MadGraph5_aMC@NLO for e^+e^- collisions

Marco Zaro, Milan U. & INFN

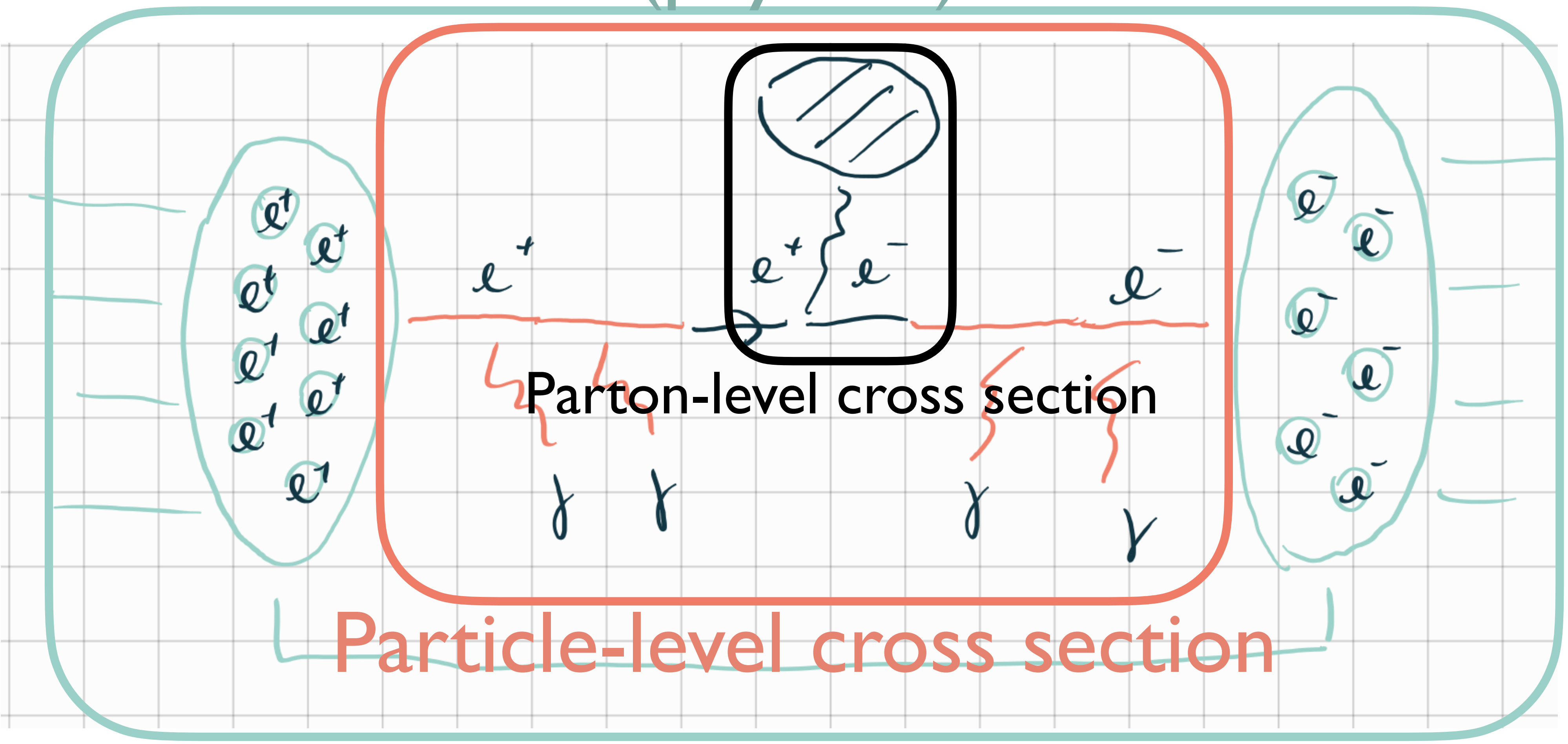
Lepton collisions

(In a collinear-factiorisation inspired picture)

$$d\Sigma_{e^+e^-}(P_{e^+},P_{e^-}) = \sum_{kl}\int dy_+ dy_-\, \mathcal{B}_{kl}(y_+,y_-)\, d\sigma_{kl}(y_+P_{e^+},y_-P_{e^-})$$

$$d\sigma_{kl}(p_k,p_l) = \sum_{ij}\int dz_+ dz_+\, \Gamma_{i/k}(z_+,\mu,m)\,\Gamma_{j/l}(z_-,\mu,m)\, d\hat{\sigma}_{ij}(z_+p_k,z_-p_l,\mu)$$

Beam-level (physical) cross section



Lepton collisions

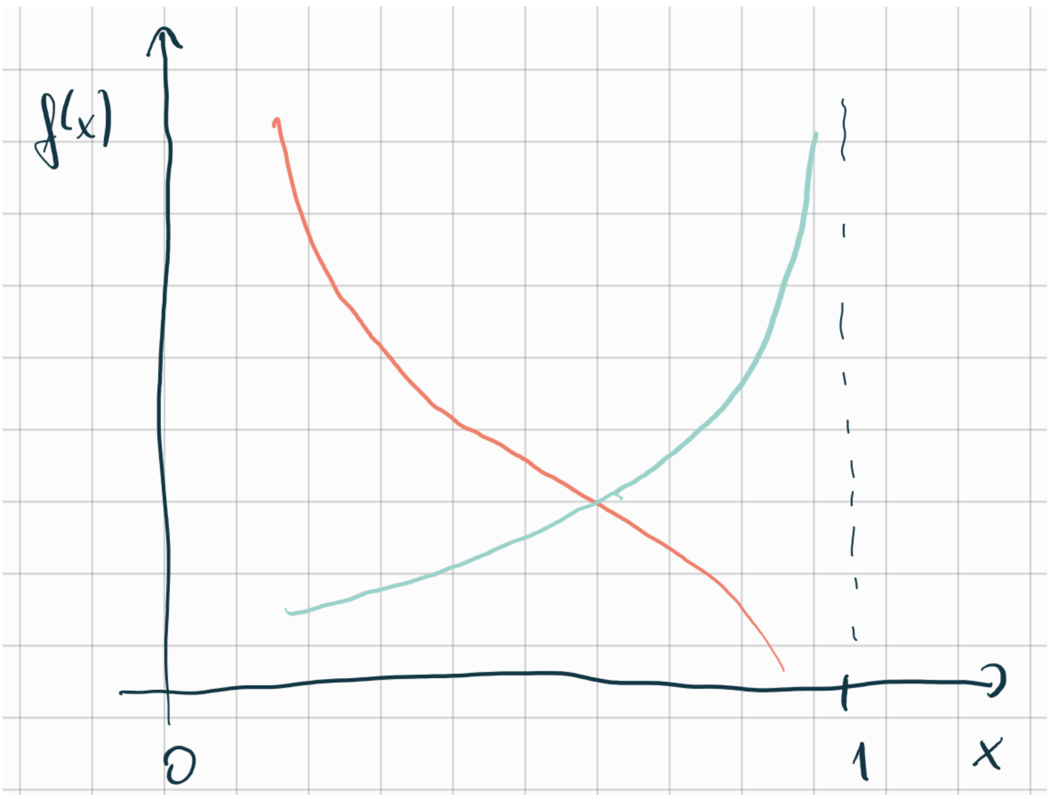
- **Beam-beam interactions** (aka beamstrahlung) are machine-dependent collective effects. Can be fitted with ad-hoc tools (e.g. GuineaPig, Circe, …). Less important for circular colliders than for linear ones
- **ISR** is universal (like hadronic PDFs), and can be computed perturbatively (*un*like hadronic PDFs)
- The **partonic cross section** is the usual one. Because of the form of PDFs, needs new phase-space and momentum mappings

ISR (at LL)

GRIBOV V. N. and LIPATOV L. N.
Sow. J . Nucl. Phys., 15 (1972) 438

$$D_{\rm GL}(x,Q^2)=\frac{\exp\left[(1/2)\eta(3/4-\gamma_{\rm E})\right]}{\Gamma(1+(1/2)\eta)}\,\frac{1}{2}\eta(1-x)^{(1/2)\eta-1}\simeq\frac{1}{(1-x)^{1-\eta/2}}$$

$$\left(\eta=\frac{2\alpha}{\pi}\log\frac{Q^2}{m^2}\right)$$ ~0.05 for Q=100 GeV



- **Hadronic PDFs** vanish at large x (divergence at small-x avoided by cuts)
- **Leptonic PDFs** diverge (but are integrable) at large x
- While leptonic PDFs have been substantially improved since 1972, the asymptotic behaviour is unchanged
- A different phase space mapping is required wrt pp collisions

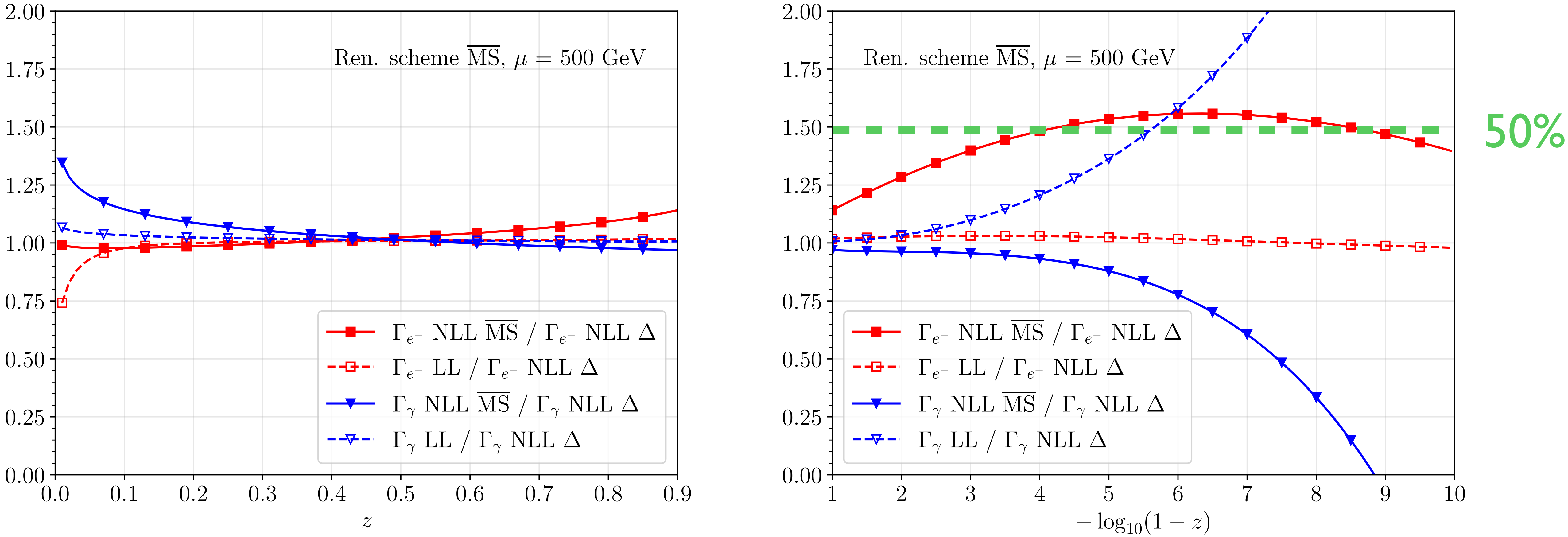
ISR
State of the art

- Recently, the ISR structure function was obtained at NLL accuracy[1]. This required the NLO initial conditions[2]
- A new factorisation scheme (alternative to MSbar) has been proposed (Δ-scheme)[3], which improves the behaviour of the evolved PDF at large x
- PDFs available with α in three ren. scheme: G_μ, $\alpha(m_Z)$, MSbar (with proper treatment of all thresholds)[4]. All available within eMELA[5]
- Photon and e^+-in-e^- densities available as well

1 Bertone, Cacciari, Frixione, Stagnitto, 1911.12040
2 Frixione 1909.03886
3 Frixione 2105.06688
4 Bertone, Cacciari, Frixione, Stagnitto, MZ, Zhao 2207.03265
5 https://github.com/gstagnit/eMELA

ISR at NLL

Bertone, Cacciari, Frixione, Stagnitto, MZ, Zhao 2207.03265



- NLL-MSbar seems very different from LL, while NLL-Δ is closer
- Differences between NLL-MSbar and NLL-Δ are 10-50% at large x
- Physical cross sections (NLO-accurate) will display much smaller discrepancies

MadGraph5_aMC@NLO

[1,2] https://launchpad.net/mg5amcnlo

- MG5_aMC is an automatic event generator for any processes of the user's choice (in the SM and beyond)
- User input limited to run/model parameters, cuts, etc
- Unweighted events for PS matching can be generated at NLO QCD accuracy, possibly including multi-jet merging[3]
- NLO EW corrections can be computed as well[2], but only at fixed-order (no PS), either exactly or in the high-energy approximation[4] (Sudakov)[5a]
- In the Sudakov approximation, (the dominant part of) EW corrections can be included in NLO QCD-accurate events via reweighing[5b]
- Several other features are available
- All this works for arbitrary processes and colliders

1 Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Stelzer, Shao, Torrielli, MZ, 1405.0301
2 Frederix, Frixione, Hirschi, Pagani, Shao, MZ, 1804.10017
3 Frederix, Frixione, 1209.6215
4 Denner, Pozzorini, hep-ph/0010201, hep-ph/0104127
5a Pagani, MZ, 2110.03714; 5b +Vitos, 2309.00452

Capabilities of MG5_aMC at e^+e^- colliders:

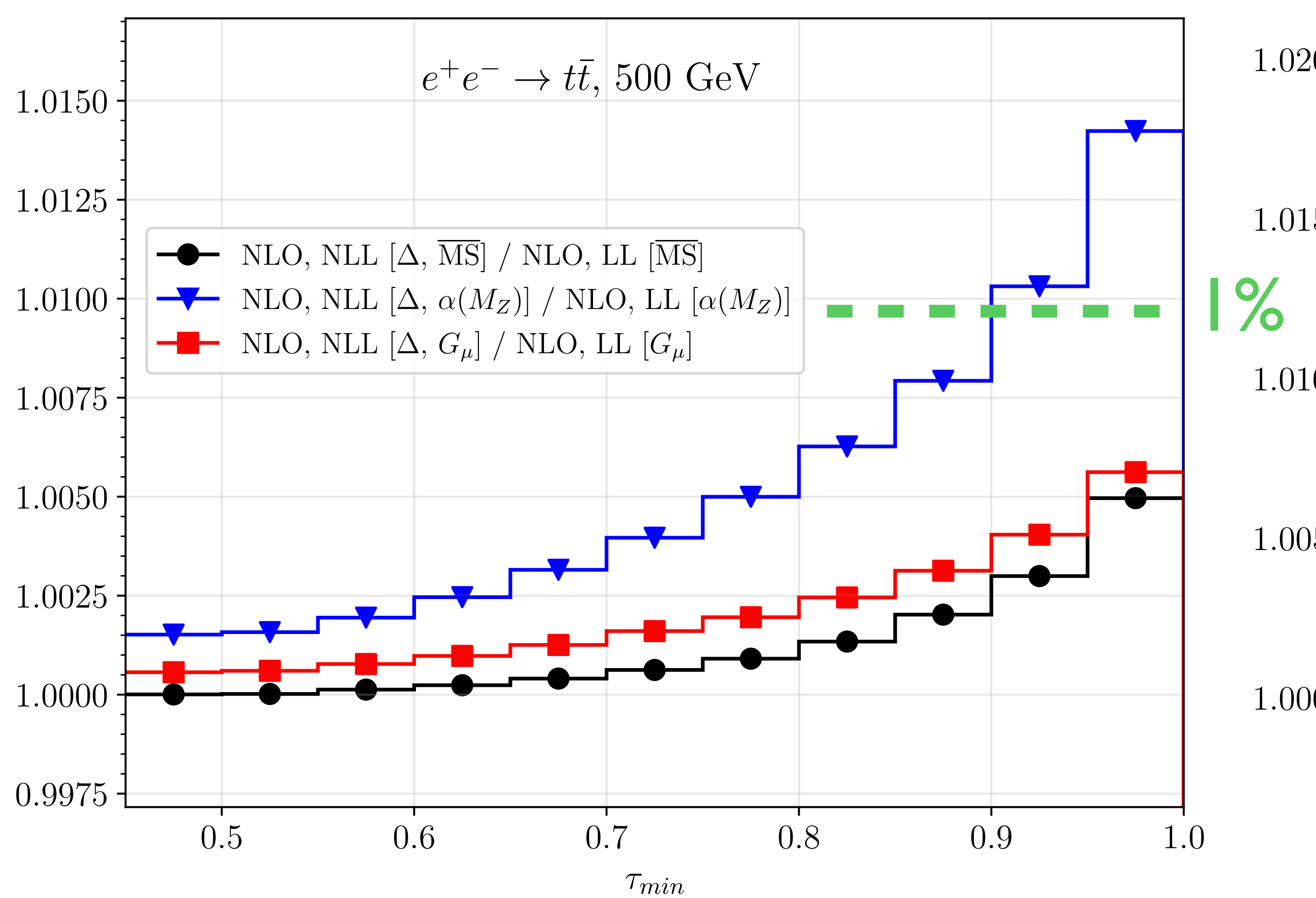
- NLO EW corrections can be included for (almost) all processes
- Through eMELA, ISR (possibly with beamstrahlung) in different ren/fact schemes can be employed
- The code automatically takes care to add to the short-distance xsection those terms necessary for consistency
  - Factorisation-scheme kernels included in the cross-section for Δ scheme and LL PDFs
  - Virtuals are corrected in order to account for different ren. scheme in model and PDFs ($\alpha(m_Z) \to$ MSbar)
- For details and how-to, see https://answers.launchpad.net/mg5amcnlo/+faq/3324

Some results:

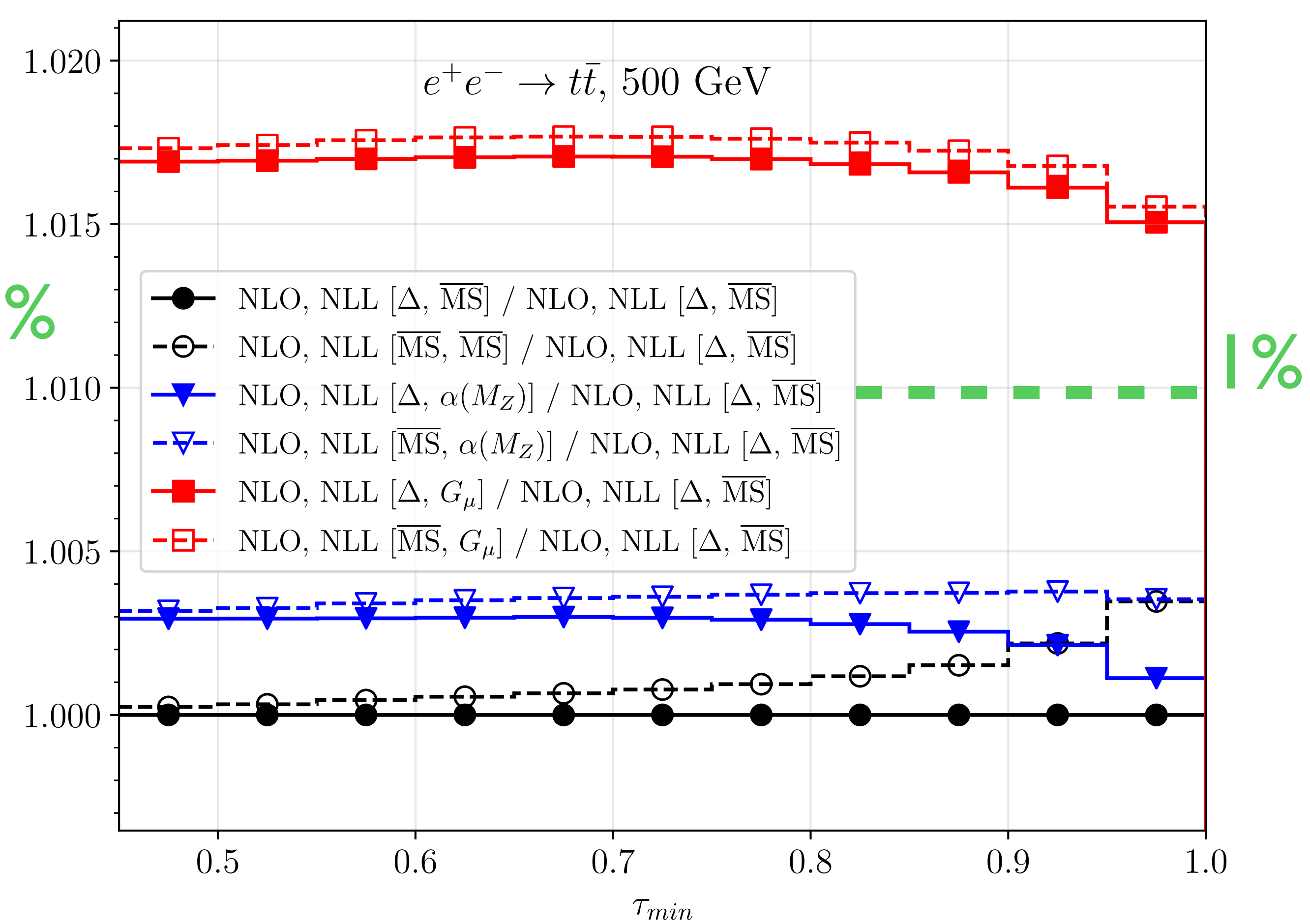
Bertone, Cacciari, Frixione, Stagnitto, MZ, Zhao 2207.03265

- $e^+e^- \to t\bar{t}$ @500 GeV; observable: $\sigma(\tau_{min}) = \int d\sigma\, \Theta\left(\tau_{min} \leq \frac{M^2_{p\bar{p}}}{s}\right)$

LL vs NLL



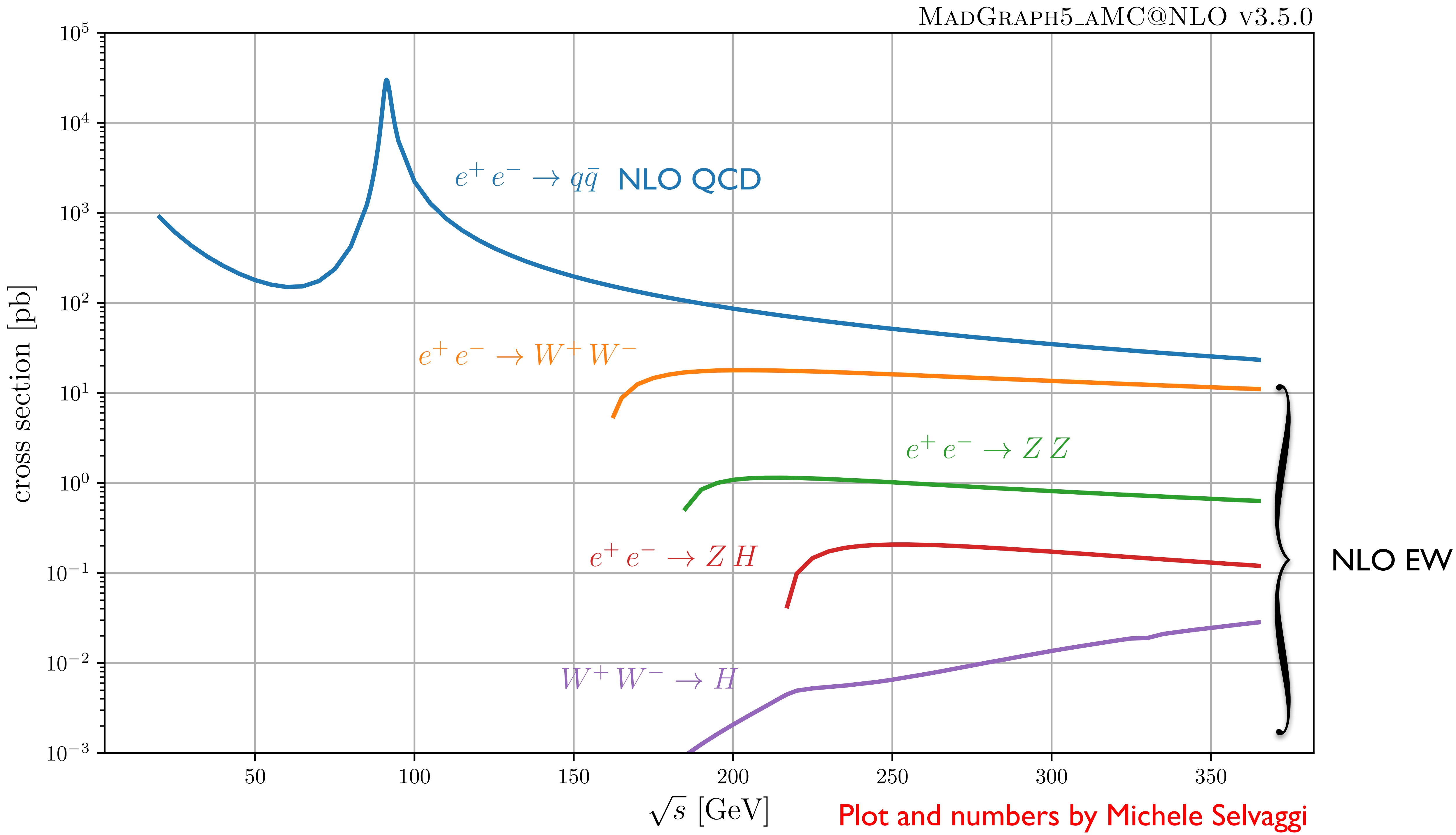
NLL different fact. schemes



- NLL-MSbar vs NLL-Δ is (at most) at the few-per-mil level

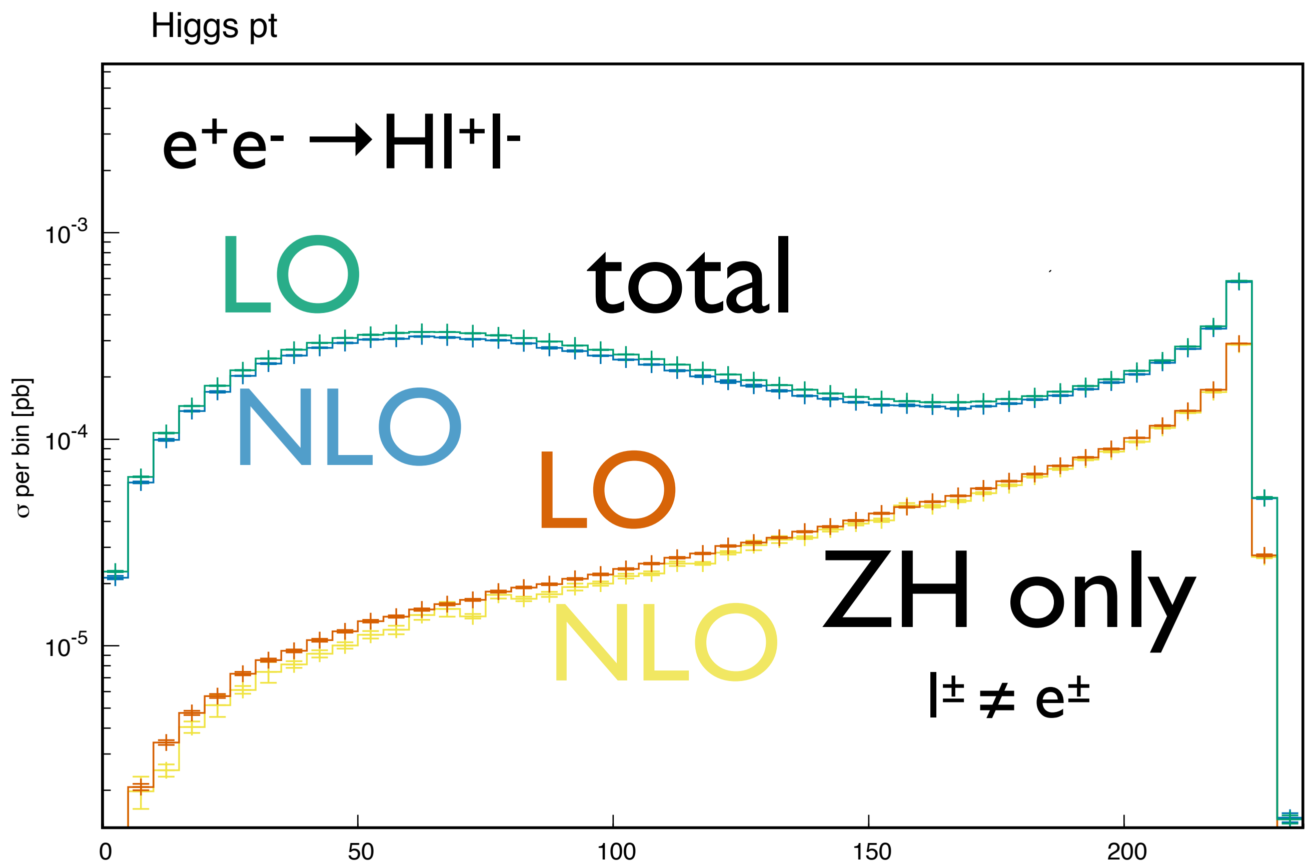
More results:

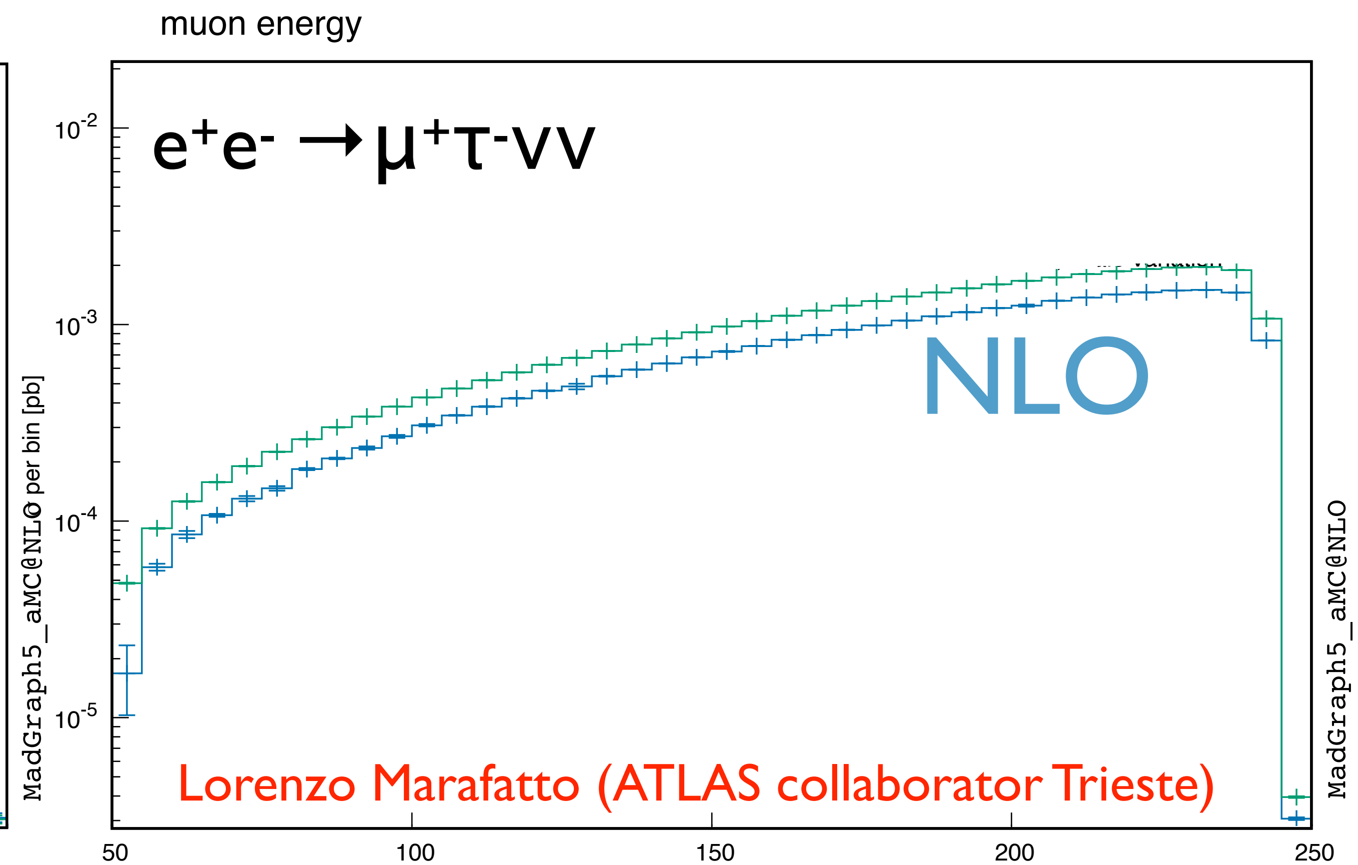
t



Plot and numbers by Michele Selvaggi

Complex-mass scheme: $e^+e^- \to Hl^+l^-$ and $e^+e^- \to \mu^+\tau^-\nu\nu$





- Qualitatively similar results to Denner, Dittmaier, Roth, Weber, hep-ph/0302198
- Results obtained in 15mins (on a cluster) @ 0.1%

Inclusive timing profile :

Overall slowest channel	0:06:15
Average channel running time	0:03:42
Aggregated total running time	8:05:57

- Very preliminary results
- Running time seems not to be an issue: for a 0.1%-accurate run:

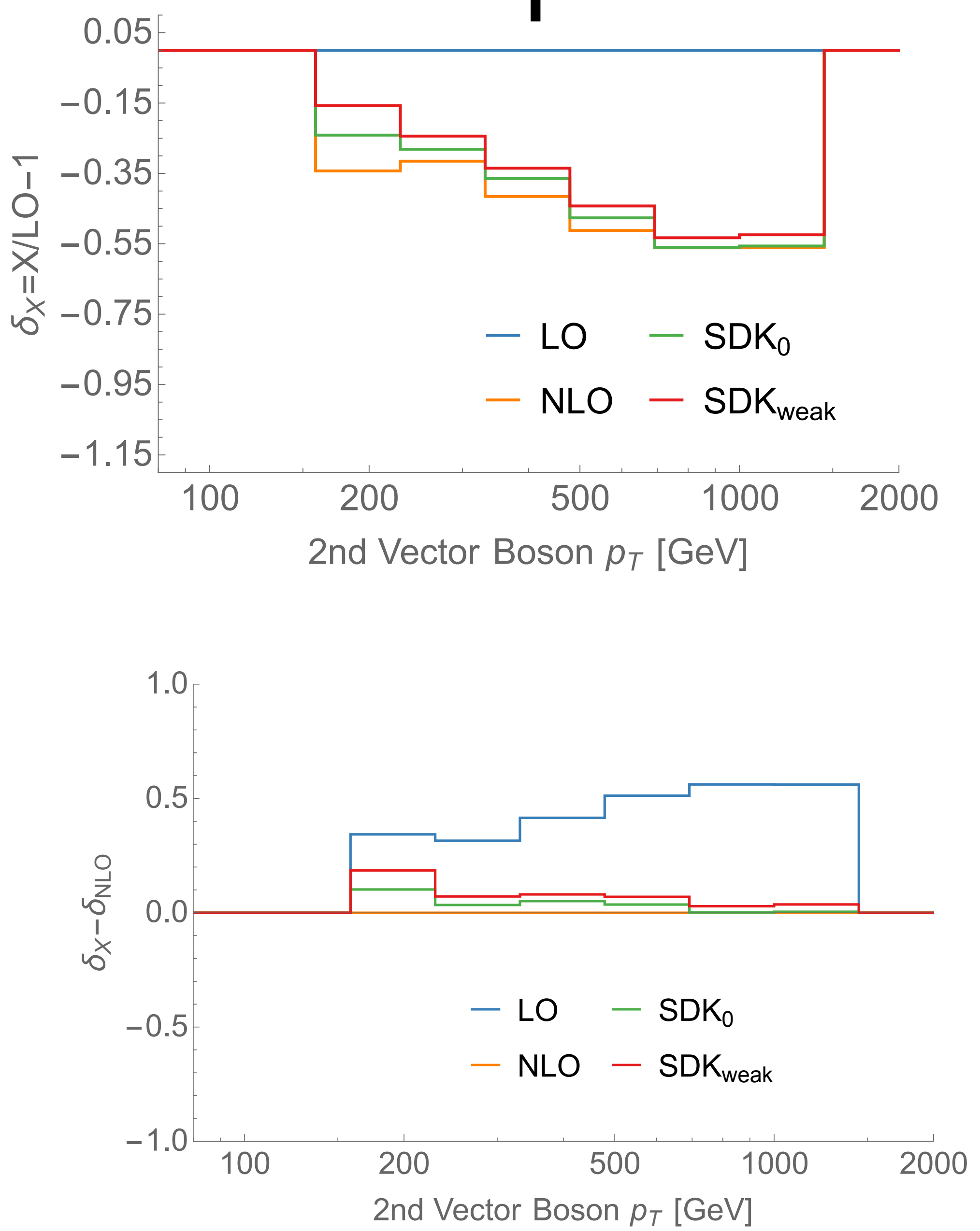
Inclusive timing profile :

Overall slowest channel	0:20:06
Average channel running time	0:13:09
Aggregated total running time	1 day, 14:34:39

EW corrections at muon colliders

WIP in collaboration with Davide Pagani, Yang Ma

3Z production @ 3 TeV



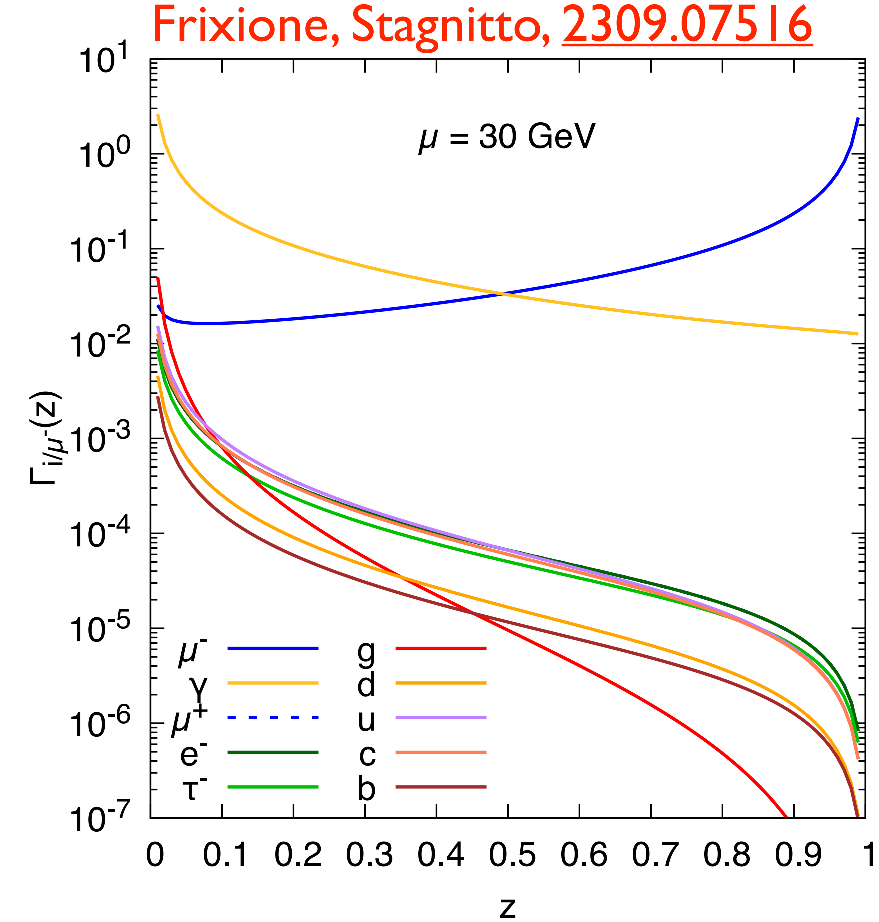
Resummation is clearly necessary.

Finite flat corrections of just a few percents from non-Sudakov effects.

(Piece of) Slide from Davide Pagani

- μ PDF obtained by LL formula, with $m_e \to m_\mu$
- EW corrections both exact and in Sudakov approx
- Very recent: LL densities with QED+QCD evolution

Frixione, Stagnitto, 2309.07516



Matching with PS: ISR at NLL?

QED Parton Shower

see for instance review in 0912.0749

It allows for exclusive photon emission in the context of collinear factorisation.

Photon energies dictated by distribution in z, whereas angles are generated independently according to the YFS formula, valid in the soft limit:

$$\cos\theta_l \propto -\sum_{i,j=1}^{N} \eta_i \eta_j \frac{1-\beta_i\beta_j\cos\theta_{ij}}{(1-\beta_i\cos\theta_{il})(1-\beta_j\cos\theta_{jl})}$$

with η_i a charge factor and β_i the speed of the emitting particle.

Algorithm adopted in $\texttt{BabaYaga}$ $[e^+e^- \to e^+e^-, e^+e^- \to \mu^+\mu^-, e^+e^- \to \gamma\gamma]$

hep-ph/0003268, hep-ph/0103117, hep-ph/0312014, hep-ph/0801.3360, hep-ph/0607181

Balossini, Bignamini, Carloni Calame, Lunardini, Montagna, Nicrosini, Piccinini

$\texttt{BabaYaga}$ also includes a matching to NLO QED in the short distance cross section

slide by G. Stagnitto

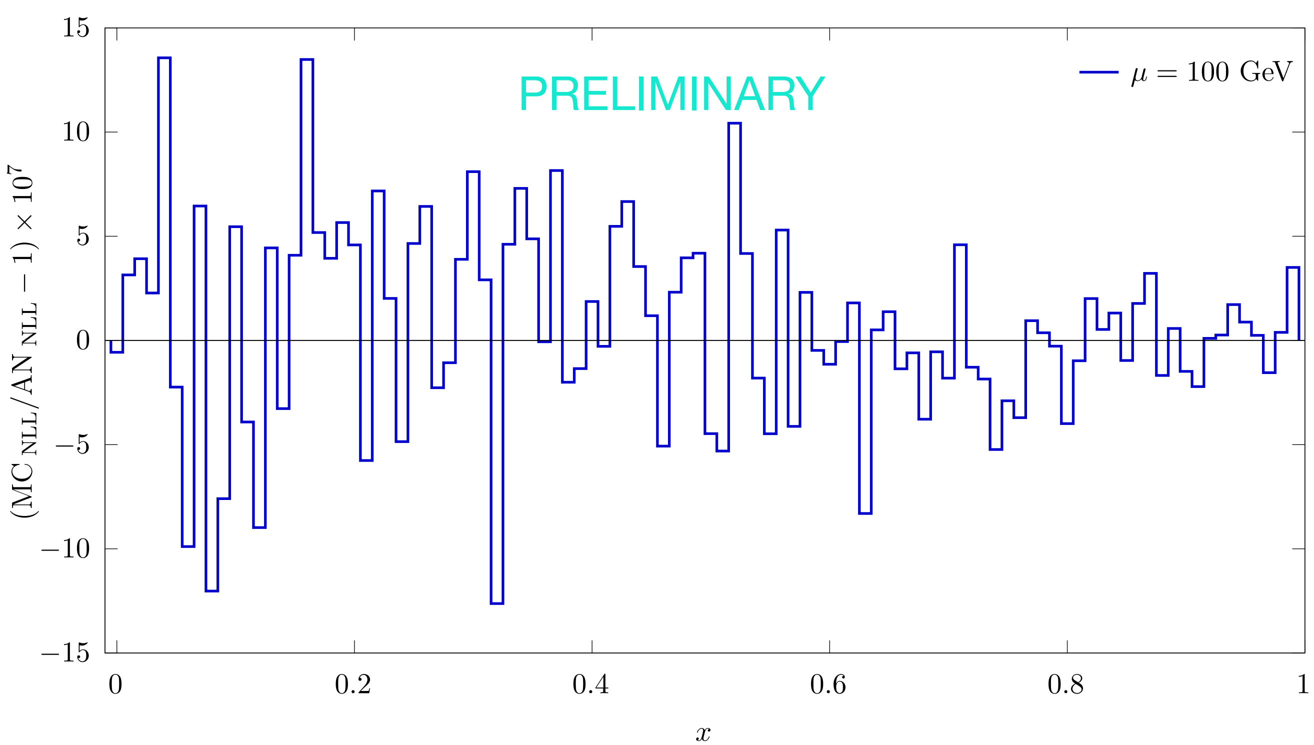
Matching with PS: ISR at NLL?

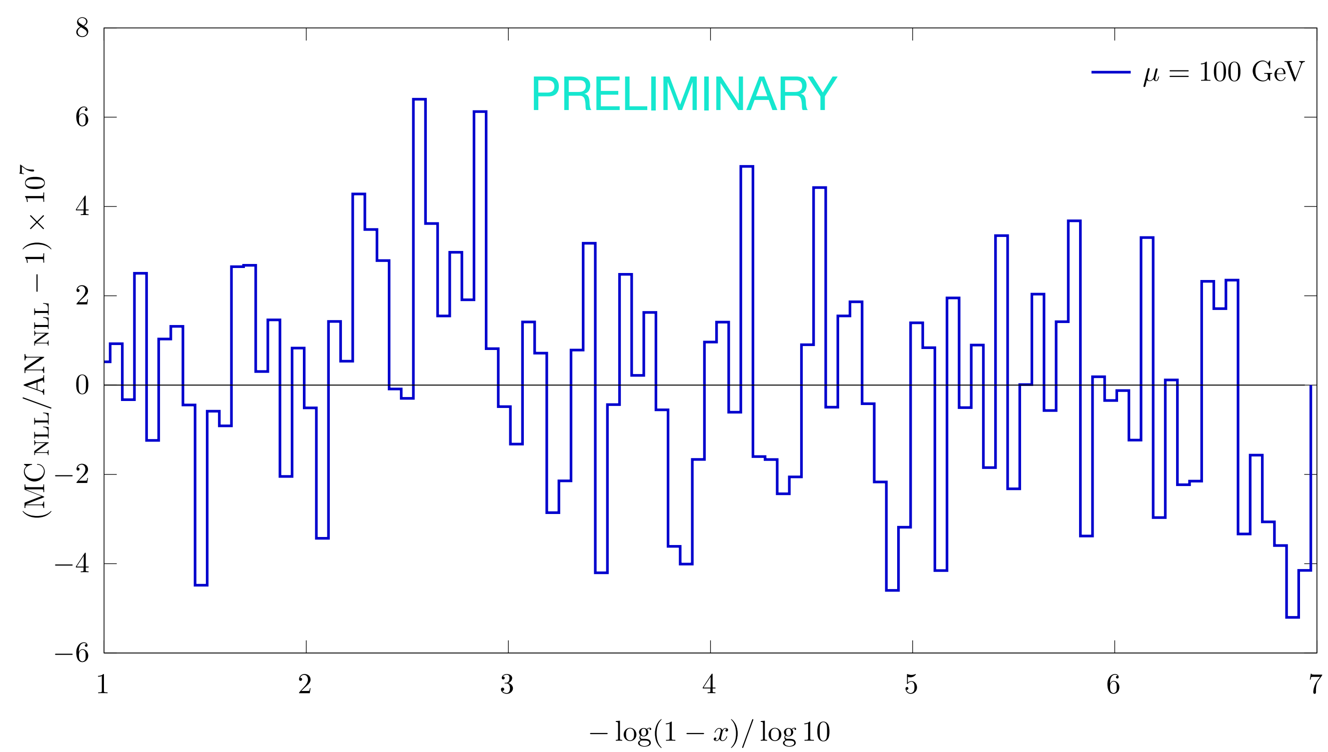
Towards a "NLL" QED Parton Shower

C. M. Carloni Calame, M. Chiesa, S. Frixione, G. Montagna, F. Piccinini, GS

$$D(x,s) = \sum_{n=0}^{\infty} \prod_{i=1}^{n} \left\{ \int_{m_e^2}^{s_{i-1}} \frac{\mathrm{d}s_i}{s_i} \Pi(s_{i-1}, s_i) \frac{\alpha}{2\pi} \int_{x/(z_1 \cdots z_{i-1})}^{x_+} \frac{\mathrm{d}z_i}{z_i} P(z_i) \right\} \Pi(s_n, m_e^2) D\left(\frac{x}{z_1 \cdots z_n}, m_e^2 \right)$$

With a NLL iterative solution, we recover the known (non-singlet) NLL PDFs





WIP towards exclusive kinematics of final-state photons and singlet components

slide by G. Stagnitto

The road ahead

- The new functionalities for lepton collides are in MG5_aMC from v3.5.0; EW Sudakov will be in the next big release (3.6)
- The code has some limitations, due to the underlying phase-space mapping
- Try the code, do pheno, and please report bugs/issues!
- In particular, the study of processes such as 4-lepton production, fully-decayed ttbar (+Higgs?) can be an excellent test-bench for the code
- Event generation is the next big step, which requires the ad-hoc matching for initial-state emissions


Thank you!