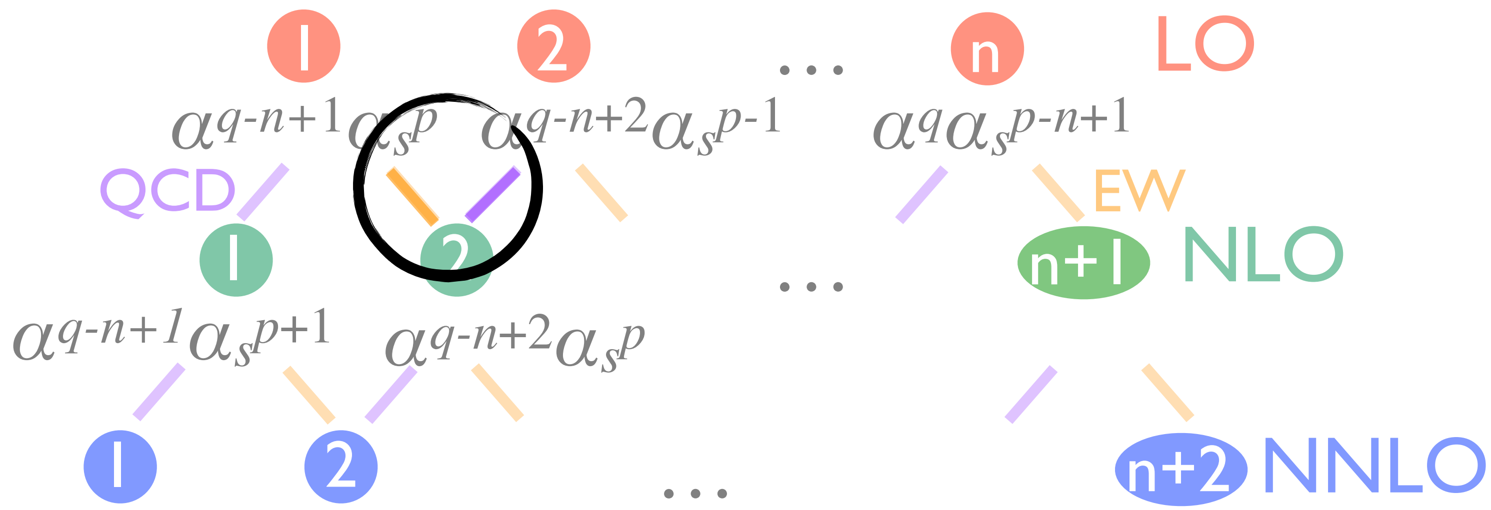

- For IR-finiteness, contributions of QCD and EW origin to a given contribution must *both* be included

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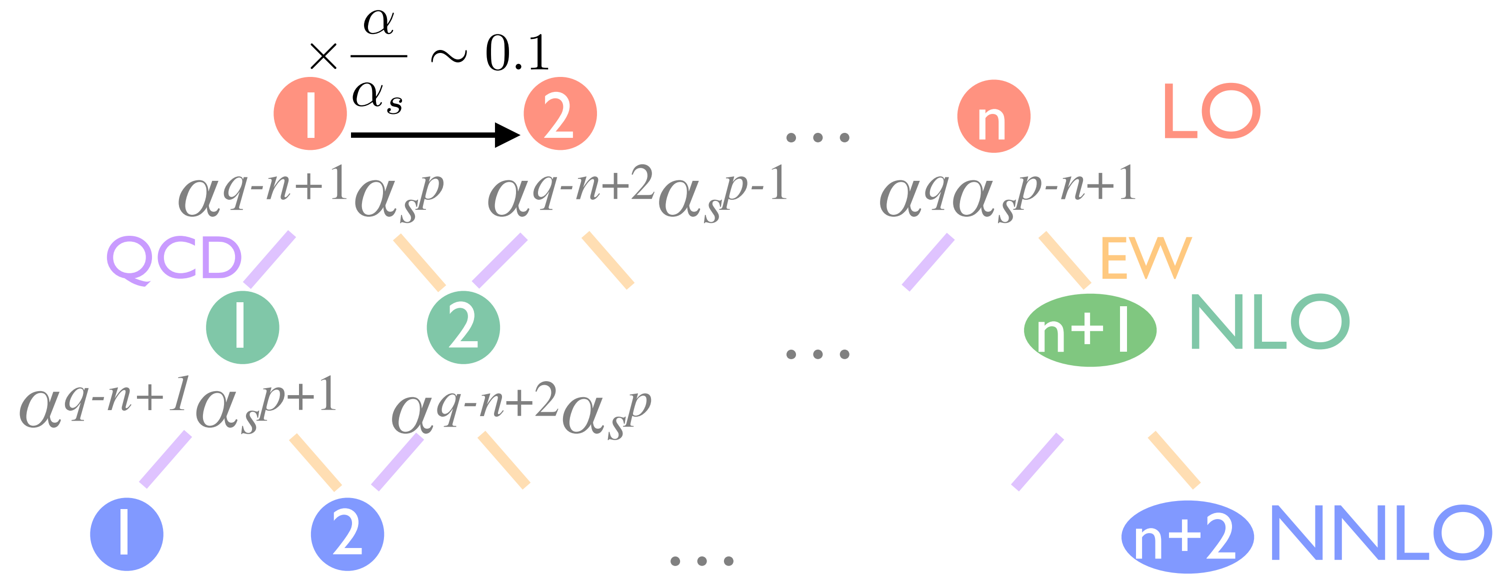

- For IR-finiteness, contributions of QCD and EW origin to a given contribution must *both* be included
- The presence of different powers of α and α_s hints at a power-counting estimate for the contributions. Such an estimate is often misleading!

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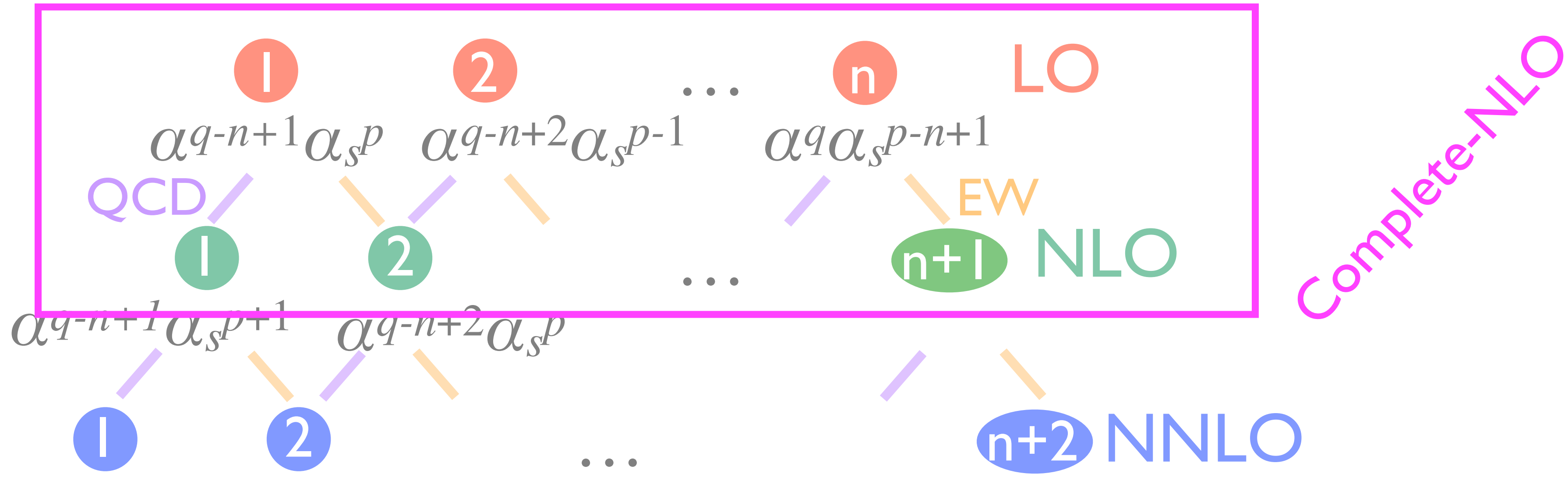

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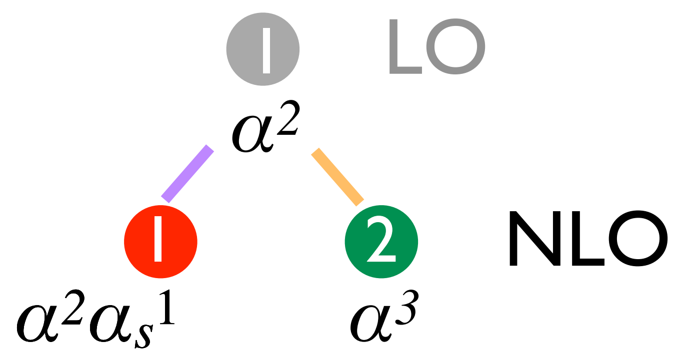
- The presence of different powers of α and α_s hints at a power-counting estimate for the contributions. Such an estimate is often misleading!
- Predictions including all the contributions at LO/NLO/… are typically called "Complete-LO/NLO/…"
  NLO EW and Complete-NLO predictions can be obtained with automatic (and mostly public) tools

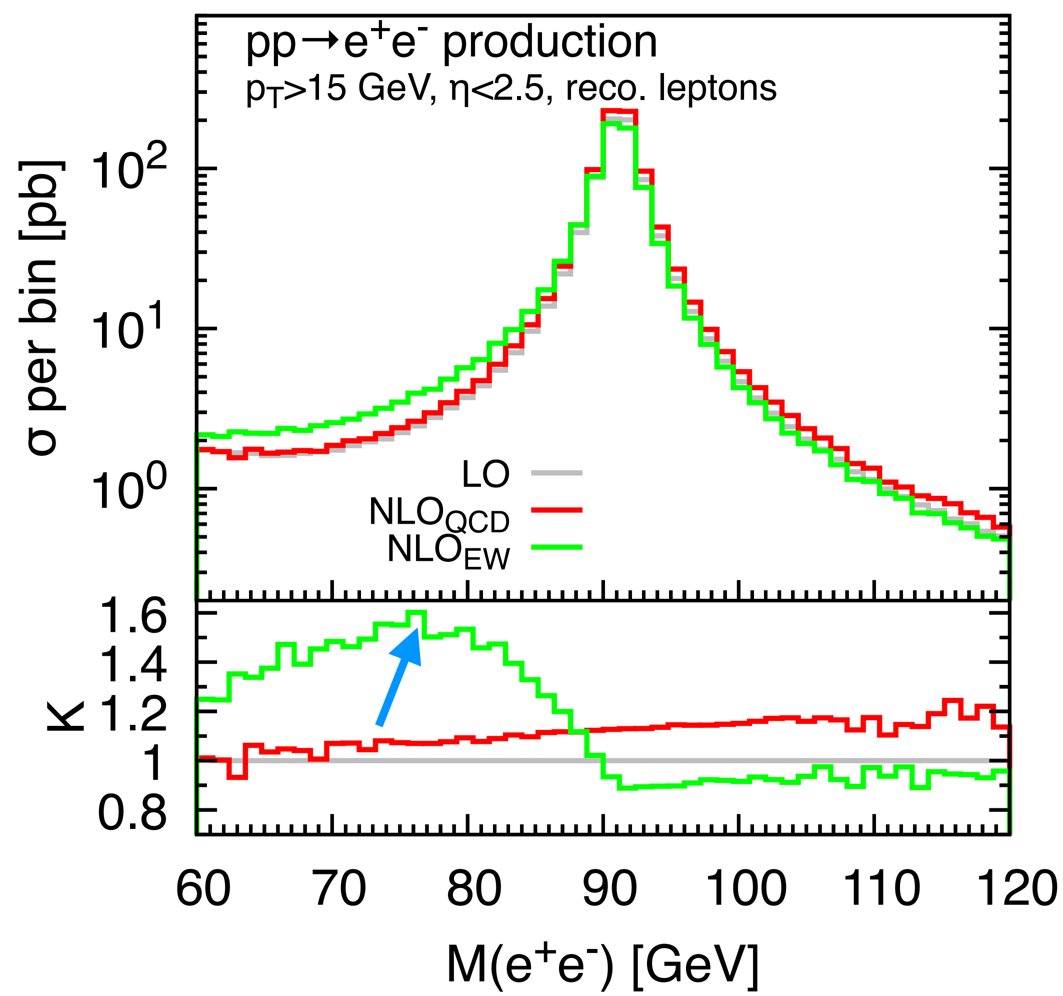
  Collier, GoSam, MG5_aMC, Recola, Sherpa+Collier/OpenLoops/OpenLoops2/…

Coupling-hiearchy violation Drell-Yan

Dittmaier et al, 0911.2329

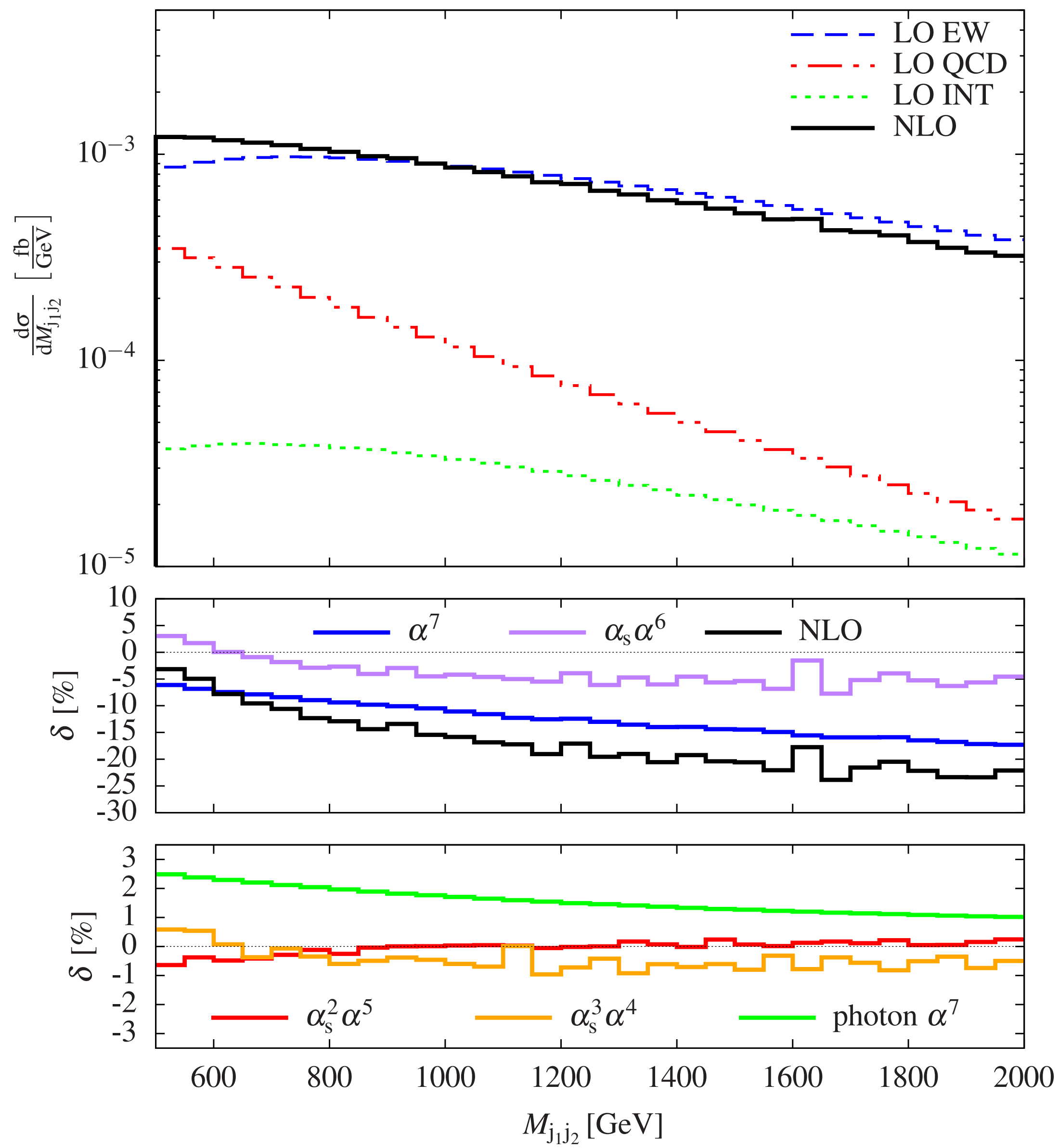


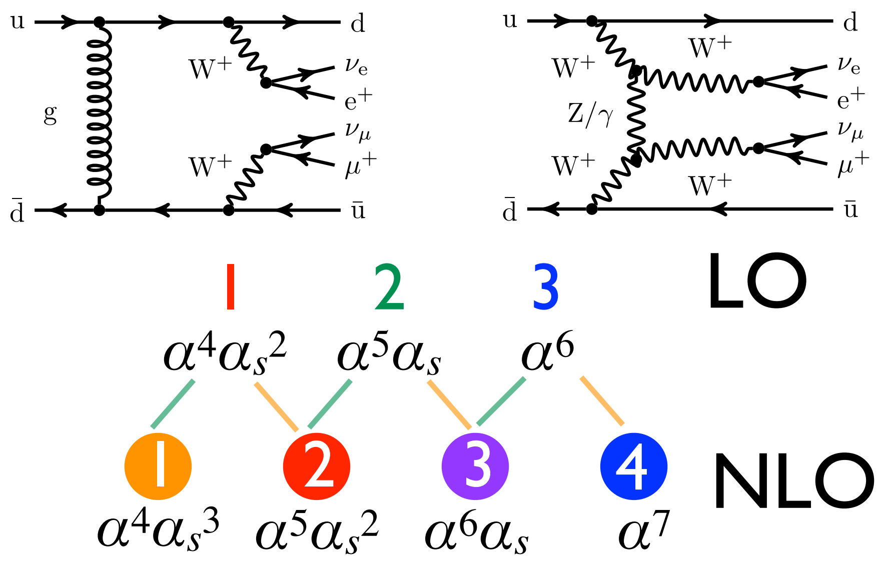
- *Because of photon radiation from events on the peak, the region $M(e^+e^-)<m_Z$ receives huge EW corrections*
- *NLO QCD corrections remain fairly stable across the peak*



Coupling-hiearchy violation VBS

Biedermann et al, 1708.00268

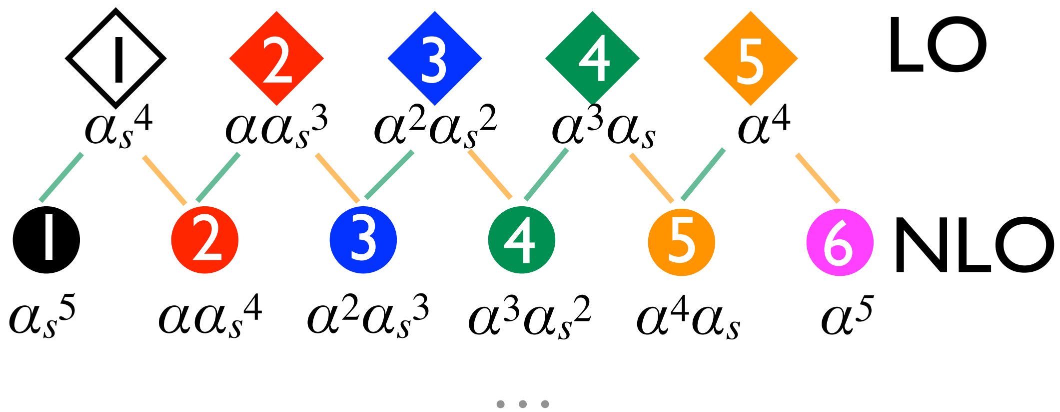


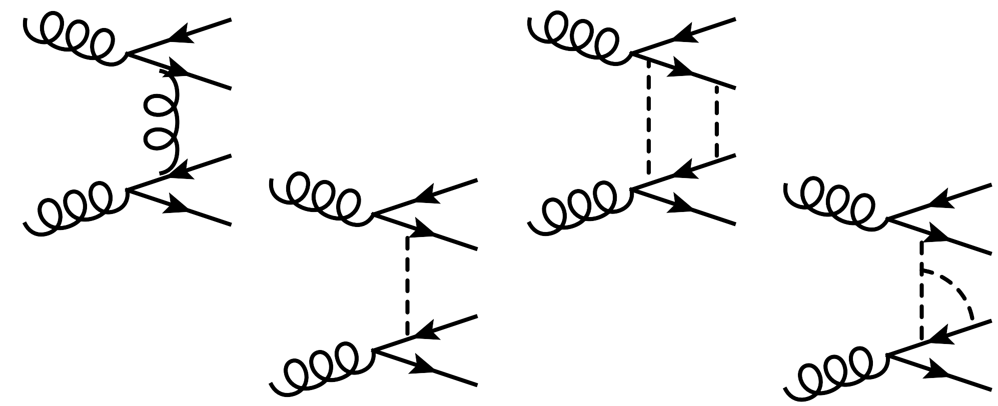


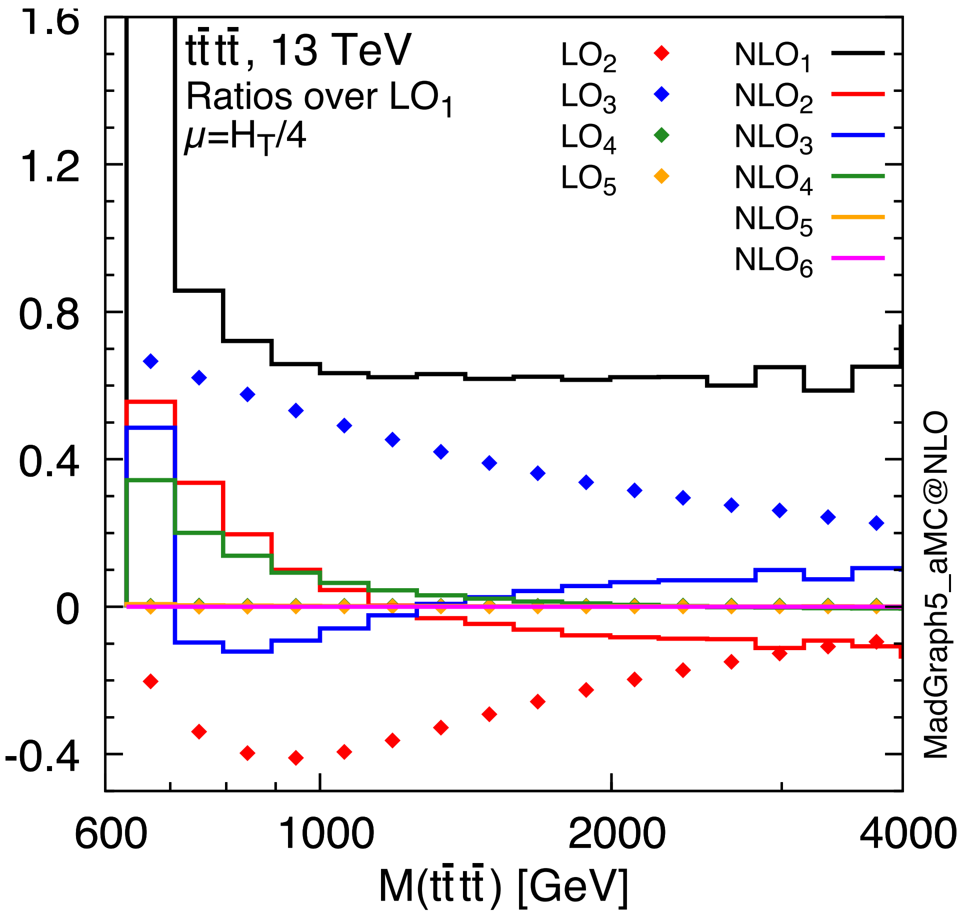
- *In VBS, EW and QCD induced production modes comparable at LO*
- *NLO EW corrections to EW-induced mode (NLO_4) are by far the dominant NLO contribution*
- *Not only for ssWW, but general feature of VBS processes*
  WZ: Denner et al, 1904.00882

Coupling-hiearchy violation
4 top

Frederix, Pagani, MZ, 1711.02116







- *4top production receives contributions induced by y_t which ends up in (N)LO_2→…*
- *Despite being subleading by power-counting, even NLO_4 can amount to some 10%s wrt LO_1*
- *Accidental cancelations occur among the various contributions with the complete-NLO being very close to LO_1+NLO_1 (NLO QCD)*
- *A non-SM y_t will spoil these cancelations*
  - *4top as BSM probe*

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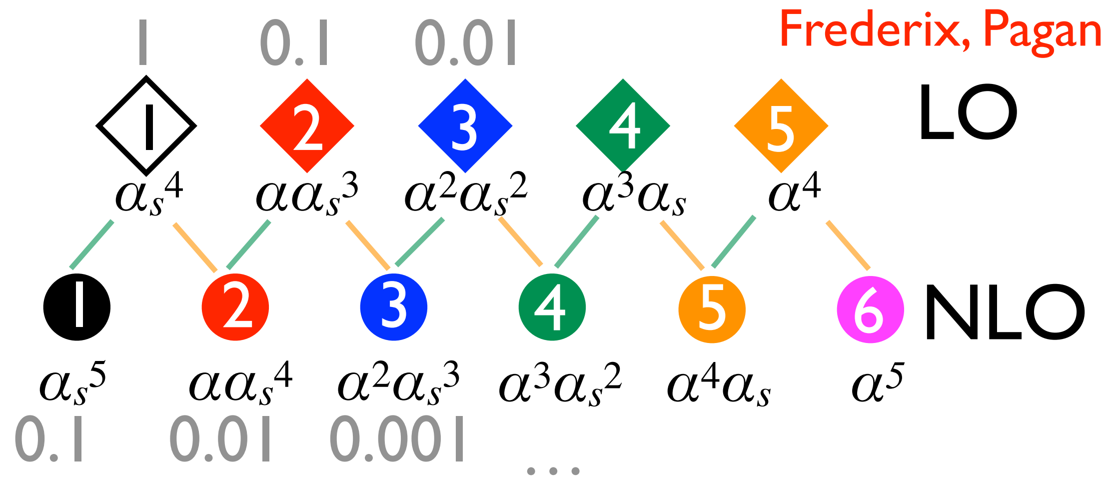

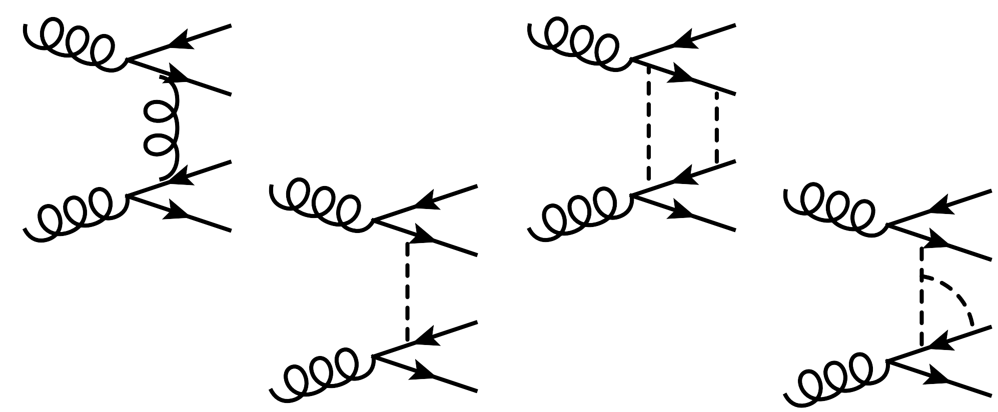

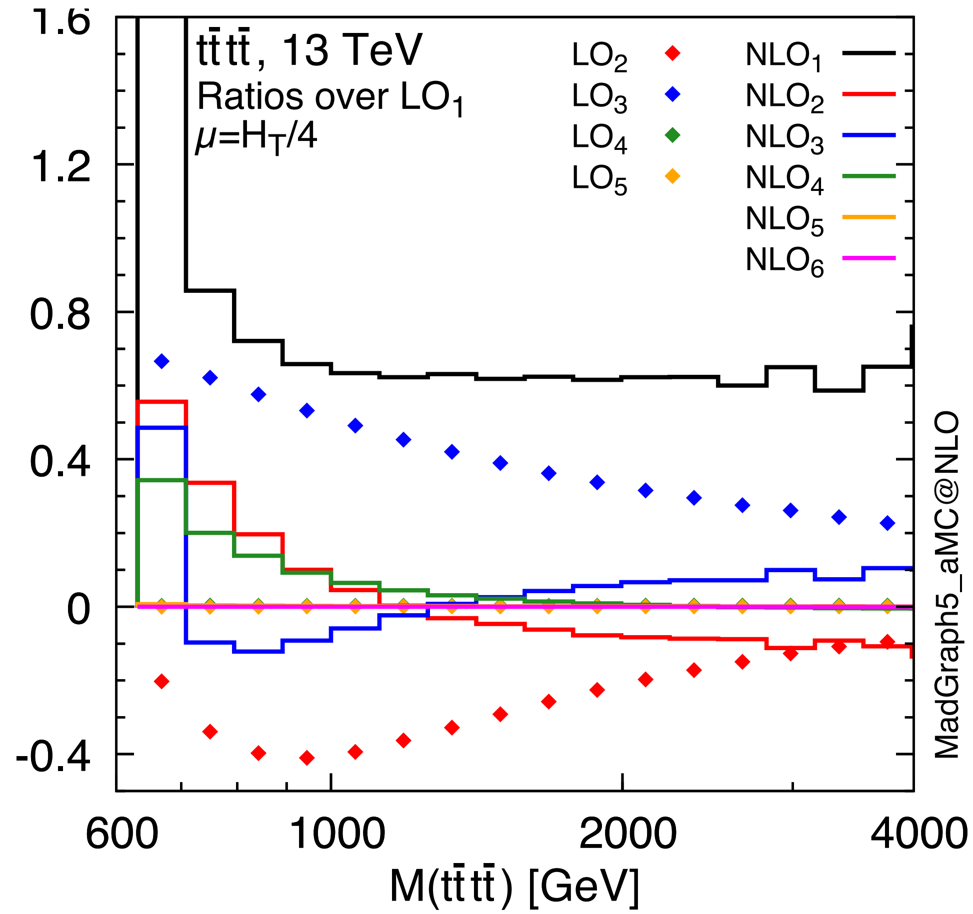

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Approximate EW corrections in the high-energy limit

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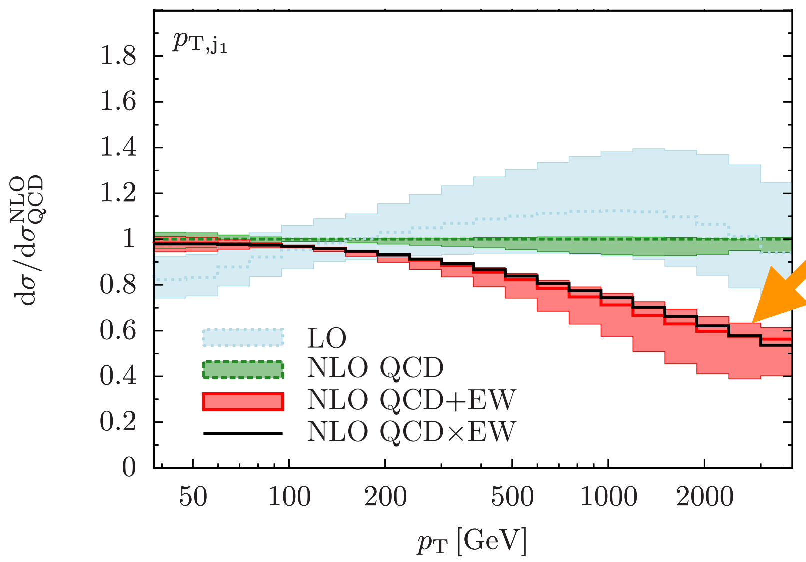
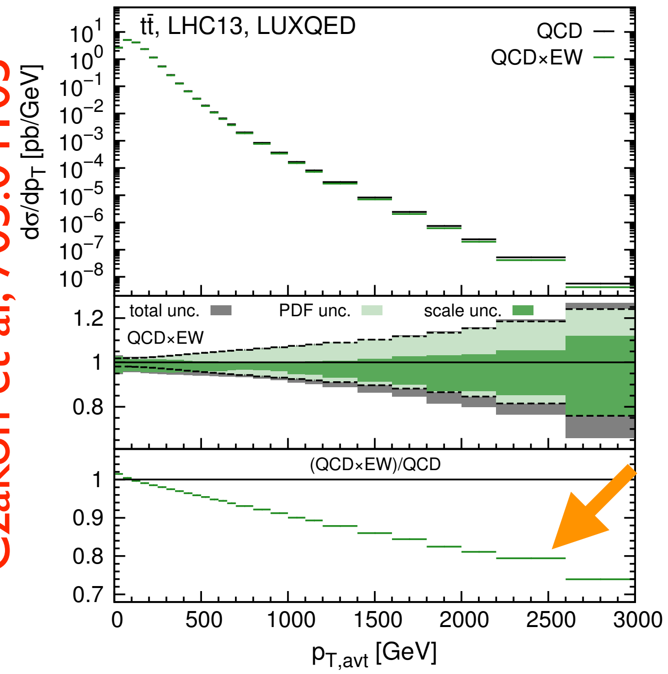
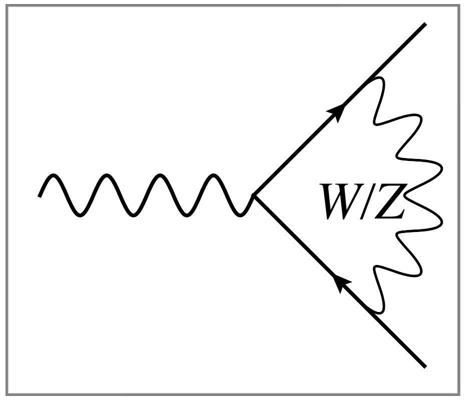
Kallweit et al, 1511.08692



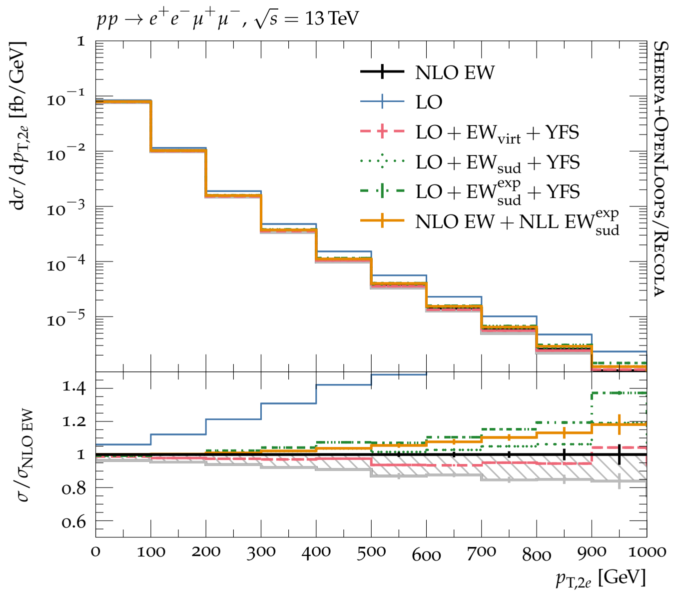
Czakon et al, 705.04105

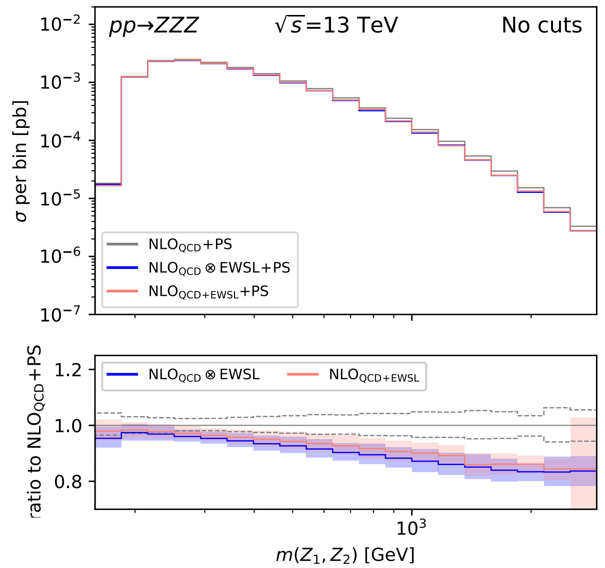


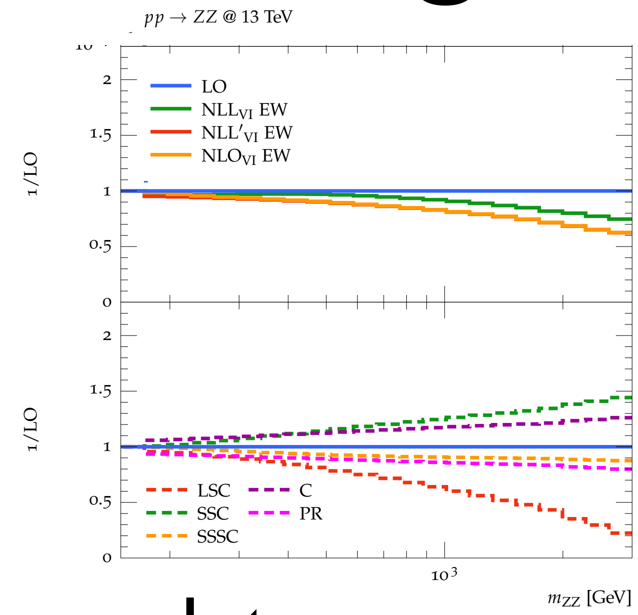


- EW corrections show universal behaviour when all invariants are large
- Logarithmic enhancement due to would-be IR singularities related to W and Z masses, the so-called Sudakov logs
- In this limit, the logarithmic contribution can be computed using only tree-level amplitudes Denner, Pozzorini, hep-ph/0010201 & hep-ph/0104127
- This can be very helpful *if* EW corrections for a given process are dominated by Sudakov logs, *if* the large-invariants regime is considered, and *if* the process is not mass-suppressed

EW Sudakov logs are back on stage



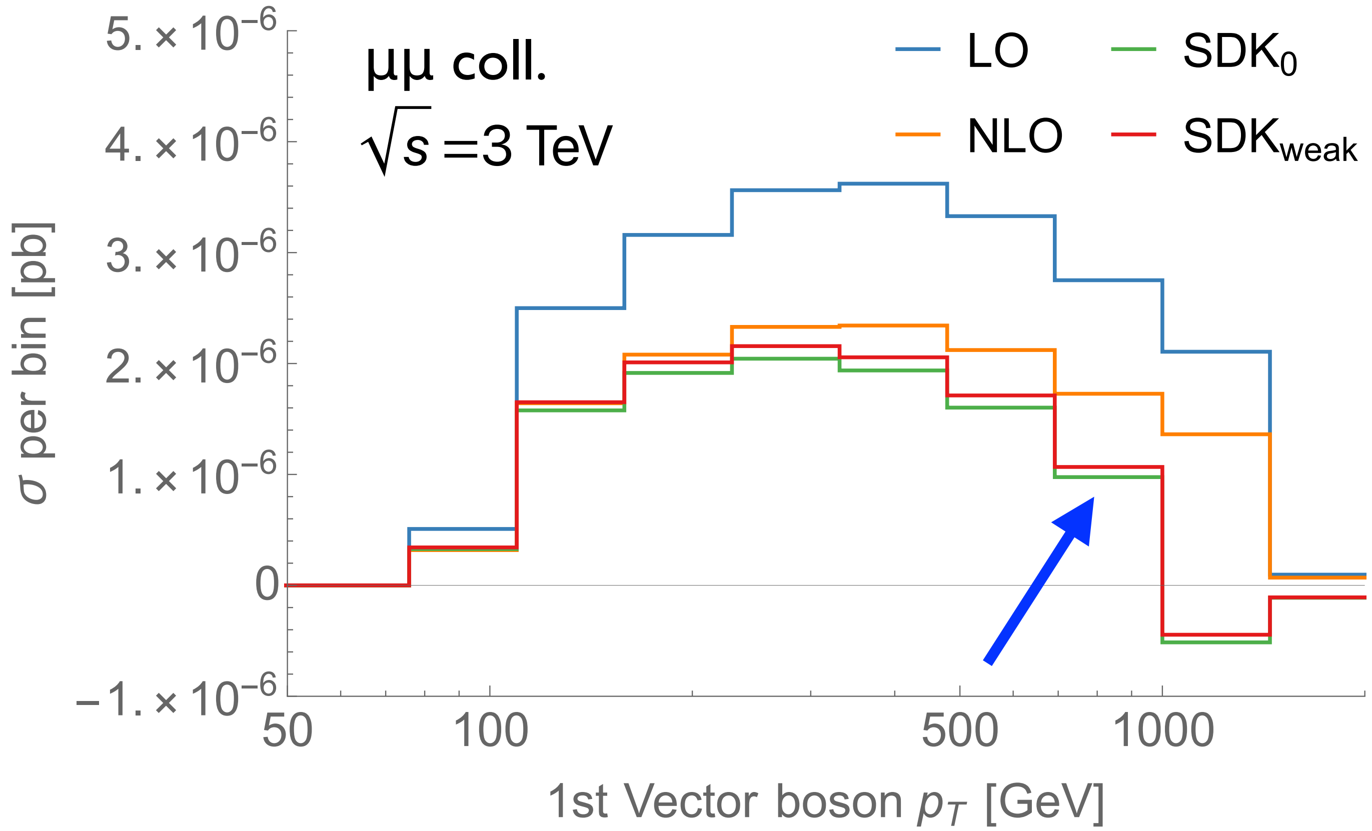




- In the recent years, interest towards EWSL has grown a lot
  - Automated by 3 different collaborations
    Sherpa: Bothmann et al, 2006.14635; MG5_aMC: Pagani, MZ, 2110.03714; OpenLoops: Lindert et al, 2312.07927
- They provide easy solutions to difficult problems:
  - Much more stable and faster than EW corrections
  - Possibility to combine approximate-EW corrections with NLO-QCD predictions matched to PS (possibly in multijet-merged samples)
    Bothmann et al, 2111.13453; Pagani, Vitos, MZ, 2309.00452
  - They exponentiate and can be resummed to all-orders
- However, one should always check whether the Sudakov approx holds against the exact EW corrections

Don’t buy everything they sell

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



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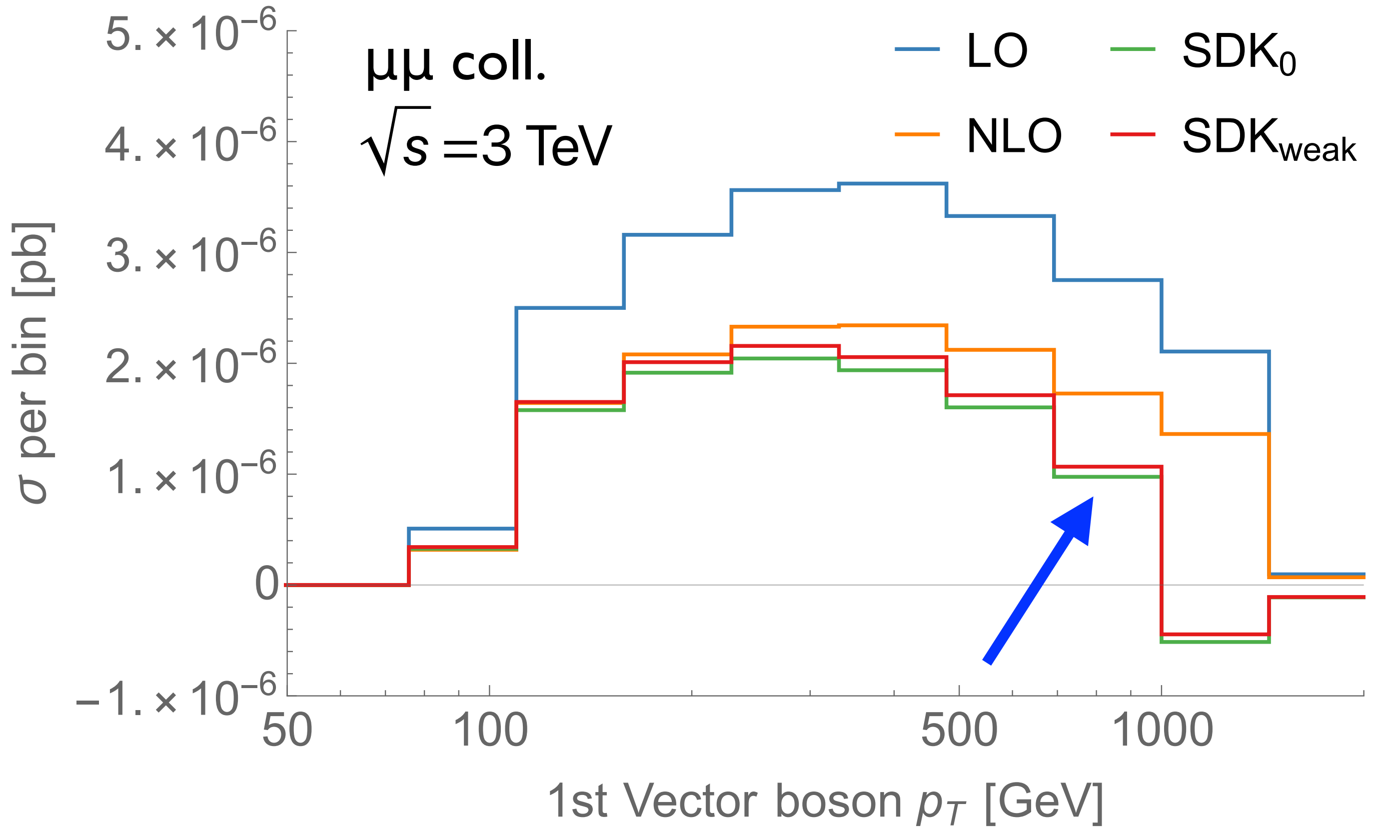
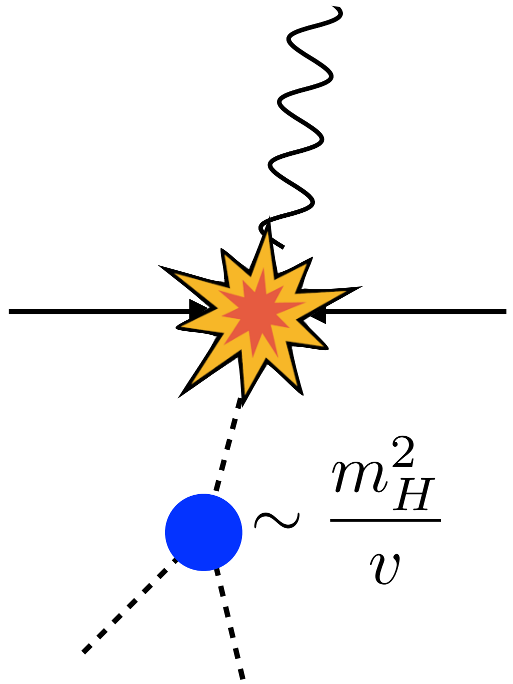


WIP with Y. Ma, D. Pagani

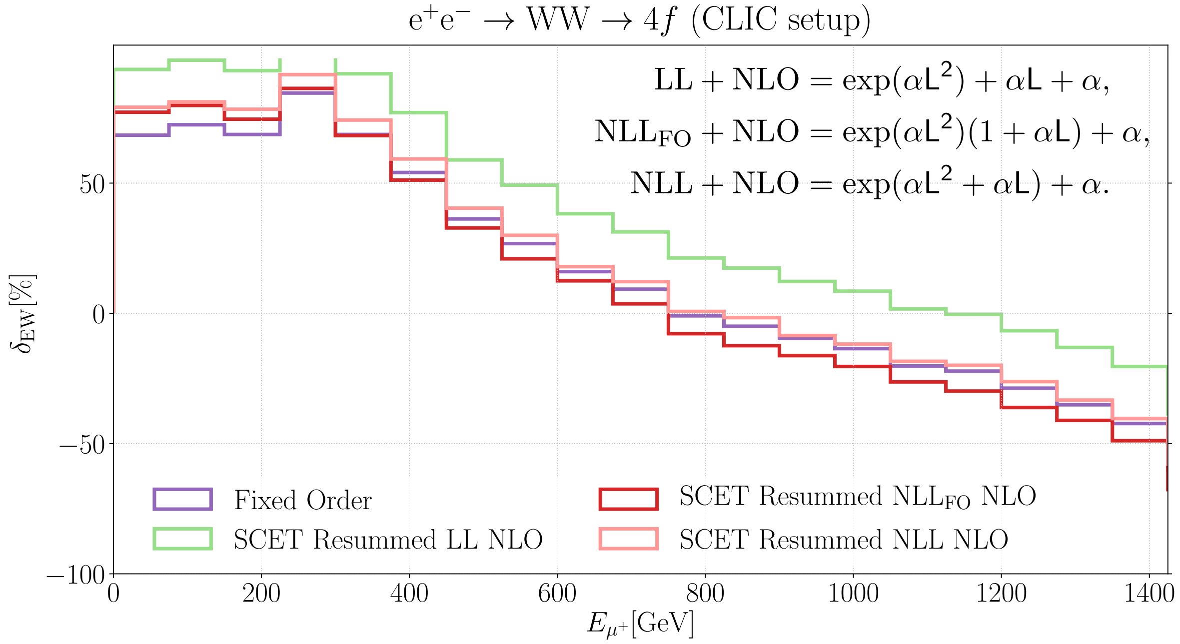


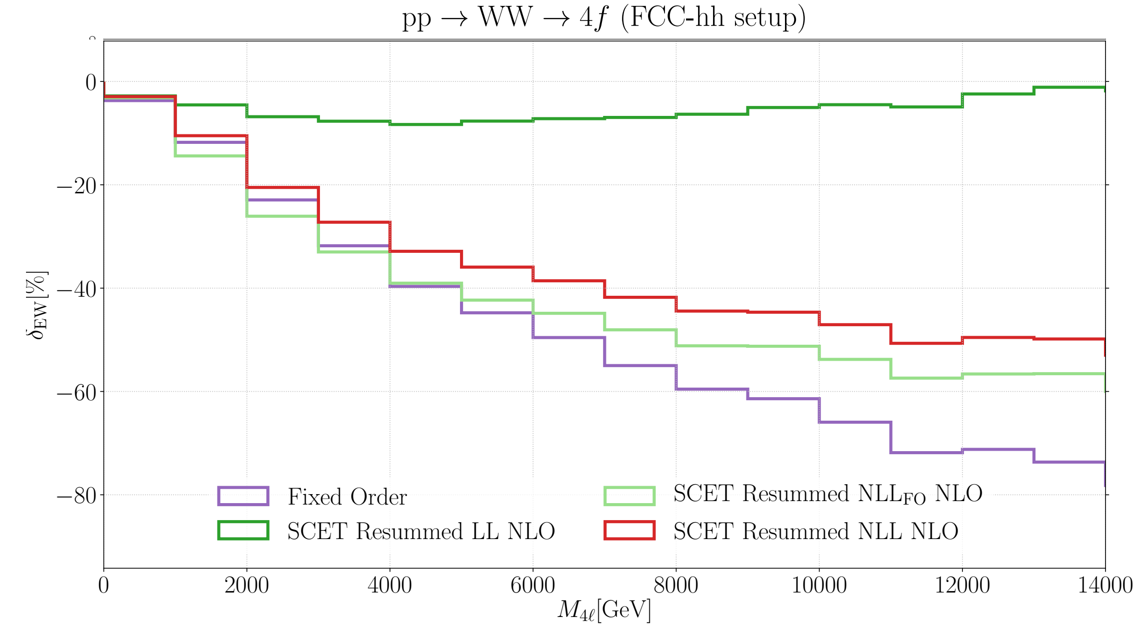
- These configurations are dominated by low M(HH) and are mass-suppressed (dominated by the trilinear diagram)

Resummation of EW Sudakov logs

Denner, Rode, 2402.10503

- Since EW corrections are non-diagonal wrt flavour, exponentiation of Sudakov-logs is highly non-trivial
- Seminal studies for 2-loop amplitudes suggested to exponentiate separately weak and QED terms, and about their order Denner et al, hep-ph/0301241
- Resummation achieved using the EW version of SCET, included in a fully-differential MC
- Results presented for CLIC@3TeV and FCC-hh@100 TeV



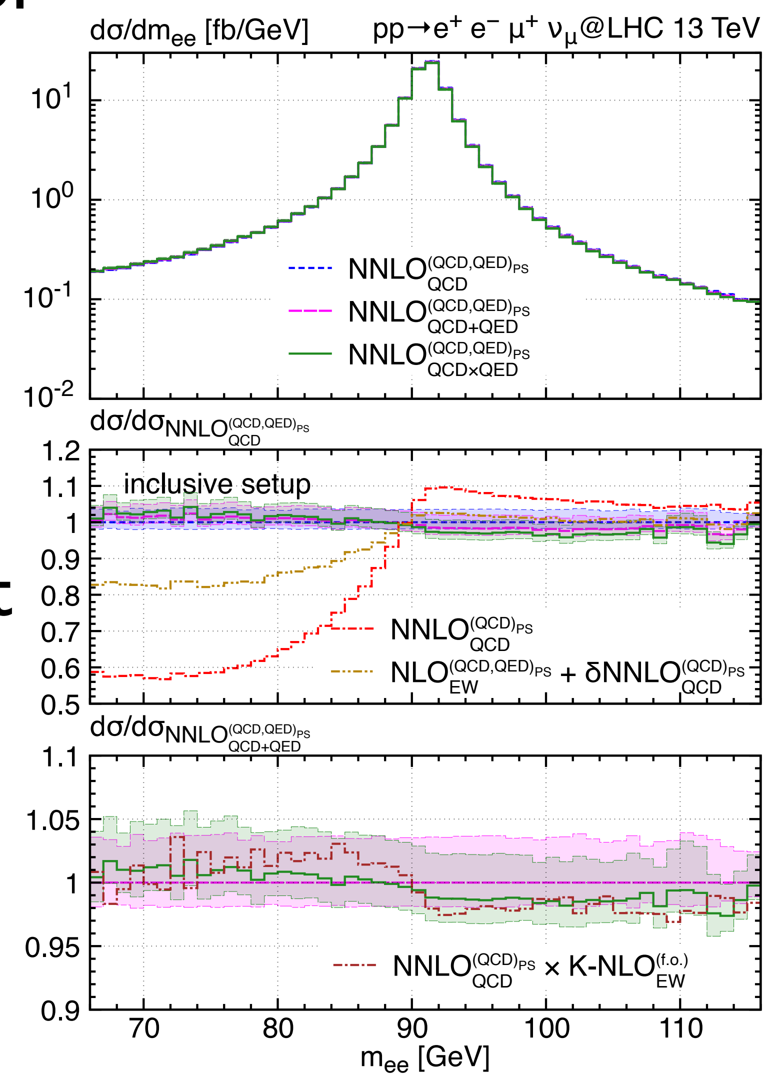


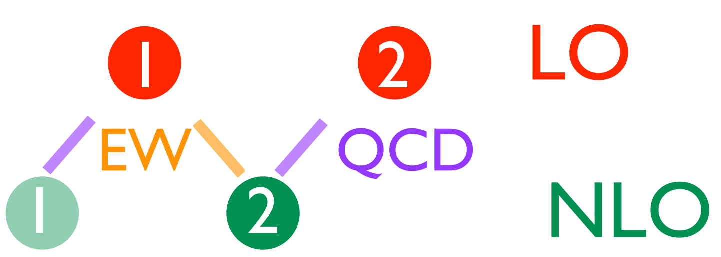
While the resummation of large EW logarithms is a must at future high-energy colliders, the application of the $SCET_{EW}$ formalism to realistic diboson processes is nontrivial and requires a number of approximations that need to be carefully checked.

Matching with parton shower?

- EW corrections matched with PS still not available for general processes
  - Approximate approaches exist, only including n-body contribution ("EWvirt" or EWSL). Accuracy depends on kinematics region
    EWVirt: VV(J): Brauer et al, 2005.12128; top: Gutschov et al, 1803.00950; V+jets: Kallweit et al, 1511.08692, …
  - Exact matching performed only for processes with just LO_1 (in the Powheg scheme)
    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
- Main issue: how to assign colour-flows to interferences (LO_2 is mostly an interference contribution) Some ideas: Frixione et al, 2106.13471

Lindert et al, 2208.12660





Attaining the highest precision: Drell-Yan NNLO QCD×EW

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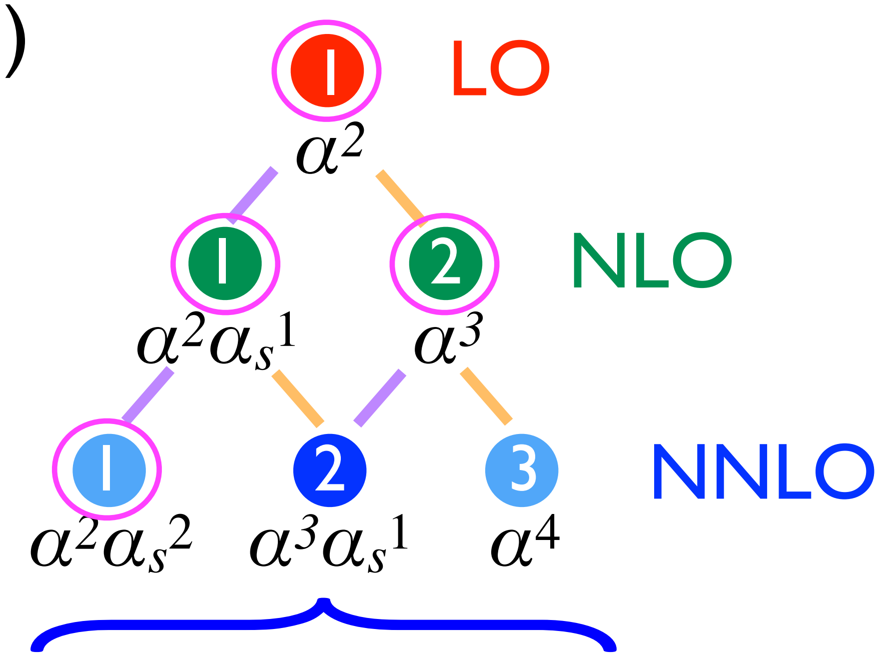
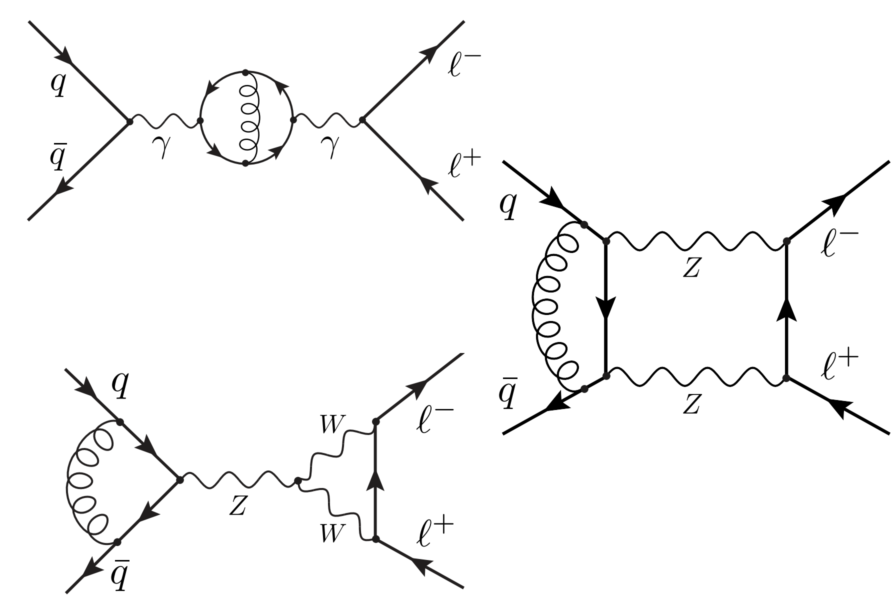
- Lepton-pair production (Drell-Yan) is a high-precision probe of the EW sector (M_W, $\sin\theta_W$, …)
- NNLO QCD+NLO EW not enough for current and upcoming exp. data
- $NNLO_2$ has been the frontier for long time:
  - Historically, different approaches have been pursued for the pole vs large-$m(l^+l^-)$ region
  - Complicated topologies (massive double box)
- Recently, full computations of $NNLO_2$ have become available, both for NC and CC process
- I will briefly review these works, focusing on pheno results





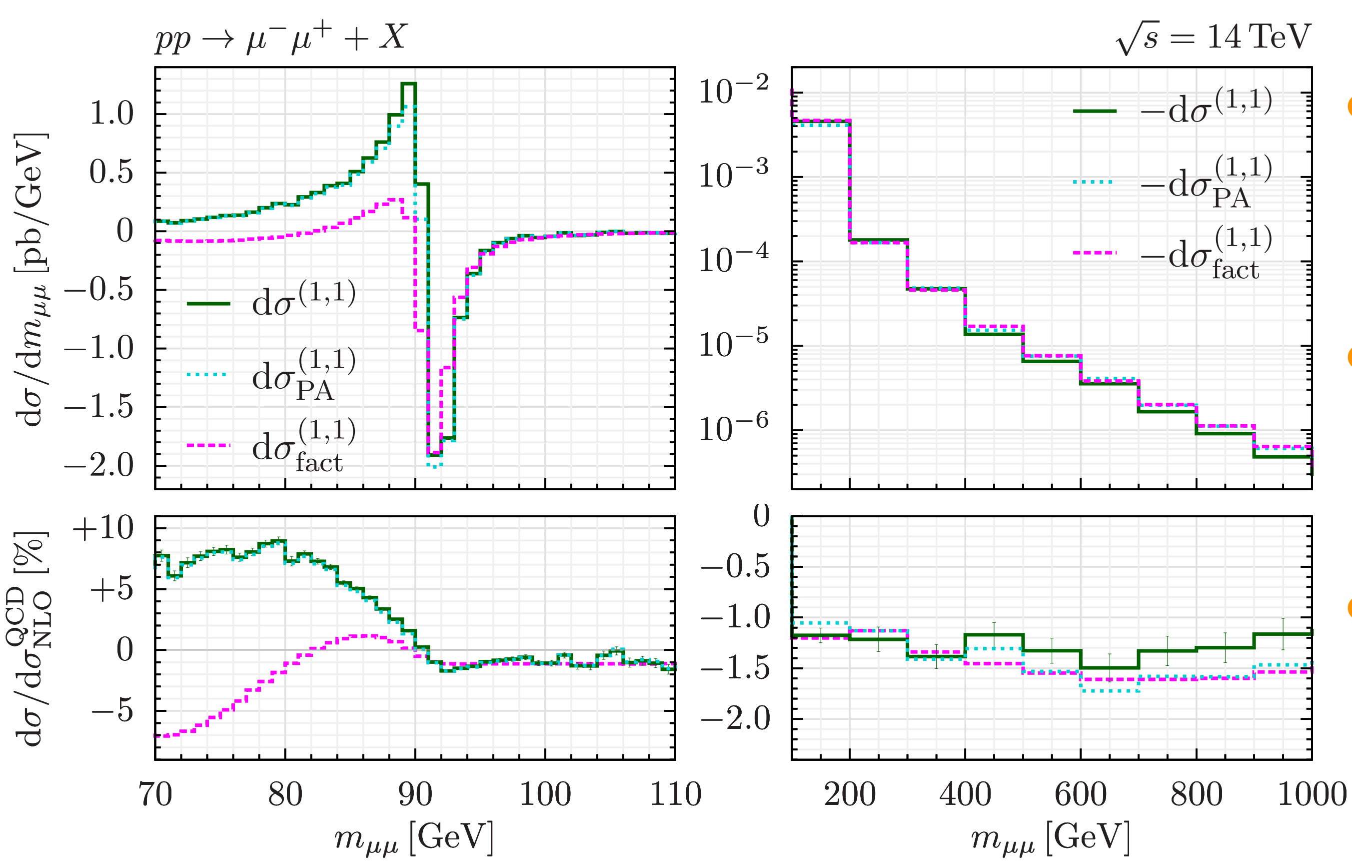
Mixed QCD-EW corrections to NC Drell-Yan

Mixed Strong-Electroweak Corrections to the Drell-Yan Process

Roberto Bonciani[1,*] Luca Buonocore[2,†] Massimiliano Grazzini[2,‡] Stefan Kallweit[3,§]
Narayan Rana[4,‖] Francesco Tramontano[5,¶] and Alessandro Vicini[4,**]

2106.11953

- First computation of $NNLO_2$ (with massive leptons)
  - Amplitues computed with semi-analytical approach
  - IR Subtraction with Matrix Grazzini et al, 1711.06631
- Comparison with pole approx and naive factorisation of K-factors



- Peak region: excellent agreement with PA. Very large effects due to radiation. Naive factorisation fails
- Large inv.mass: O(0.5%) difference wrt PA and naive fact, due to genuinely non-factorisable contributions
- $NNLO_2$ corrections at the 1% level in the large inv.mass region

Mixed QCD-EW corrections at large invariant mass

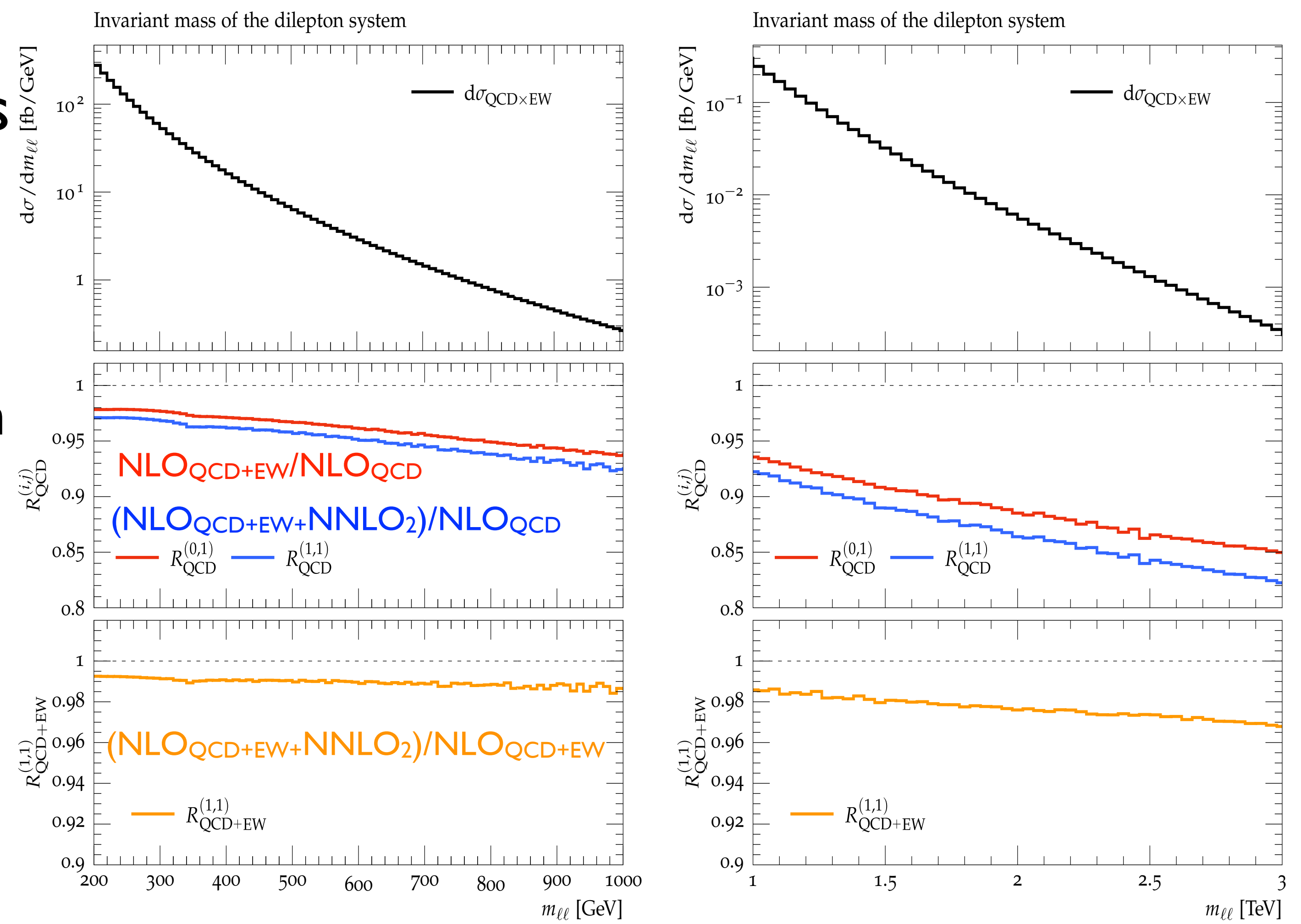
- Two-loop amplitudes computed in 2020, without widths
  Heller et al, 2012.05918
- IR subtraction with nested soft-collinear scheme
  Caola et al, 1702.01352
- Computation with massless leptons (recombination needed)

Mixed QCD-electroweak corrections to dilepton production at the LHC in the high invariant mass region

Federico Buccioni,[a] Fabrizio Caola,[a,b] Herschel A. Chawdhry,[a] Federica Devoto,[a] Matthias Heller,[c] Andreas von Manteuffel,[d] Kirill Melnikov,[e] Raoul Röntsch[f] and Chiara Signorile-Signorile[e,g]

2203.11237

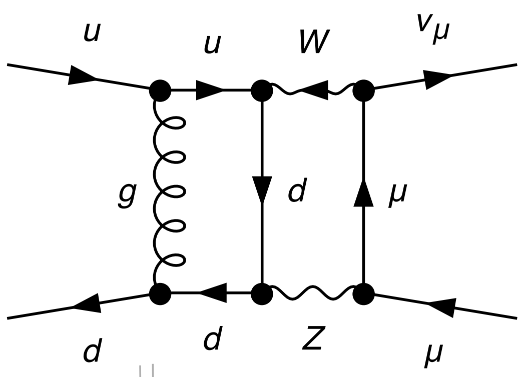
- $NNLO_2$ corrections at the 1% level wrt NLO_{QCD+EW} in the large inv.mass region (up to 1 TeV)
- Growth with invariant mass due to Sudakov effects, up to 3% at 3 TeV
- Surprisingly large size in the TeV region wrt to power counting

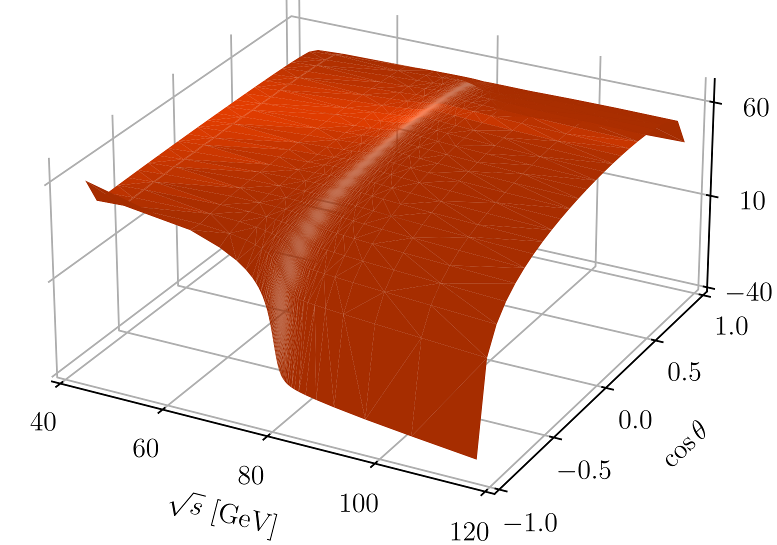


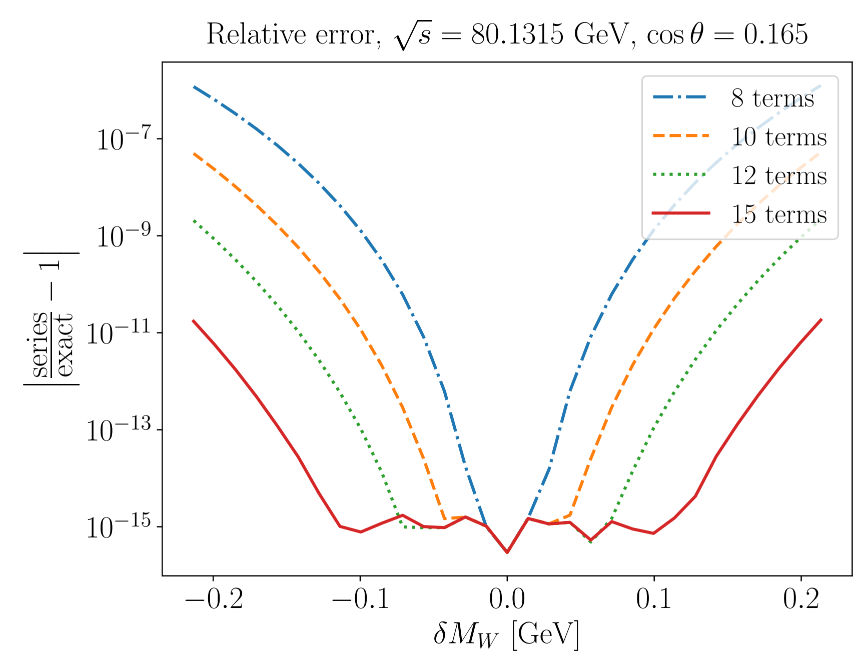
From NC to CC

Armadillo, Bonciani, Devoto, Rana, Vicini, 2405.00612

- The CC case requires new topologies wrt the NC one
  - Most complicated: double-box, with 2 different internal masses
  - Solved by in-house package for differential equations, based on LiteRed and SeaSyde (series expansion wrt invariants)
  - Boundary condition evaluated with AMFlow
  - Checked that the result matches the equal-masses topology
  - Complex-mass scheme and lepton mass≠0
- Results available as a grid, including full dependence on W mass







LiteRed: Lee, 1310.1145; **AMFlow**: Liu et al, 2201.11669; **SeaSyde**: Armadillo et al, 2205.03345

Resummation of QED effects

Buonocore, Rottoli, Torrielli, 2404.15112

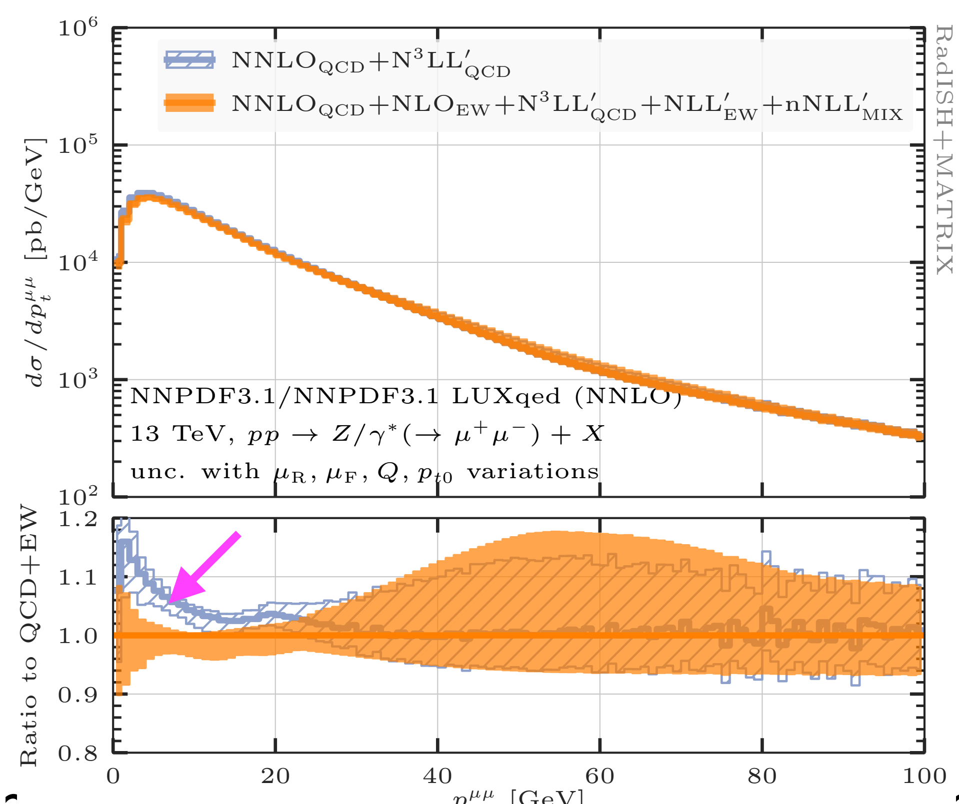
- Soft QED and mixed effects added on top of QCD ones, within the Radish framework Monni et al, 1604.02191
- QED soft effects due to correlations with final-state leptons included
  - See also earlier work with stable W/Z Autieri et al, 2302.05403

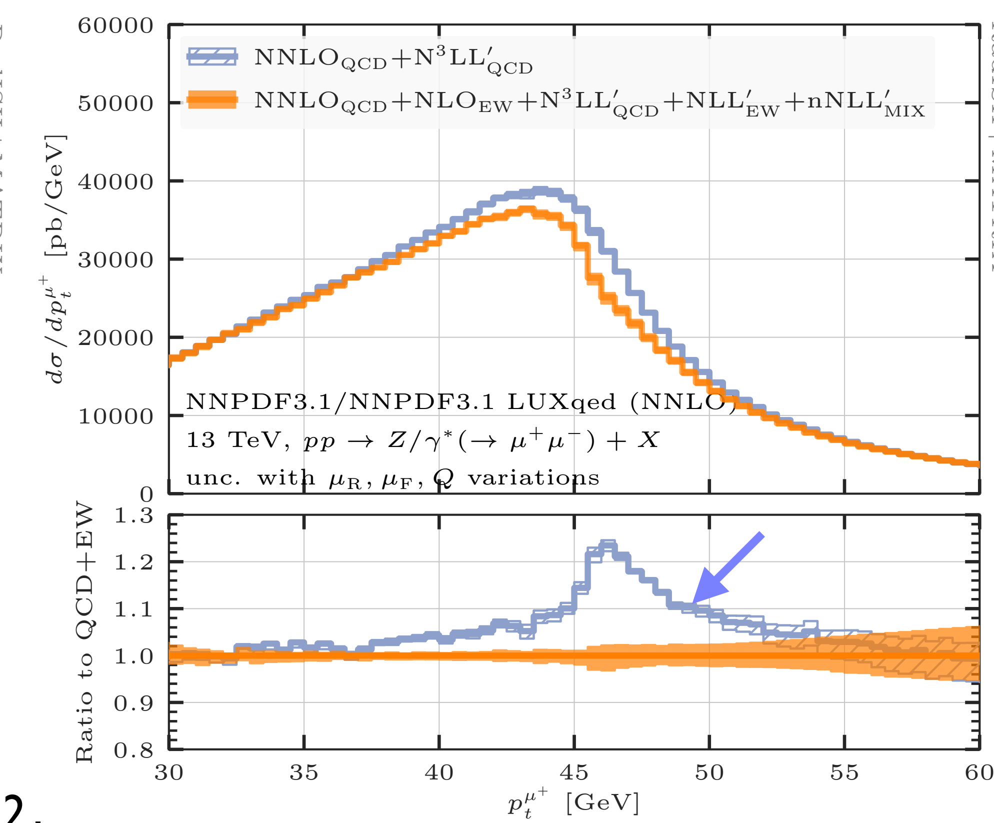
N³LL' QCD NLL' MIX $\alpha_s^m \alpha^n L^{m+n}$

$$R(k_{t1}) = \Big[R(k_{t1})\Big]_{\text{eq. (2.4)}} + R^{\text{QED}}(k_{t1}) + R^{\text{MIX}}(k_{t1}) + \frac{\alpha_s}{2\pi}\frac{\alpha}{2\pi} B^{(1,1)} L$$

NLL' QED FORMALLY NNLL' MIX

5-10% effects at low $p_T(V)$
Th.Unc do not overlap





Very large (20%) effects on the Jacobean peak, due to QED

Part 2

Recent and planned developments for MC tools

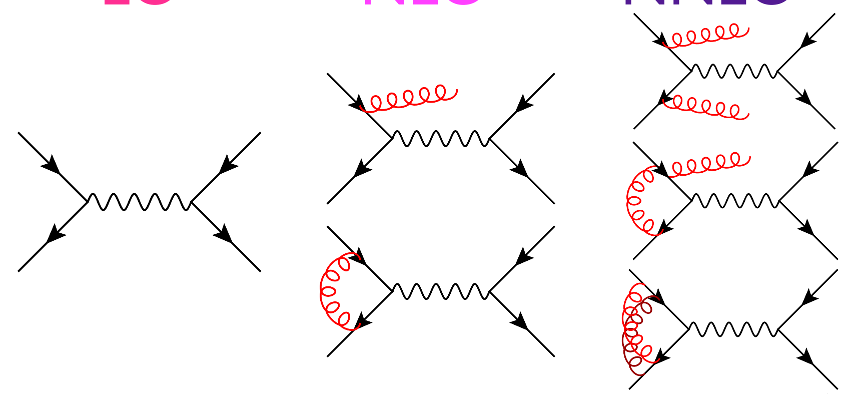
NNLO+PS predictions

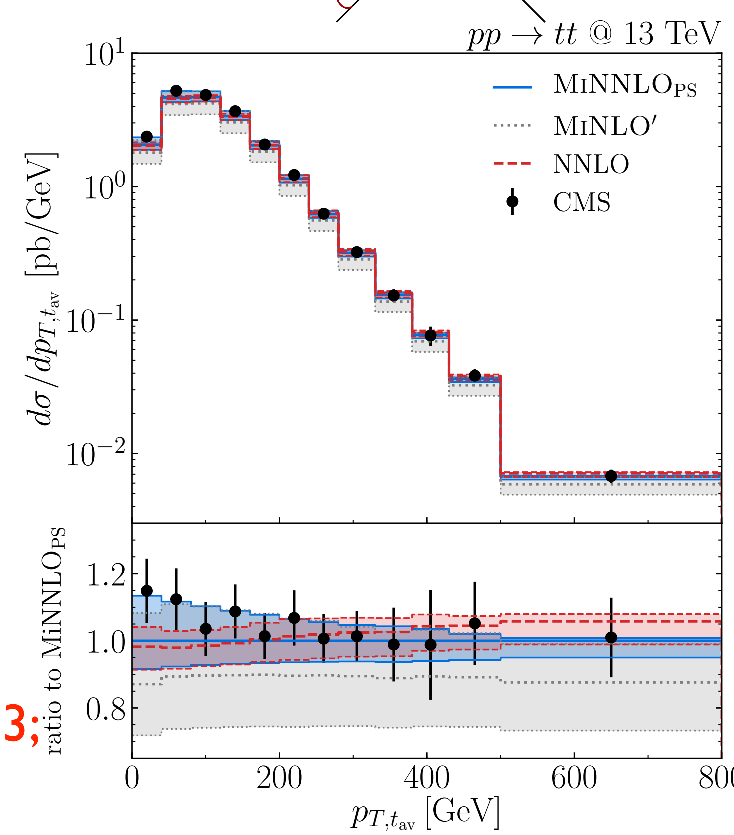
MiNNLO+PS

- NLO QCD+PS has been the golden standard for long time MG5_aMC/Sherpa/Powheg
- Going beyond NLO: NNLO
  - NNLO+PS relies on rather mature technology (MiNNLOPS)
    Monni et al, 1908.06987
  - All currently-available NNLO QCD computation can (in principle) be included into a NNLO+PS generator
  - Implementation is still process-dependent, and mostly done by hand
    bbH: Biello et al, 2402.04025; b prod: Mazzitelli et al, 2302.01645; WZ (+EW) Lindert et al, 2208.12660; ZH (SMEFT): Haisch et al, 2204.00663; top: Mazzitelli et al, 2112.12135, …

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

LO NLO NNLO

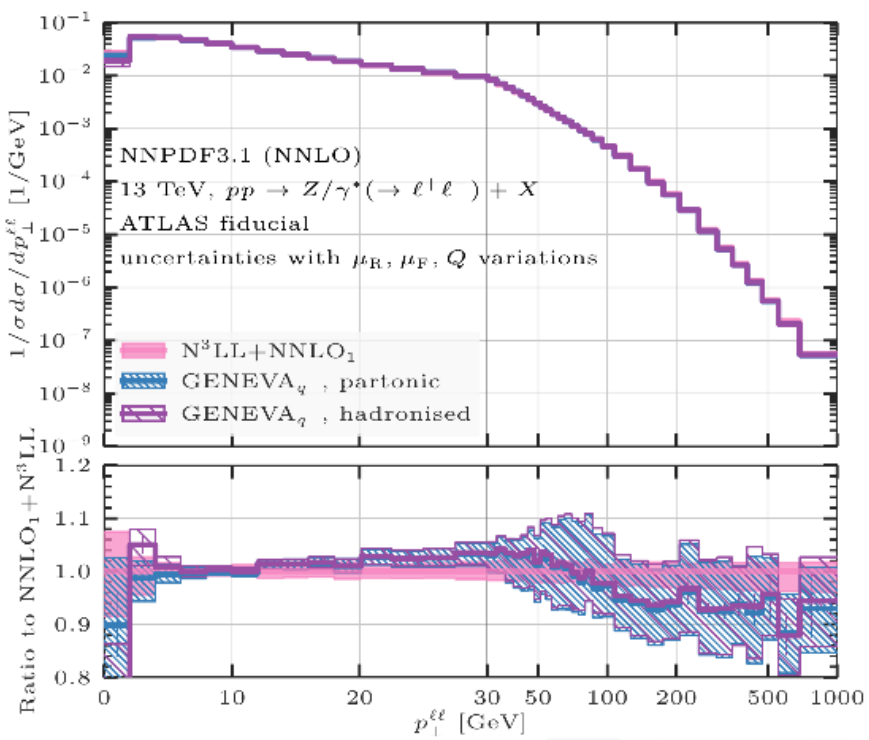


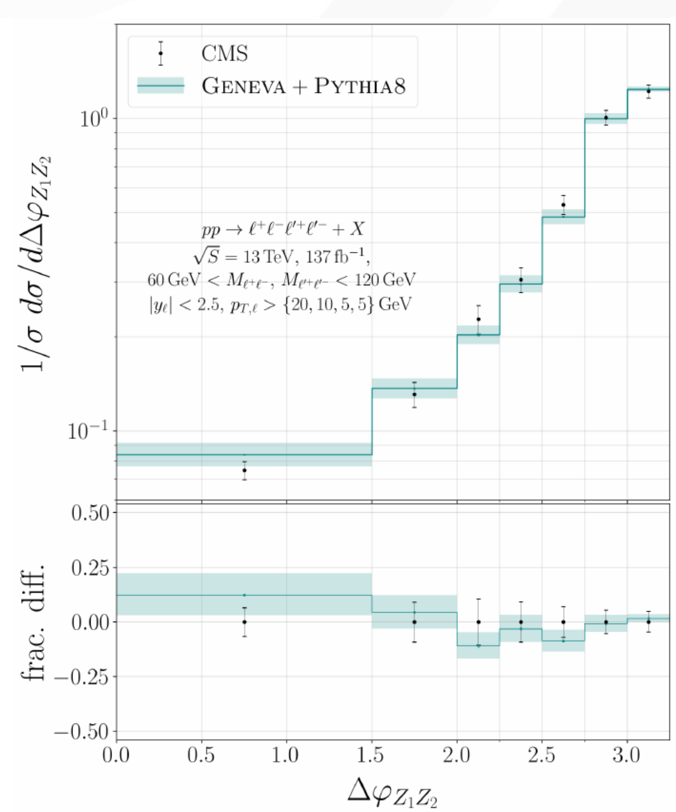


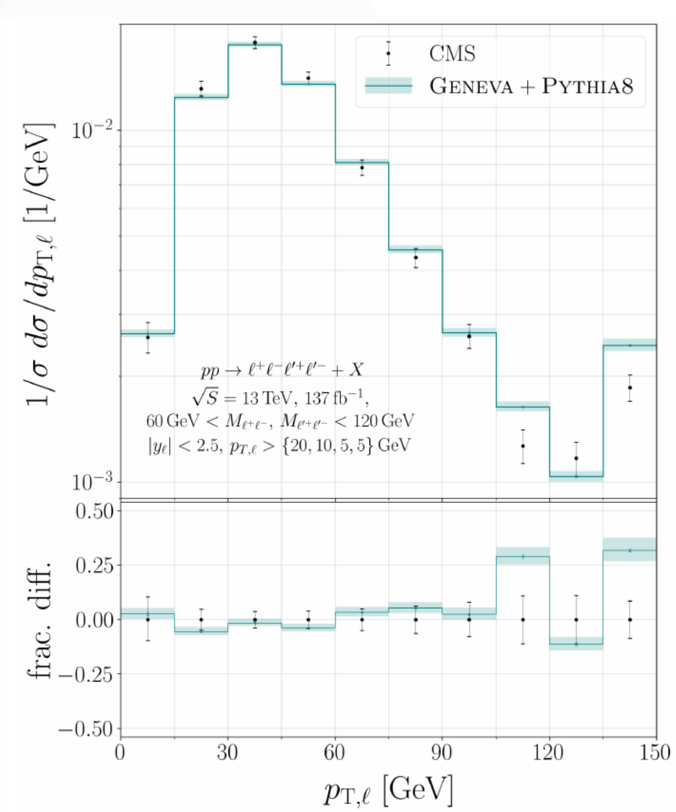
Mazzitelli et al, 2012.14267

NNLO+PS in Geneva

- The Geneva method combines NNLO+PS with N-jettiness resummation at NNLL’ Alioli et al, 1211.7049
- Implemented and validated for several color-singlet processes





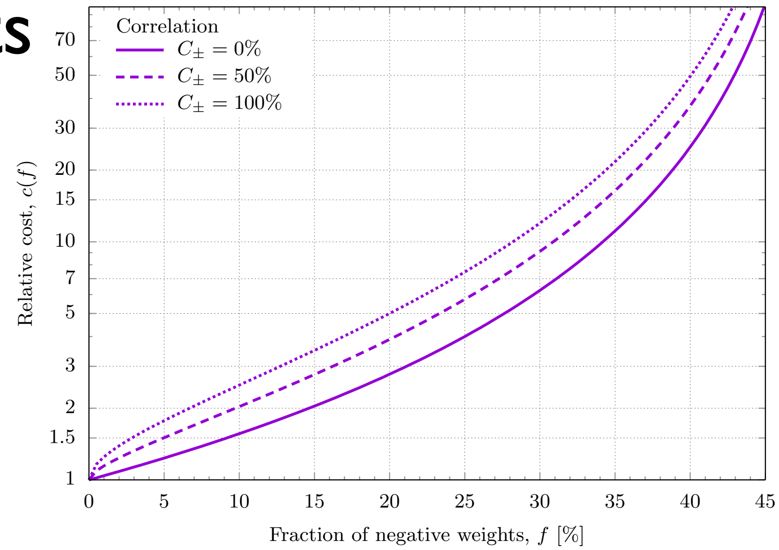


- New developments:
  - Resumming second jet resolution at NLL’
  - Extension towards color-singlet+jet processes WIP

Reduction of negative weights in MC@NLO-type matching

Reduction of negative weights in MC@NLO-type matching

- MC@NLO-matched MCs affected by negative weights
  - Reduce the statistical quality of the event sample
  - More events need to be generated than with positive-only events
- Recent progress both in Sherpa and MG5_aMC:
  - MG5_aMC: modify the matching by a term which improves the IR behaviour of the MC counterterms Frederix et al, 2002.12716
    Alternatively, spread the Born over the radiative PS in order to compensate for over-cancelation of local CTs or negative virtuals Frederix, Torrielli, 2310.04160
  - Sherpa: use leading-colour approximation+move K-factor to low-mult. processes in merged samples Danzinger et al, 2110.15211
- Other approaches (MC-agnostic):
  - Positive resampler: resample cross section to eliminate negative weights Andersen et al, 2005.09375

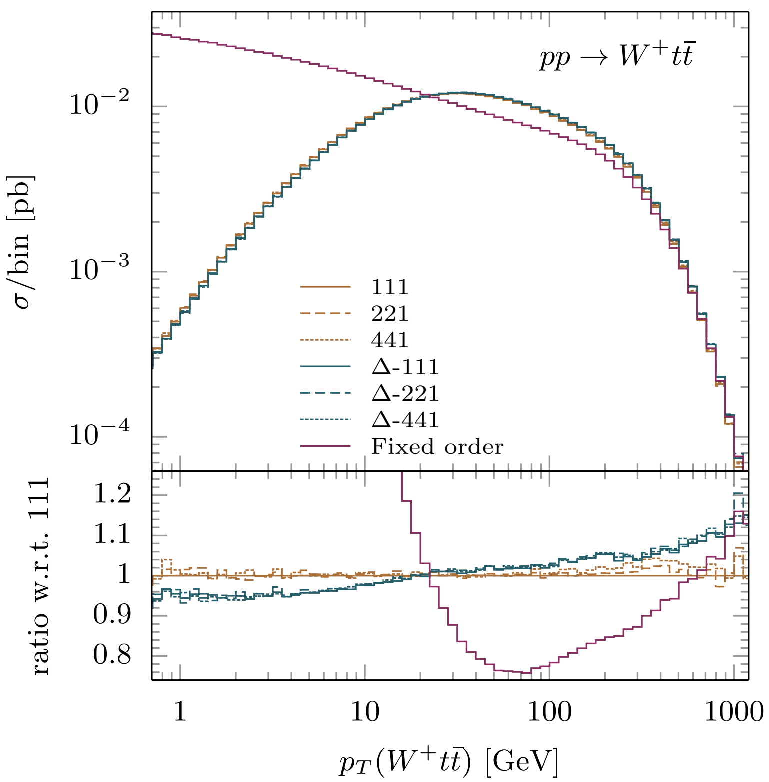


2002.12716

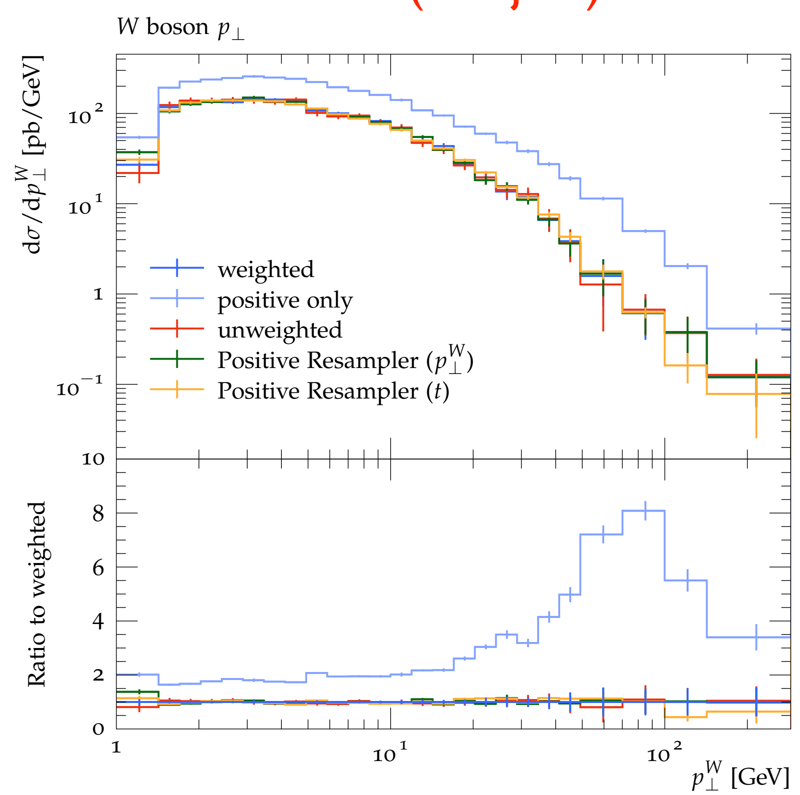
	MC@NLO	MC@NLO-Δ
$pp \to e^+e^-$	3.5% (1.2)	2.4% (1.1)
$pp \to e^+\nu_e$	3.8% (1.2)	2.5% (1.1)
$pp \to H$	4.9% (1.2)	2.0% (1.1)
$pp \to Hb\bar{b}$	38.4% (19)	32.6% (8.2)
$pp \to W^+j$	16.5% (2.2)	7.9% (1.4)
$pp \to W^+t\bar{t}$	15.2% (2.1)	11.9% (1.7)
$pp \to t\bar{t}$	20.2% (2.8)	9.3% (1.5)

Results

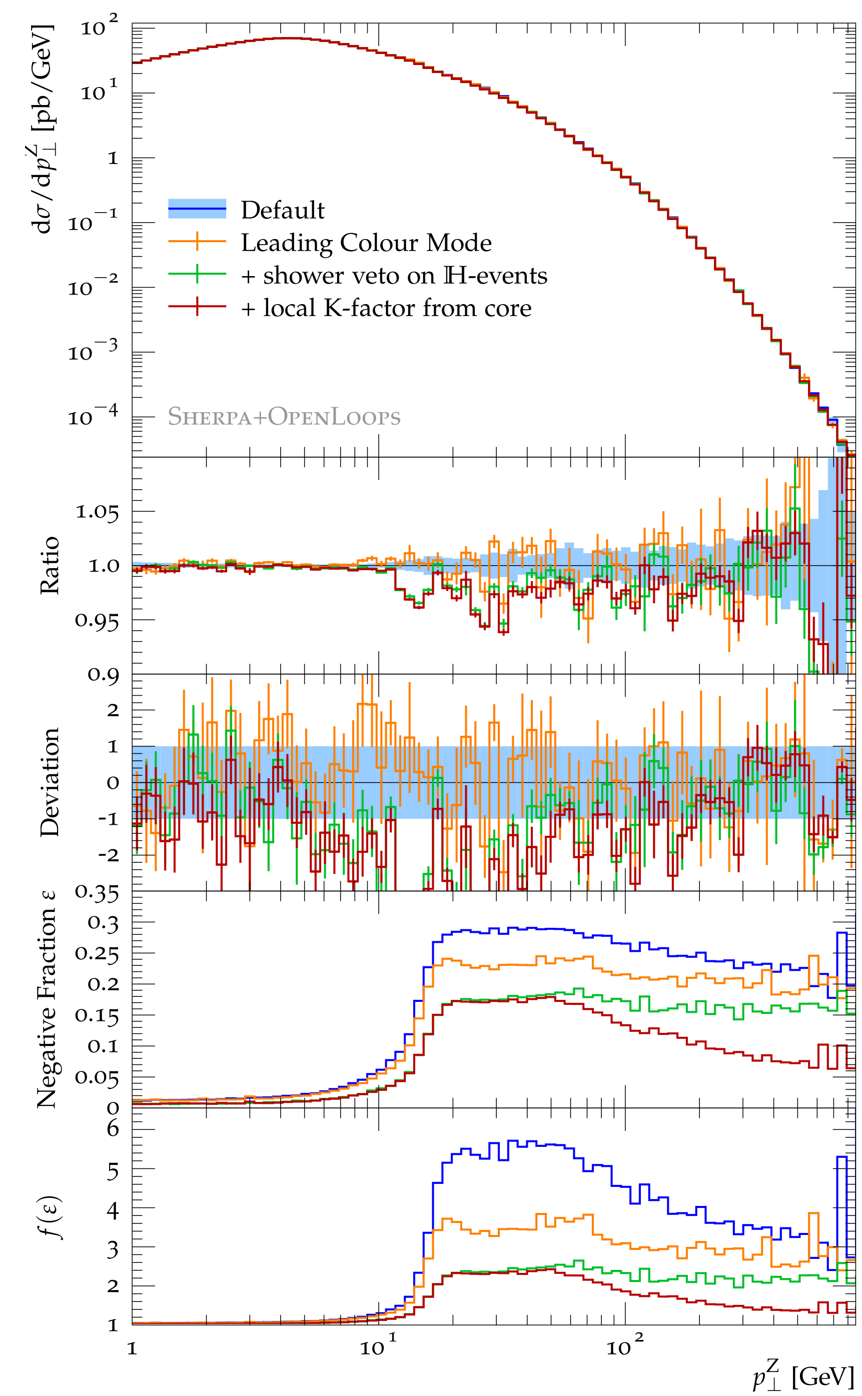
2002.12716 (ttW)



2005.09375 (W+jets)



2110.15211 (Z+jets)



- Take home message: differences due to new matching/resampling are generally small (5%), with some exceptions
- Reduction of neg. weights may entail some extra cost (ie slower code) at event generation, which is (over)compensated with full sim.

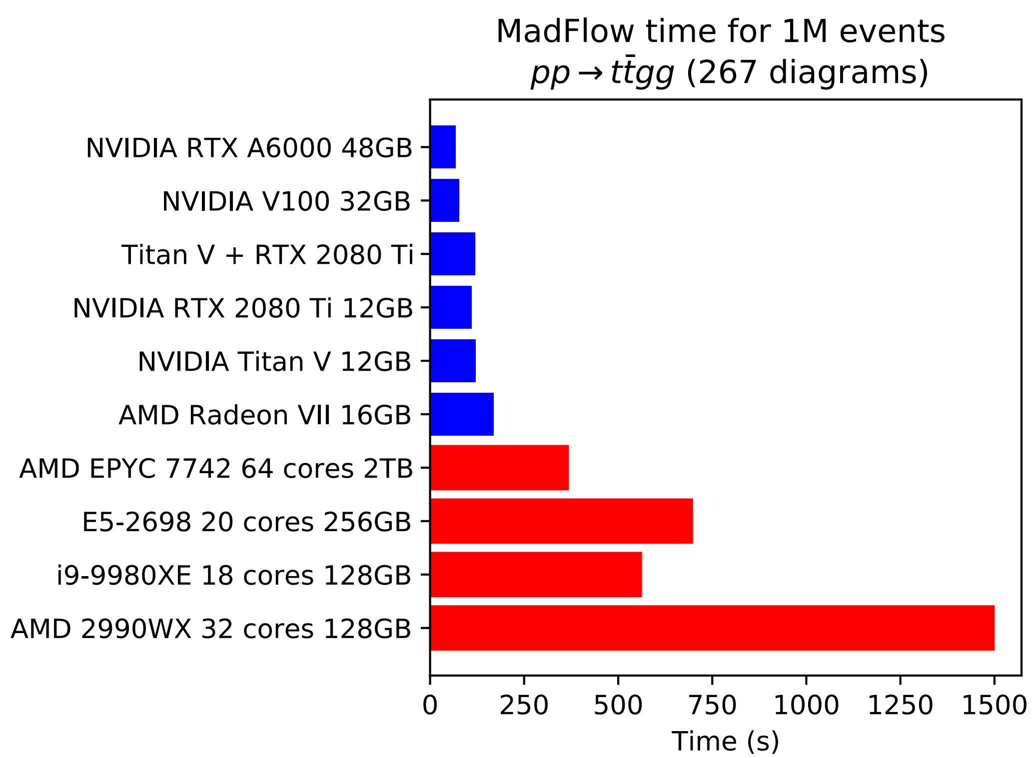
Towards the usage of GPUs and AI in the MG5_aMC framework

Improving computing performances

- Computing demand requires more efficient and smarter handling of resources
- On one side, move away from multi-threading in favour of multiprocessing (SIMD/OpenMP), suitable for GPUs
  - This requires rewriting and rethinking our (old) codes
- On the other, benefit from AI to improve some specific aspects (integration/event-gen./…)
- See also:
  "Event Generators for High-Energy Physics Experiments", 2203.11110
  "Machine learning and LHC event generation", 2203.07460
  "Challenges in Monte Carlo event generator software for High-Luminosity LHC", 2004.13687

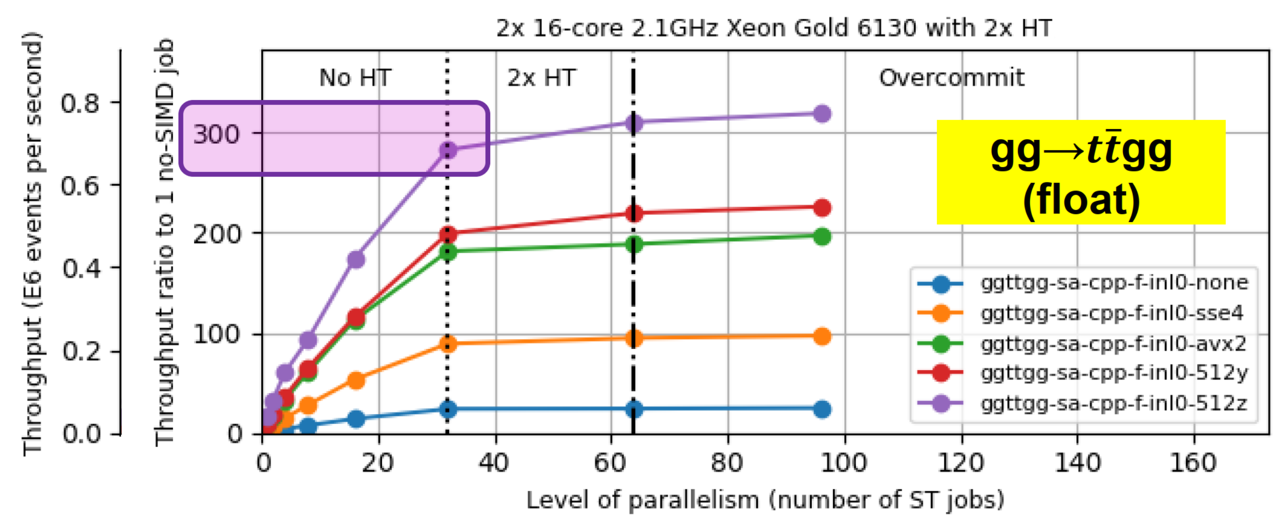
Towards MG5_aMC on GPU

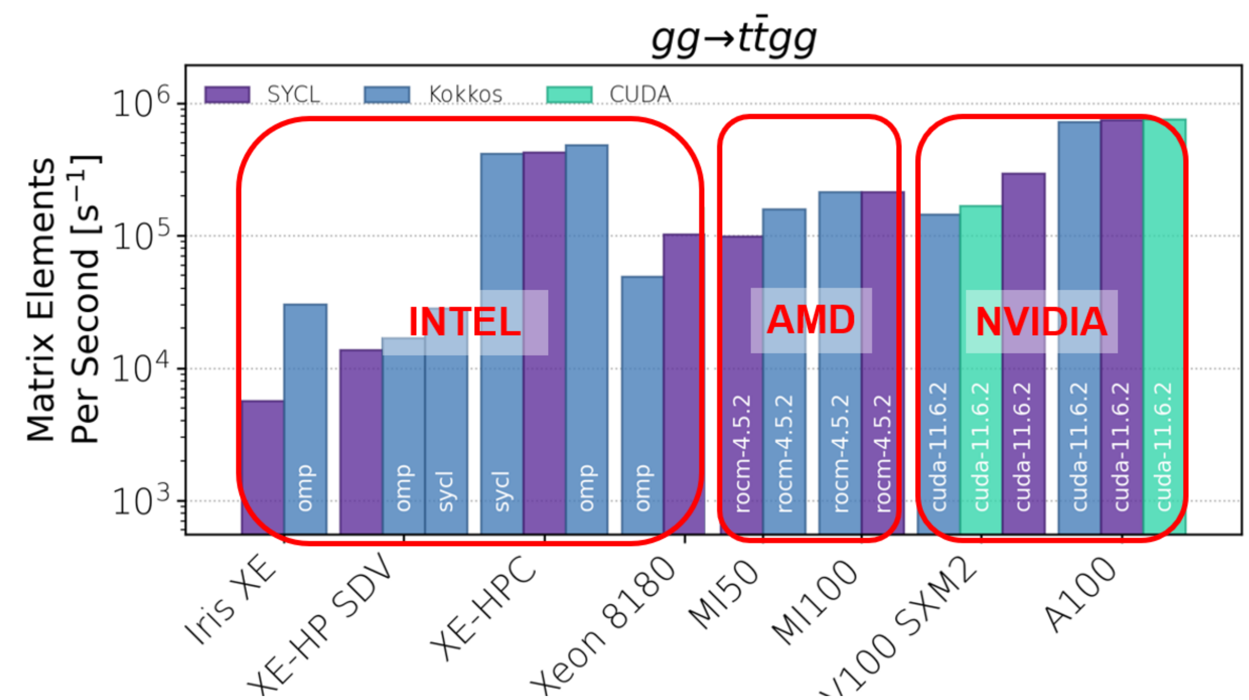
MadFlow:
Carrazza, Cruz-Martinez, Rossi, MZ, 2106.10279



Process	MadFlow CPU	MadFlow GPU	MG5_aMC
$gg \to t\bar{t}$	9.86 μs	1.56 μs	20.21 μs
$pp \to t\bar{t}$	14.99 μs	2.20 μs	45.74 μs
$pp \to t\bar{t}g$	57.84 μs	7.54 μs	93.23 μs
$pp \to t\bar{t}gg$	559.67 μs	121.05 μs	793.92 μs

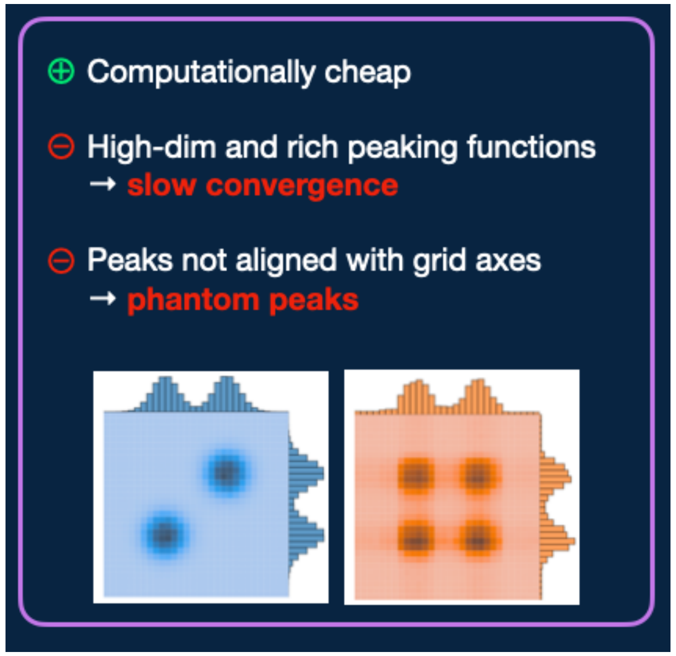
MG5onGPU:
Valassi et al, 2106.12631, 2303.18244, 2312.02898

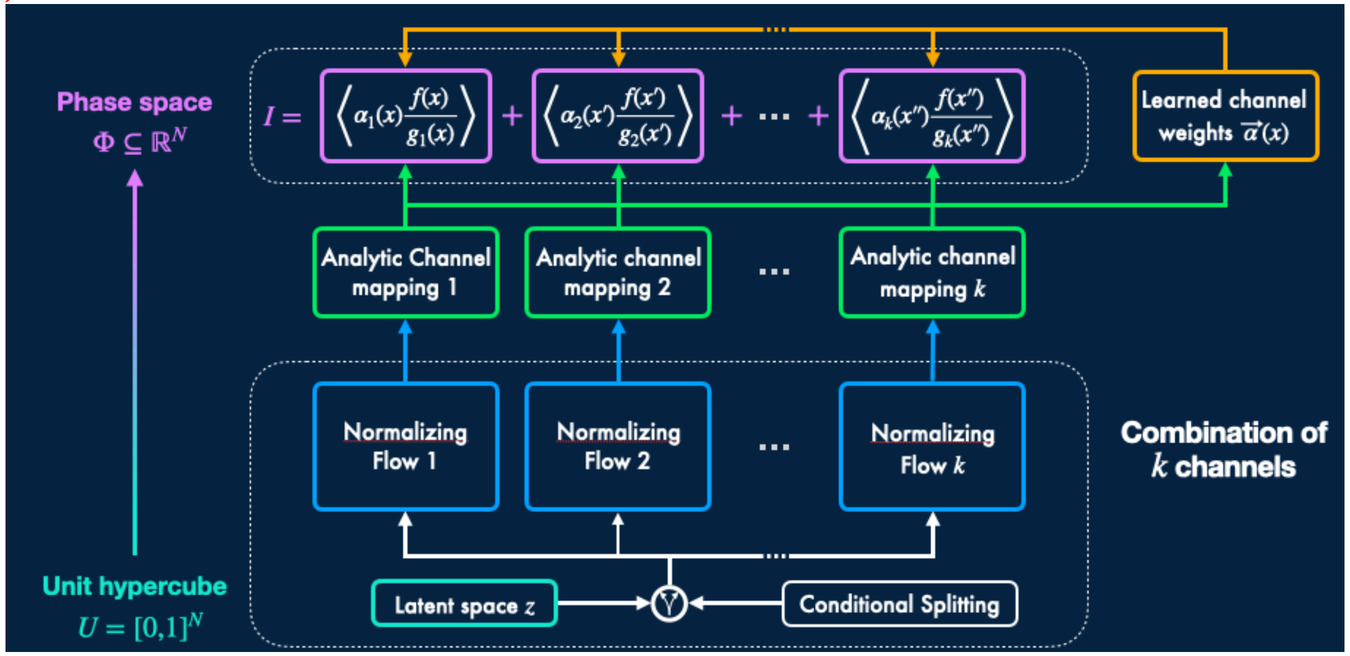




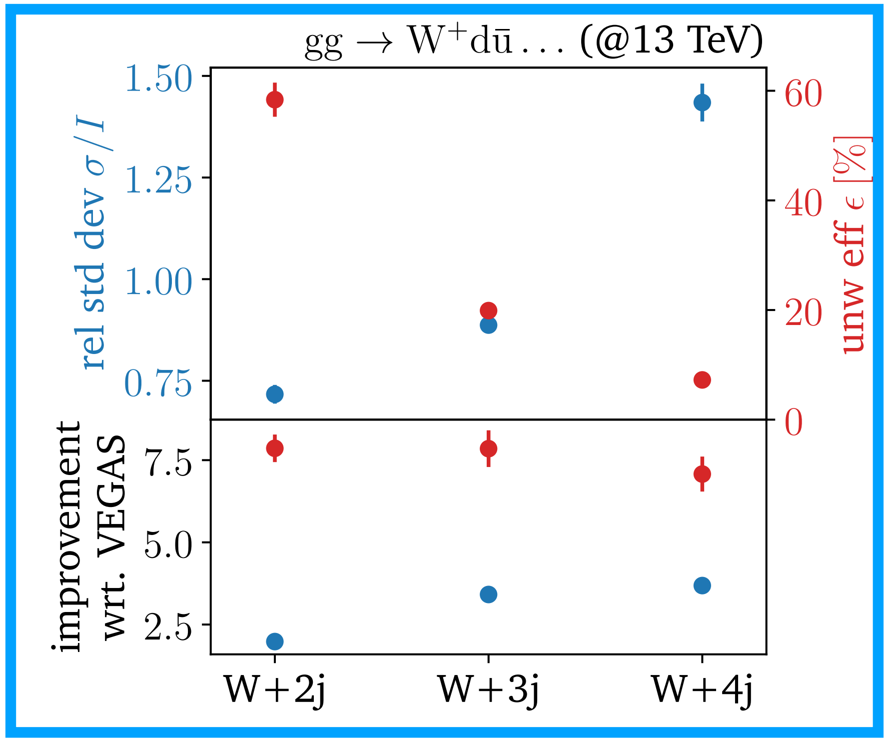
Using NN's for importance sampling: MadNIS

Hiemel et al,2212.06172 &2311.01548





- Use NN to overcome some limitations of VEGAS
- Do not reinvent the wheel:
  - Pre-training with VEGAS (fast) used as starting point of normalizing-flow
  - Use NF on top of known analytical mappings
  - NF adjust the weight of each channel
- Important improvement both on variance and on unweighting efficiency, even for large multiplicities



All figures by R.Winterhalder

Conclusions

Part I

- EW corrections are not just 1% effects: several mechanisms can enhance them:
  - Kinematics, couplings (e.g. Yukawa), radiative return, EWSL
- EW corrections are moving beyond NLO
  - Drell-Yan corrections available for $NNLO_2$, both NC and CC
  - Resummation available both for soft γs (jointly with QCD) and for EWSLs
- Still, we miss a general procedure for PS matching at NLO
  - EWSL approximation +PS seems a good compromise
  - But the validity of EWSL approximation (both in principle and in practice) should always be checked
- Lot of progress also beyond LHC physics (e^+e^-/ $\mu^+\mu^-$colliders, g-2) not covered in this talk

Conclusions

Part 2

- Understanding and improving MC tools is crucial for a proper and efficient collaboration between theory and experiments
- Lot of recent activity, only a glimpse of it in these slides
  - Inclusion of higher orders beyond NLO QCD
  - Reduction of negative weights leads to reduction in needed n of events. Some methods already implemented in public tools
  - Faster simulations can profit of modern hardwares (GPUs) and of AI for integration/event generation. At the moment most WIP, but stay tuned!