Event selection and background simulation in the dimuon channel at the CMS experiment

The Section of Nuclear Physics of the Physical Sciences Division
of the Russian Academy of Sciences

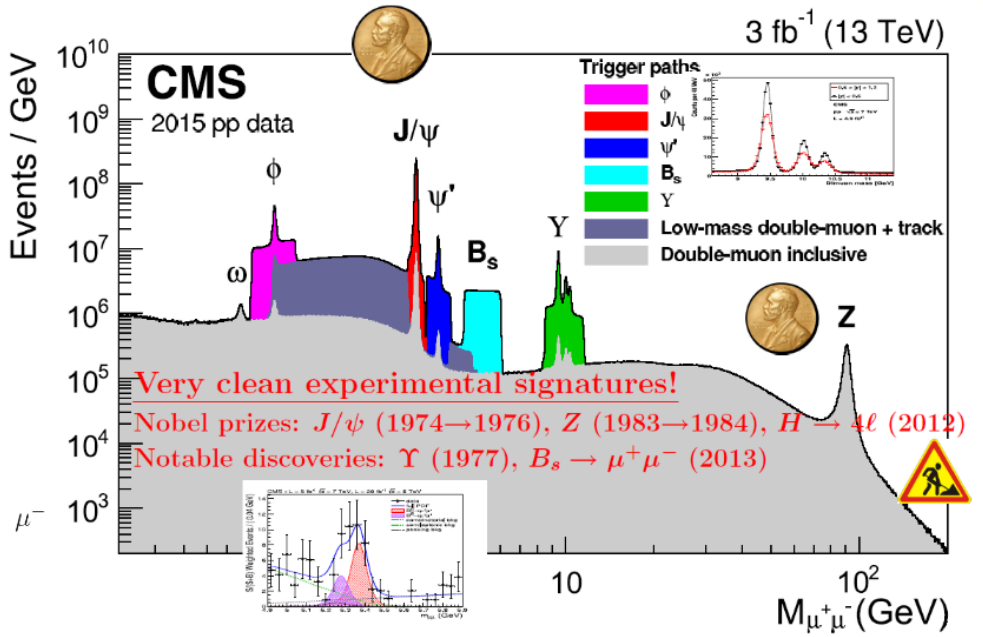
I. Zhizhin, S. Shmatov, A. Lanyov

JINR, Dubna, 04.04.2024

SM processes and beyond

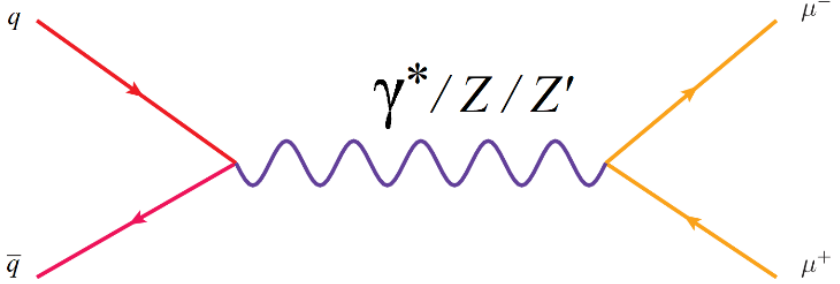
Motivation to search for new physics

- Many theoretical scenarios beyond the Standard Model predicts phenomena that can be discovered in the channel with a pair of muons;
- The Drell-Yan process - $q\bar{q} \rightarrow \gamma/Z^0/Z' \rightarrow l^+l^-$ - is one of the critical tests of the SM. In SM the process is calculated with great precision: NNLO QCD & NLO EW;
- Test the Standard Model on a new energy scale (~ several TeV);
- Events with a pair of muons have a simple experimental signature;
- The Compact Muon Solenoid (CMS) experiment at the LHC is optimized for measuring high p_T muons (up to several TeV).



Phenomena not explained:

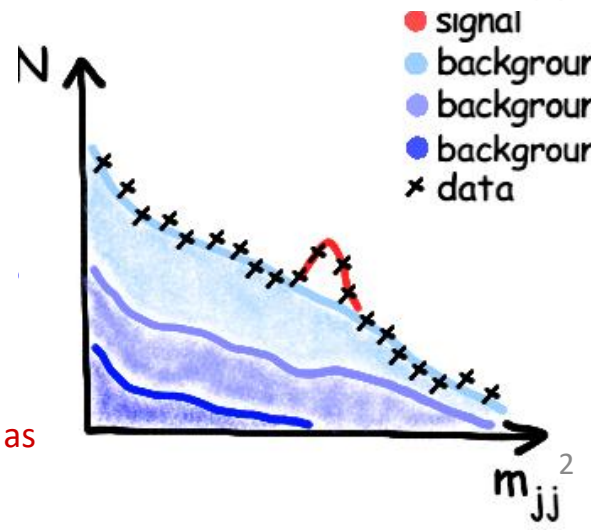
- Gravity
- Dark matter
- Hierarchy problem
- Strong CP-problem
- Number of parameters
- Matter–antimatter asymmetry



New Physics ($Z'/Z_{KK}/G_{KK}$) contributions to SM processes:

- Spin-1 resonances
- Spin-2 resonances
- Non-resonant signals
- Rare Higgs Decays *(H →μμ)*

Signals: di-leptons resonance states in high (~TeV) invariant mass range ⇒ new particles would be observed as a bump, excess in the mass spectrum

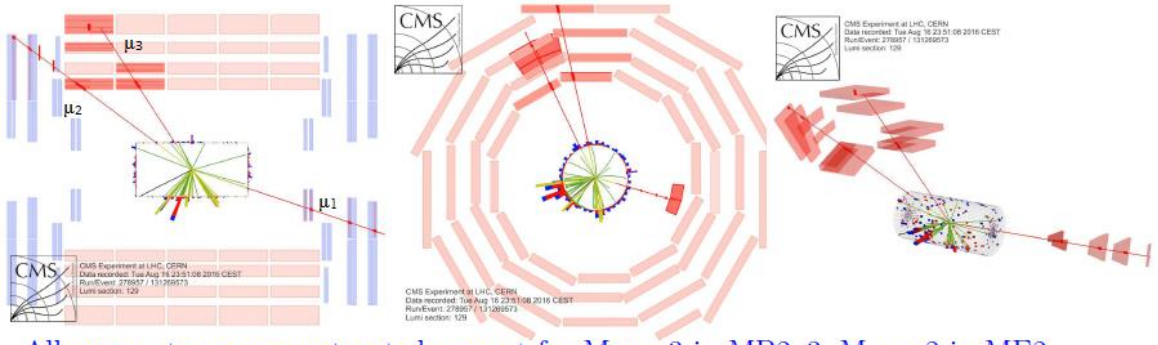


Muon Pair Selection Optimization

Events with more than 2 good muons

- Muon 1: μ^-: $\eta = +1.812$, $\varphi = -0.283$ rad, $p_T = 341 \pm 23$ GeV
- Muon 2: μ^+: $\eta = -1.106$, $\varphi = +2.037$ rad, $p_T = 159 \pm 6$ GeV } give $M = 1040$ GeV
- Muon 3: μ^-: $\eta = -0.609$, $\varphi = +1.772$ rad, $p_T = 153 \pm 3$ GeV } give $M = 89.5$ GeV

- The event AOD file can be found at
  /afs/cern.ch/user/l/lanyov/cmsonly/rereco_278957_129_131269573.root



All segments are reconstructed, except for Muon 3 in MB2–3, Muon 2 in ME2.
Showers are reported for Muons 2, 3 in MB1 (two muons!), and in MB4 for Muon 3.
pfMET = 43 GeV ($\varphi = 0.147$): $\Delta\varphi = 0.430$ with Muon 1 ($\varphi = -0.283$).
Could be event with production of WZ or ZZ.

Example of an event with 3 muons

The appearance of events in Run2 with 3 or more muons with M<900 GeV requires consideration of which muons to select for pairing in the reconstruction.

It is necessary to have complete information about such events and possible dimuon candidates, rather than obtaining masses by an automatic algorithm in which the presence of several possible dimuons is lost.

Events with masses greater than 900 GeV were detected in the 2016-2018 data:

2016:	293 events
2017:	374 events
2018:	544 events

Selection criteria for Z' analysis

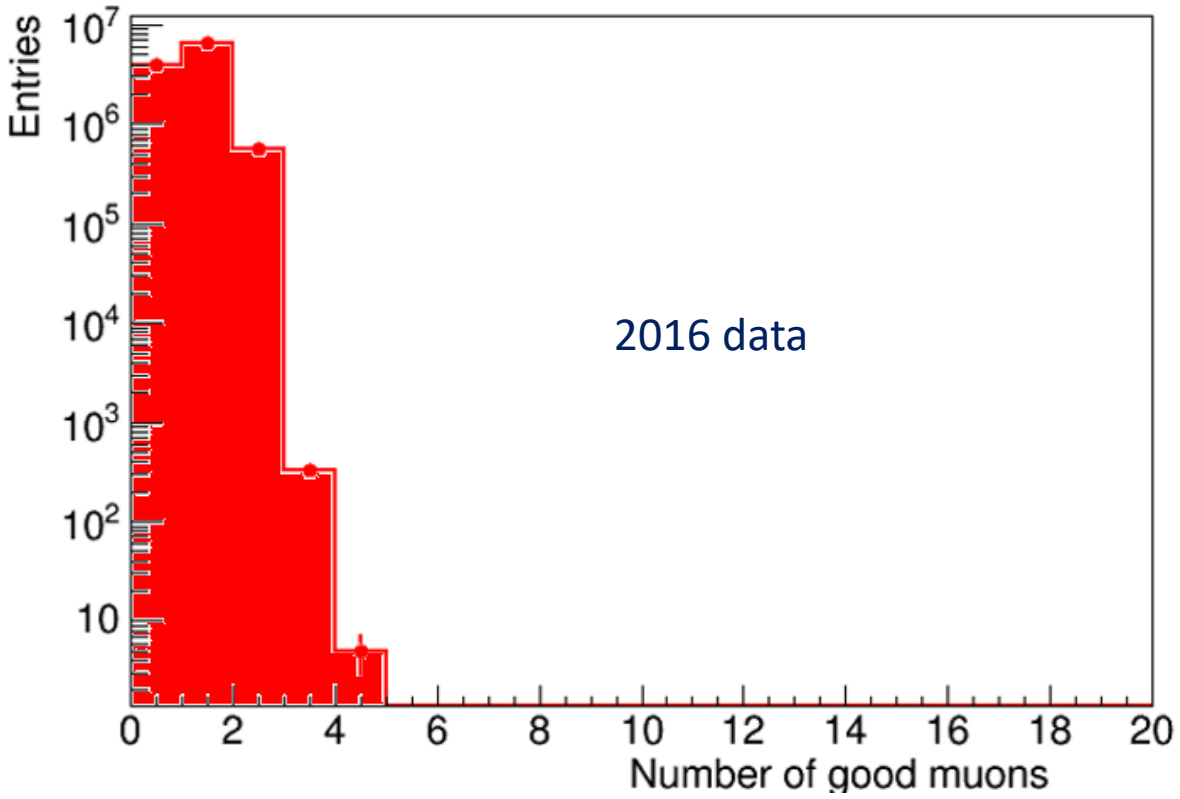
Basic standard criteria for the selection of muons and dimuons:

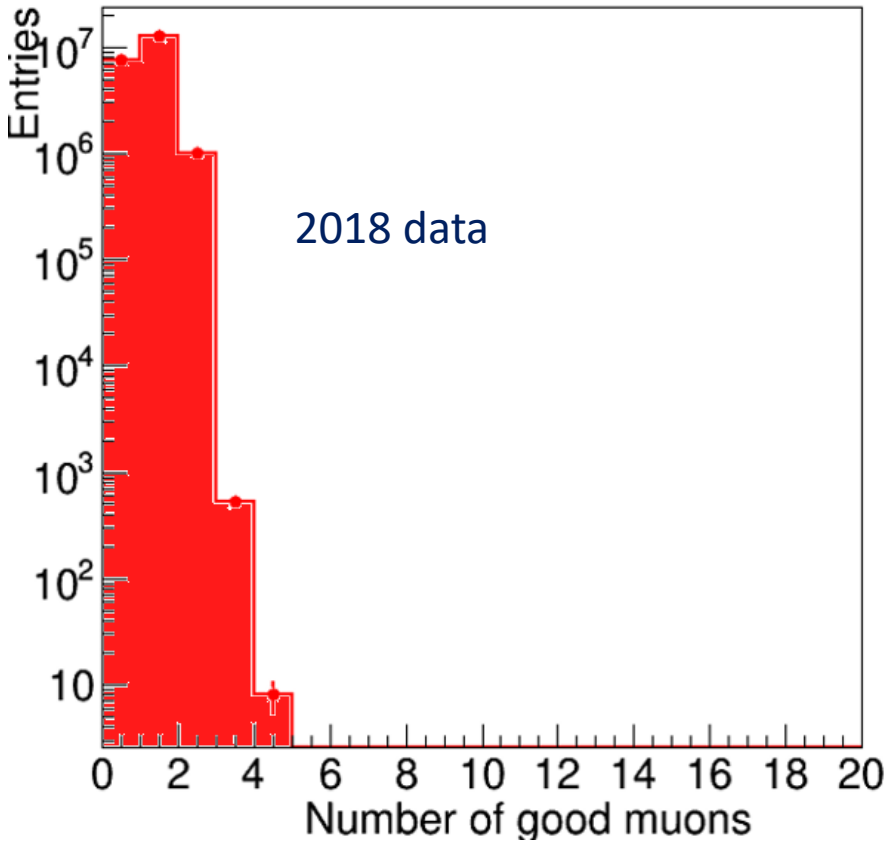
- $|\eta| < 2.4$ - muon pseudorapidity;
- $p_T > 53$ GeV - muon transverse momentum;
- $M > 60$ GeV - dimuon mass;
- HLT_Mu50 || HLT_TkMu50 (HLT_TkMu100 || HLT_OldMu100) - high-level trigger with condition(threshold) p_T>50 GeV;

Criteria for minimum number of hits in a tracker:

- N(Pixel hits) > 0 - number of hits in pixel detector;
- N(Tracker layers) > 5 - number of tracker layers;
- N(Muon hits) > 0 - number of muon hits;
- N(Matched muon stations)> 1 - number of matches in muon stations;
- sum p_T / p_T < 0.10 - muon track isolation in the tracker;
- $\sigma(p_T) / p_T$ < 0.3 - relative uncertainty of p_T;
- χ^2/ndof < 20 - good dimuon vertex;
- α > 0.02 - three-dimensional angle between muon directions (cosmic muon screening);
- ch1 * ch2 < 1 - selection of muons with different charges;
- dxy < 0.2 mm - rejection of prompt muons and muons born in secondary decays;
- jmuons - muon should be in the list of "good" run and ls, according to MuonPhys JSON file;
- Npv0good, Statgv - requirement of a good offline reconstructed interaction vertex, localized in the region |r| < 2 cm and |z| < 24 cm;

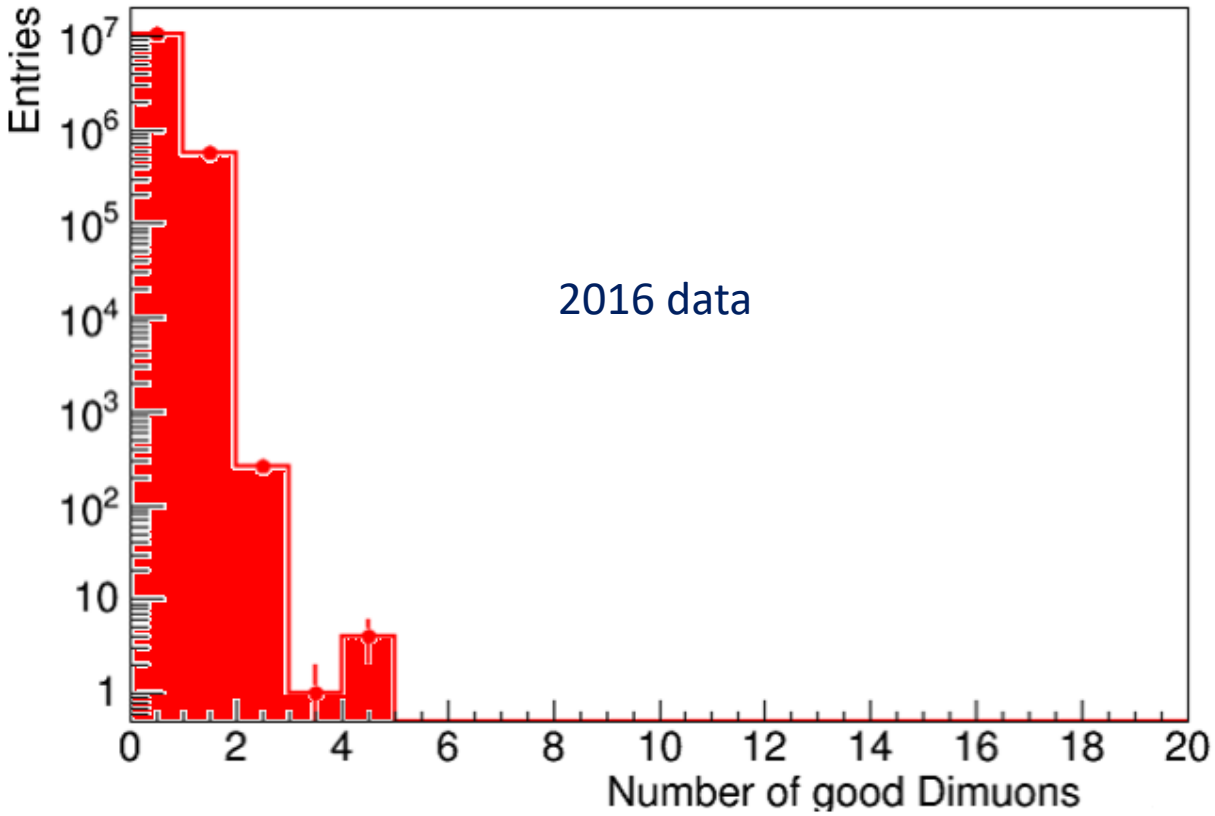
Distributions of "good" muons

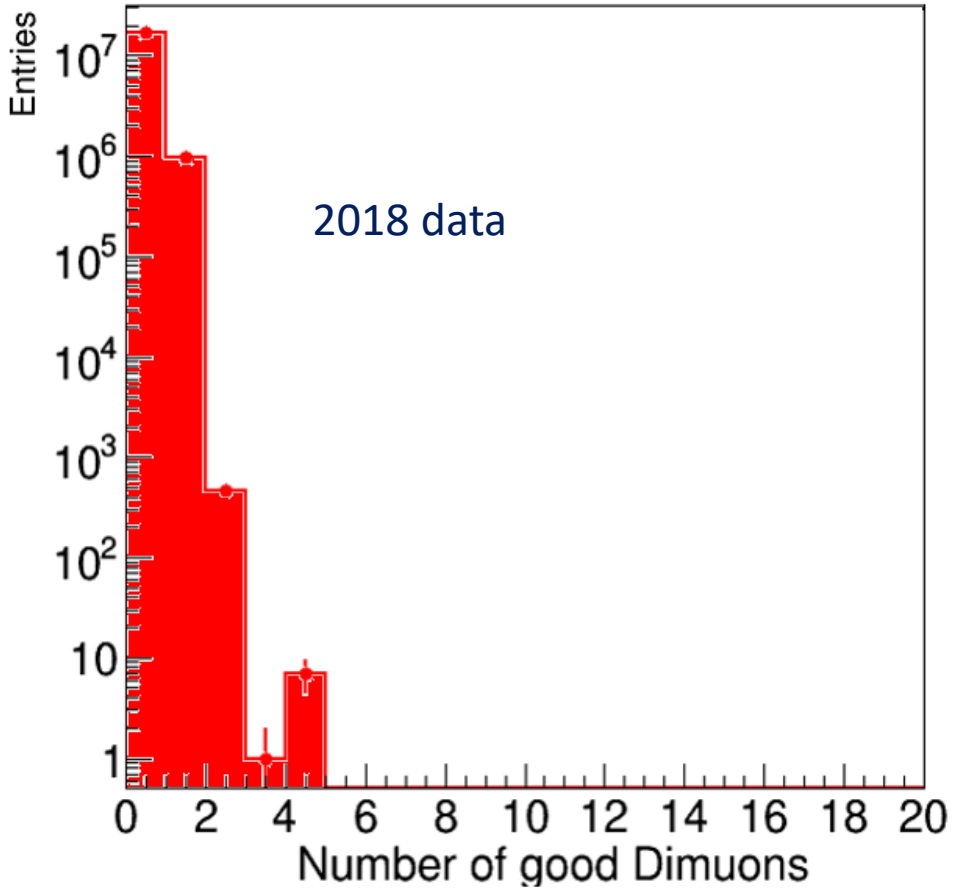




Distributions of the number of "good" muons in events,
i.e., muons satisfying the selection criteria.

Distributions of "good" dimuons

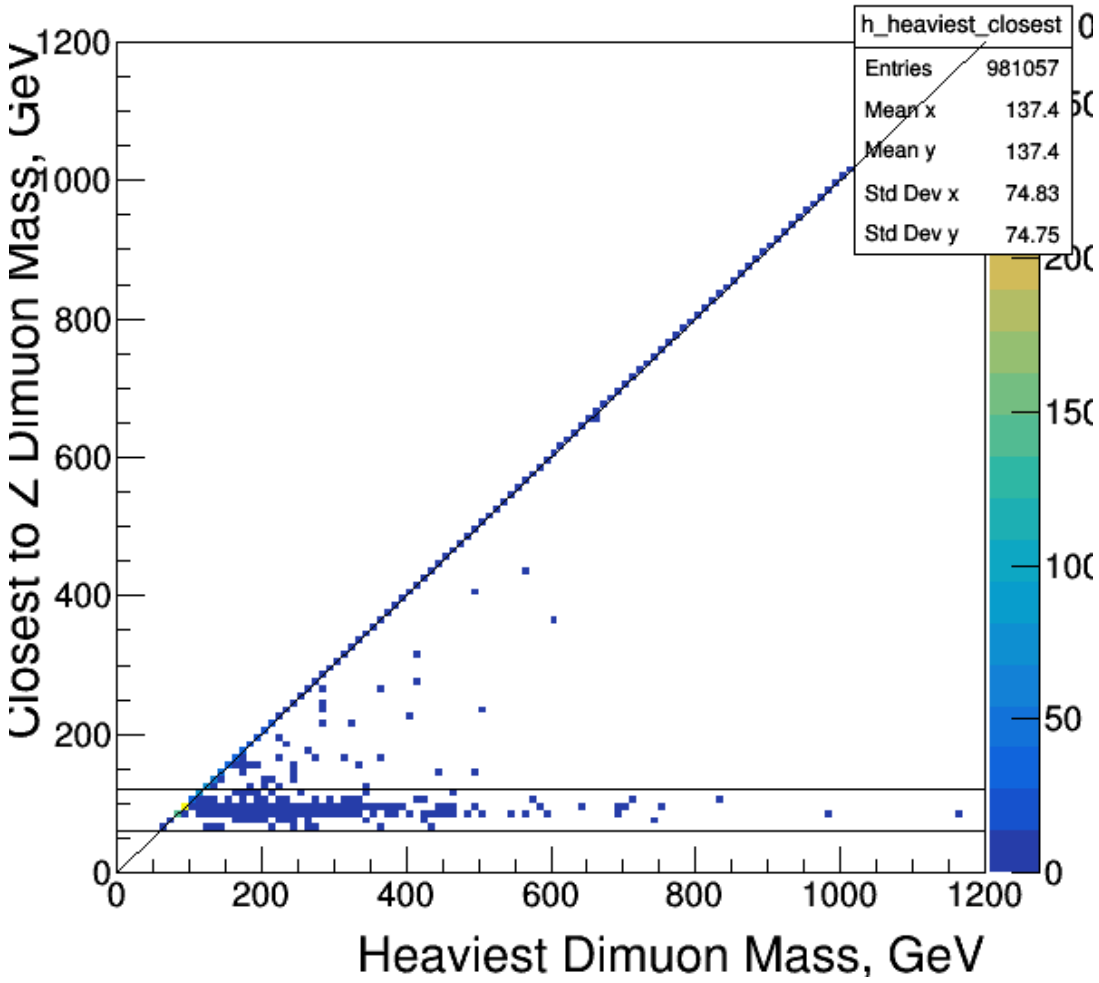


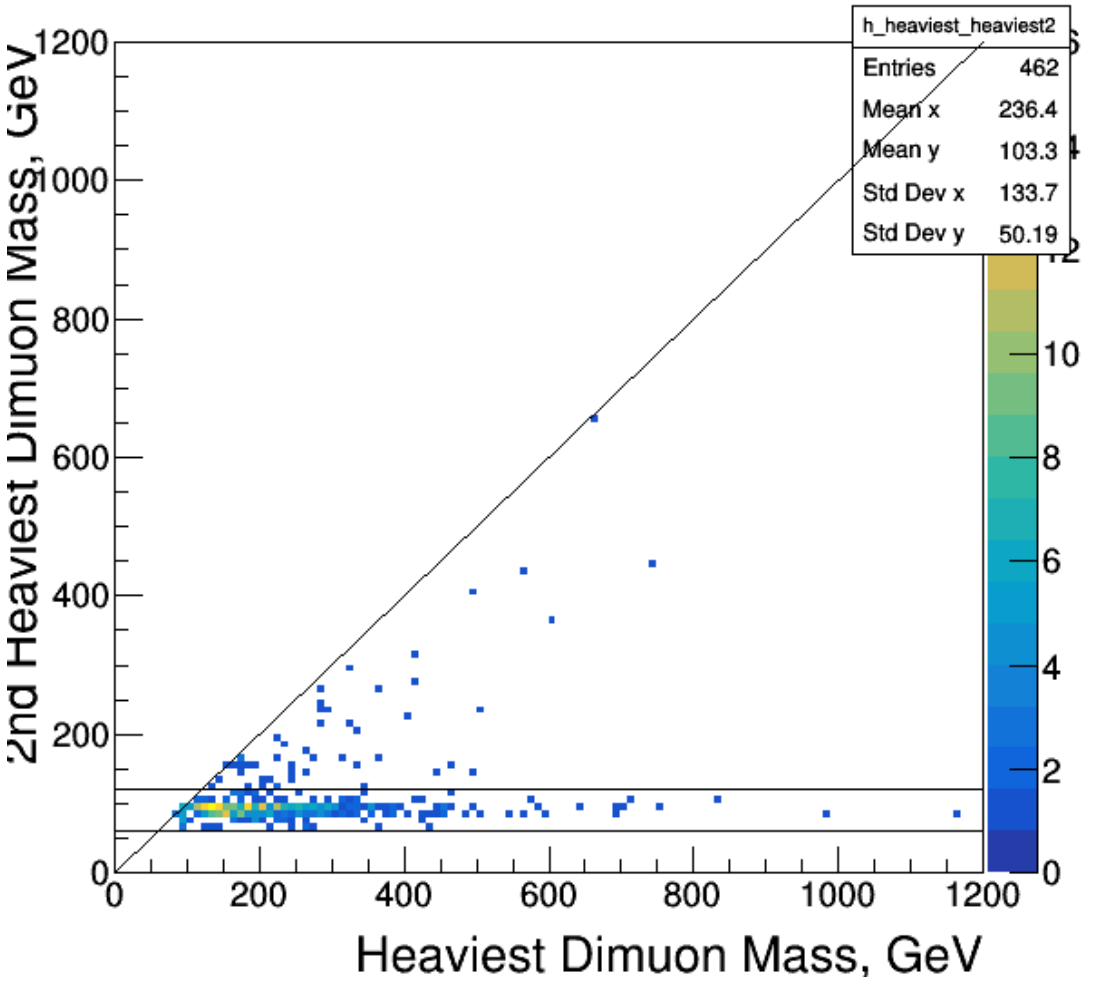


Distributions of the number of "good" dimuons.

2018 data

Two-dimensional distributions by dimuon masses





Conclusions on muon pair selection

- There was a purpose to check different ways to combine them.
- The idea was:

  if a muon pair has invariant mass within ±20 GeV range near the Z^0 boson mass,

  then that pair, otherwise take highest p_T pair.

  Pairs from Z^0 should be excluded from Z' analysis;
- The program was modified for improve event selection;

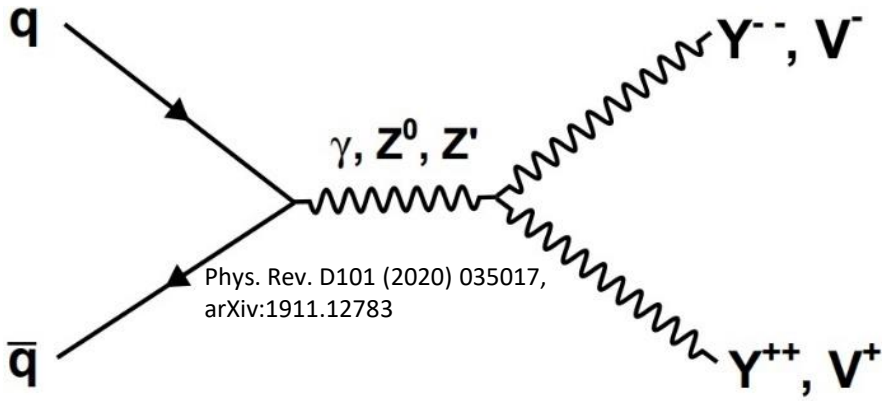
  Added selection criteria for multi-muon (>2) events and modified conditions

  on the number of good muon hits to increase efficiency;
- A method for selecting muon pairs was proposed, tested and accepted;
- The result is already applied in the CMS analysis arXiv:2103.02708;
- As a result, in the muon pair selection analysis, an additional selection criterion is applied;
- This also helps to reduce the physical backgrounds of dibosons production in the ZZ and WZ channels.

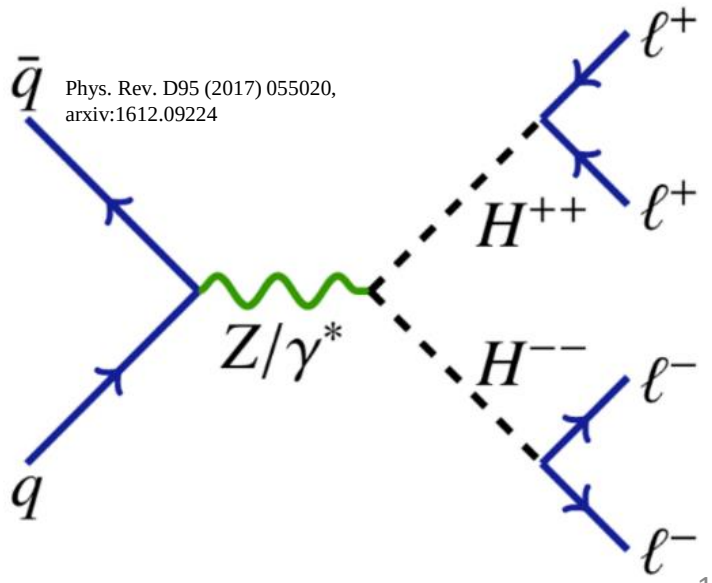
Same sign analysis of muon pairs

Doubly-charged bosons also appears in various SM extensions.

- Doubly Charged Higgs Bosons $H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$
  - *Seesaw mechanism*
- Doubly-Charged Bileptons
  - *Extension of the EW gauge symmetry $SU(3)_C \otimes SU(3)_L \otimes U(1)_X$ (model "331")*



Phys. Rev. D101 (2020) 035017, arXiv:1911.12783



Phys. Rev. D95 (2017) 055020, arxiv:1612.09224

The analysis was carried out on Run 2 data (2016-2018).

- Selected events with same charged muon pairs (++/--).

The invariant mass distribution is plotted for the data of the entire Run2

Processed data

- **UL data from 2016 - 2018 has been processed**
- ✓ CMSSW 10_6_8_patch1, 10_6_2 and 10_6_4_patch1 were used, respectively;
- ✓ Used datasets:

Ultra Legacy 2016 data [36.3 fb-1]

/SingleMuon/Run2016B-21Feb2020_ver2_UL2016_HIPM-v1/AOD
/SingleMuon/Run2016C-21Feb2020_UL2016_HIPM-v1/AOD
/SingleMuon/Run2016D-21Feb2020_UL2016_HIPM-v1/AOD
/SingleMuon/Run2016E-21Feb2020_UL2016_HIPM-v1/AOD
/SingleMuon/Run2016F-21Feb2020_UL2016_HIPM-v1/AOD
/SingleMuon/Run2016F-21Feb2020_UL2016-v1/AOD
/SingleMuon/Run2016G-21Feb2020_UL2016-v1/AOD
/SingleMuon/Run2016H-21Feb2020_UL2016-v1/AOD

Ultra Legacy 2017 data [44.98 fb-1]

/SingleMuon/Run2017B-09Aug2019_UL2017-v1/AOD
/SingleMuon/Run2017C-09Aug2019_UL2017-v1/AOD
/SingleMuon/Run2017D-09Aug2019_UL2017-v1/AOD
/SingleMuon/Run2017E-09Aug2019_UL2017-v1/AOD
/SingleMuon/Run2017F-09Aug2019_UL2017-v1/AOD

Ultra Legacy 2018 data [63.67 fb-1]

/SingleMuon/Run2018A-12Nov2019_UL2018-v5/AOD
/SingleMuon/Run2018B-12Nov2019_UL2018-v3/AOD
/SingleMuon/Run2018C-12Nov2019_UL2018-v3/AOD
/SingleMuon/Run2018D-12Nov2019_UL2018-v8/AOD

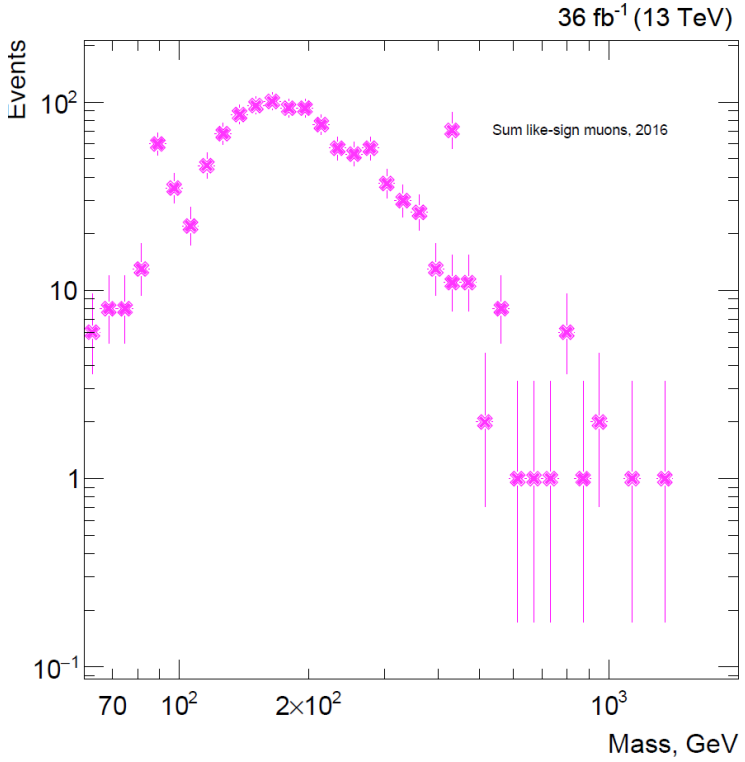
The number of charge combinations of muons:

2016		2017		2018	
+ +	629	+ +	687	+ +	987
- -	501	- -	528	- -	821
+ + -	127	+ + -	151	+ + -	236
- - +	113	- - +	122	- - +	203
+ + - -	6	+ + - -	6	+ + - -	7

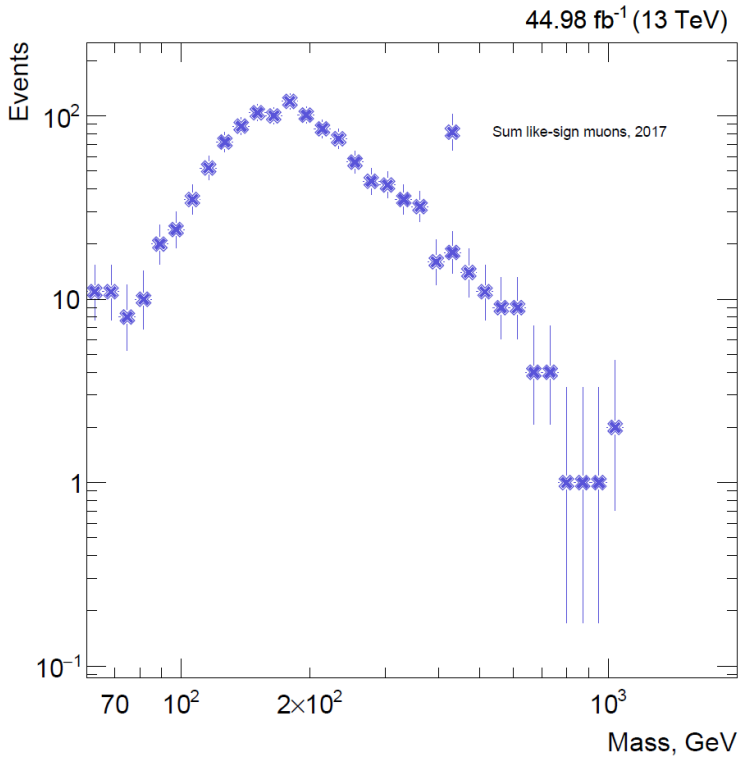
Same sign results (1)

Graphs of sums of equally charged (++ and --) pairs of muons

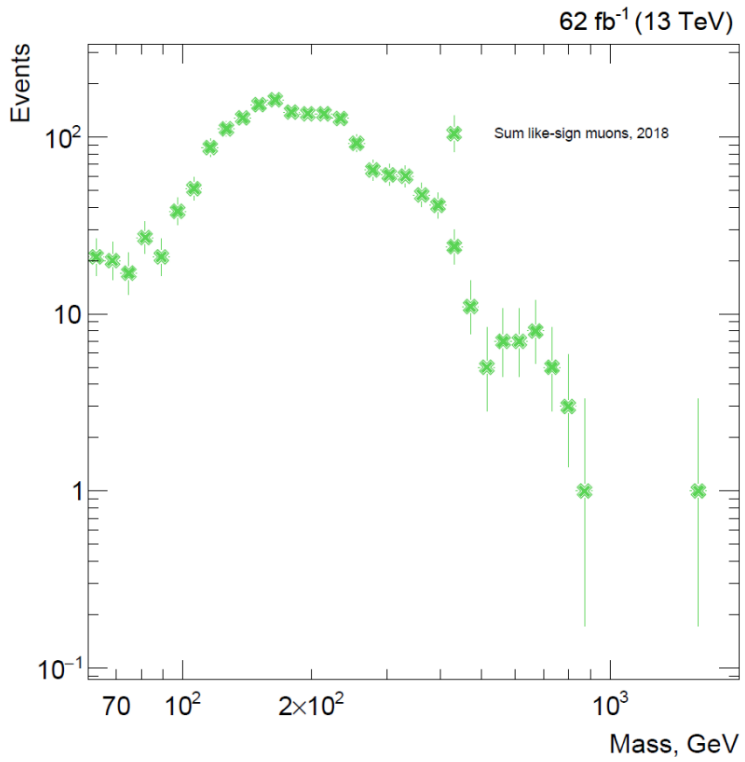
2016 data



2017 data

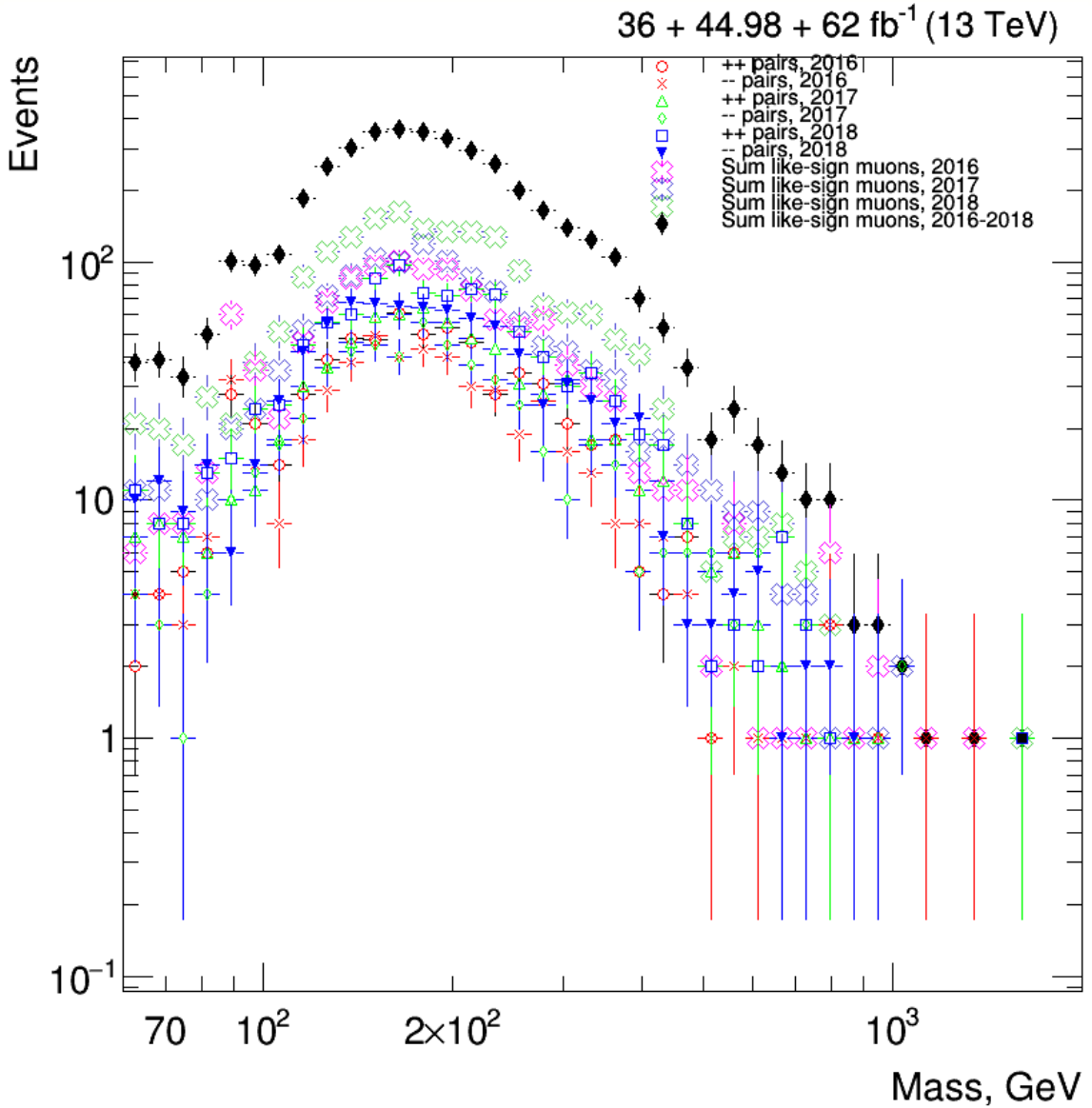


2018 data



Same sign results (2)

The invariant mass distribution of the sums of equally charged (++ and --) muon pairs for the full Run2 statistics, as well as the full sum.

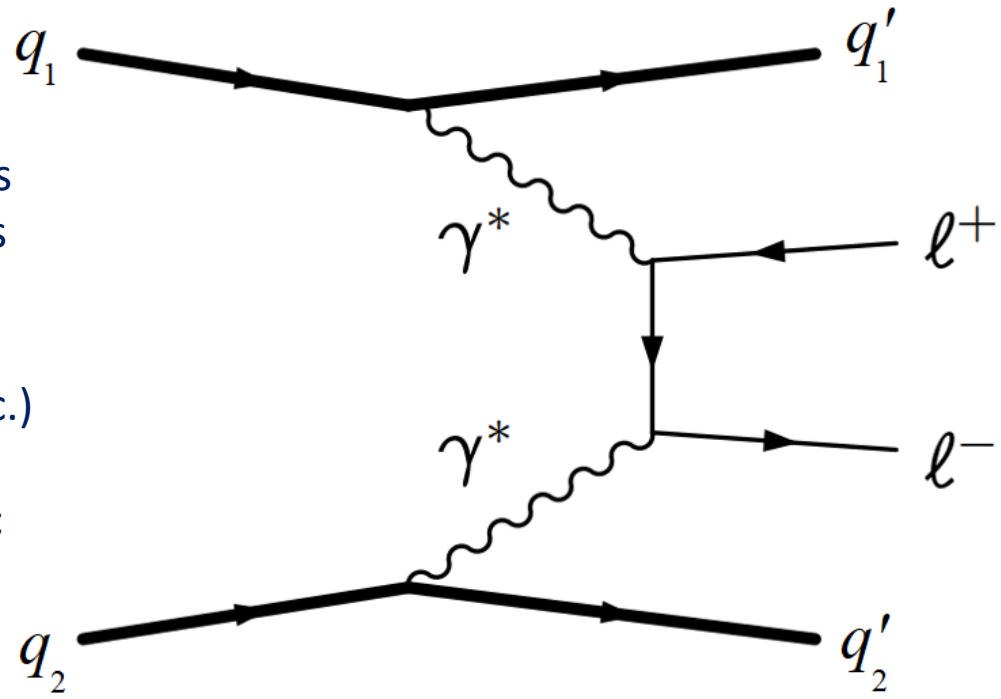


Photon-induced background

Photon-induced background

Photon-induced (PI) processes – The production of high invariant mass opposite sign lepton pairs in gamma-gamma collisions, where photons radiated by the incoming protons collide.

- In addition to DY, pairs of leptons *ee*, *μμ* (and also WW, ZZ pairs, etc.) can be produced in gamma-gamma interactions;
- To calculate this process, one needs PDFs that include the photonic component.



Simulation of photon backgrounds in the order NNLO QCD + NLO EWK in FEWZ

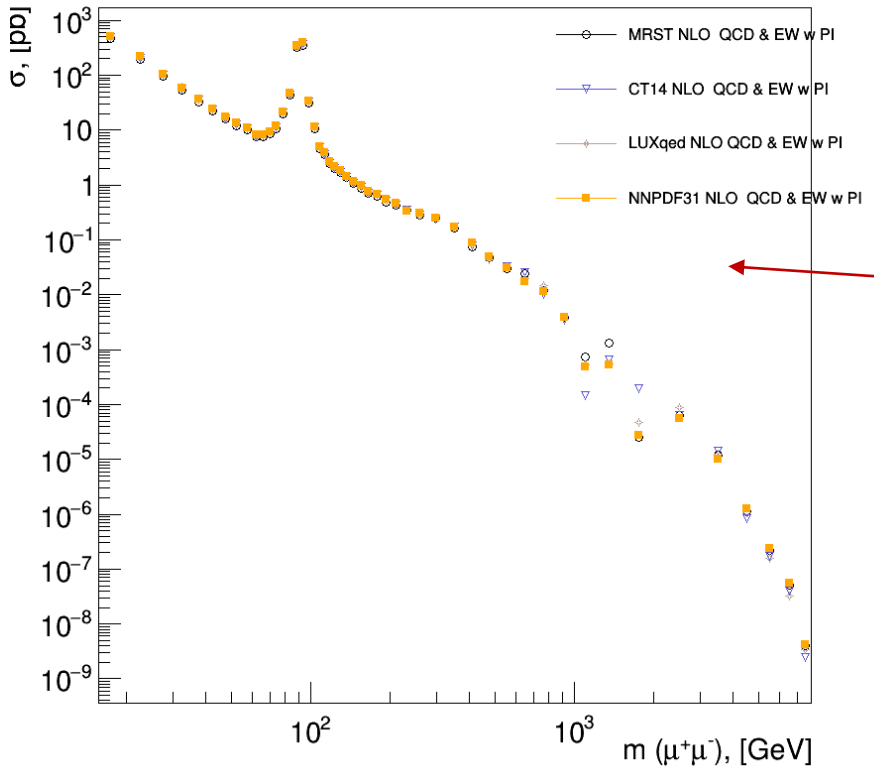
FEWZ - Fully Exclusive W and Z Production - for hadron collider production of lepton pairs through the Drell–Yan process at next-to-next-to-leading order (NNLO) in the strong coupling constant and in first order (NLO) electroweak interactions. arXiv:1011.3540

Four different PDFs were used for the analysis:

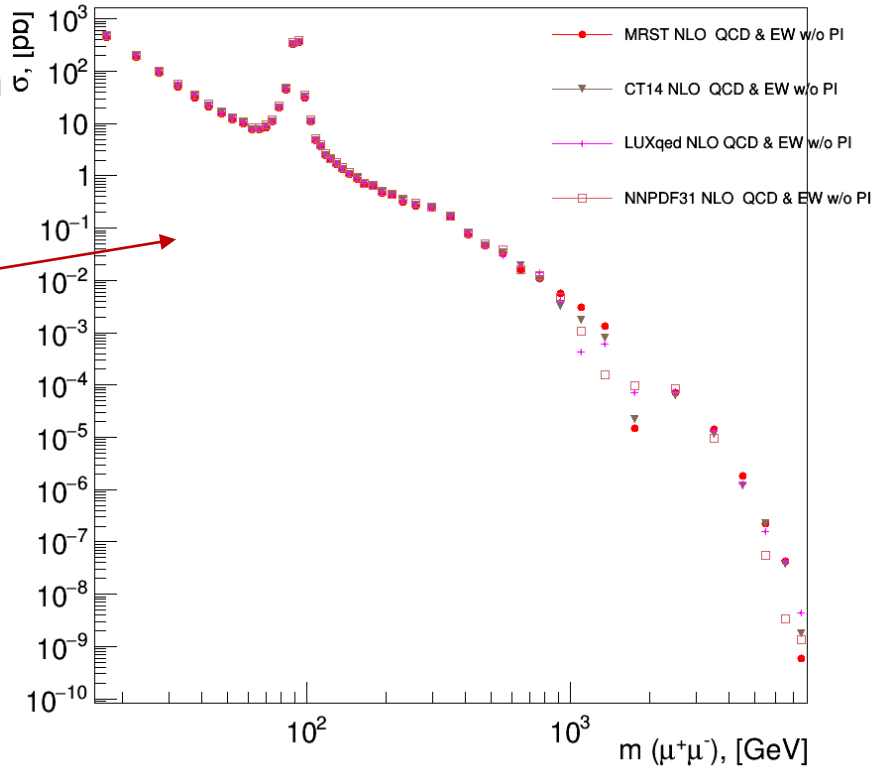
- MRST2004qed_proton
- LUXqed17_plus_PDF4LHC15_nnlo_100
- CT14qed_inc_proton
- NNPDF31_0118luxqed

with each of which simulations in FEWZ in the orders NLO QCD + NLO EWK and NNLO QCD + NLO EW in the interval from 15 to 8000 GeV have been carried out.

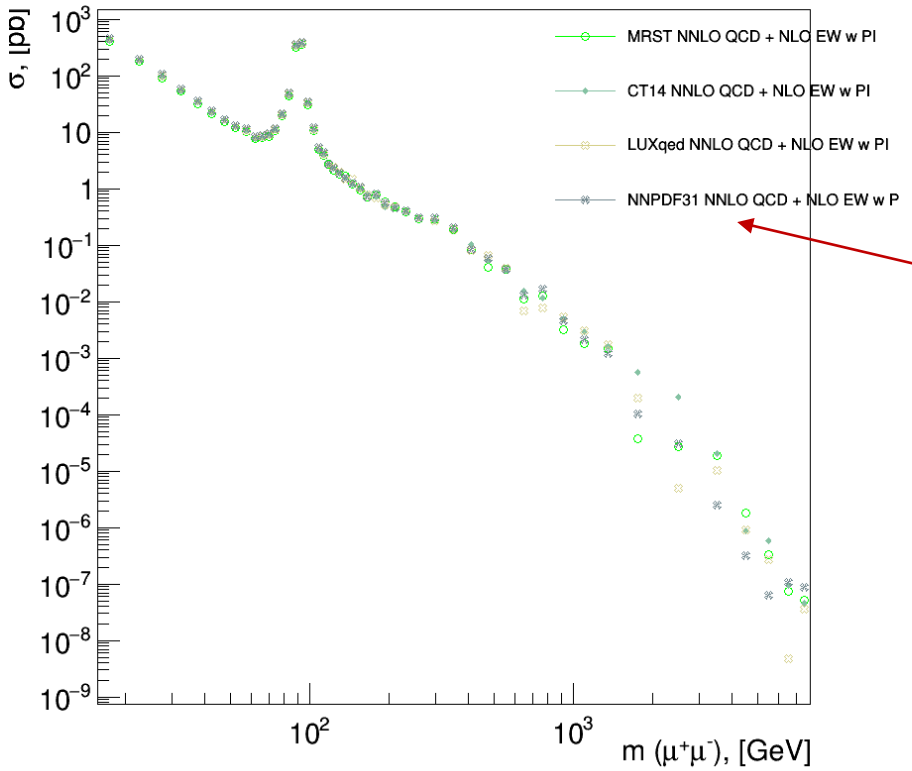
FEWZ NLO QCD results



Comparison of cross section distributions of different PDFs in the order NLO QCD with and without PI contribution
Cut: $|\eta| < 2.4$

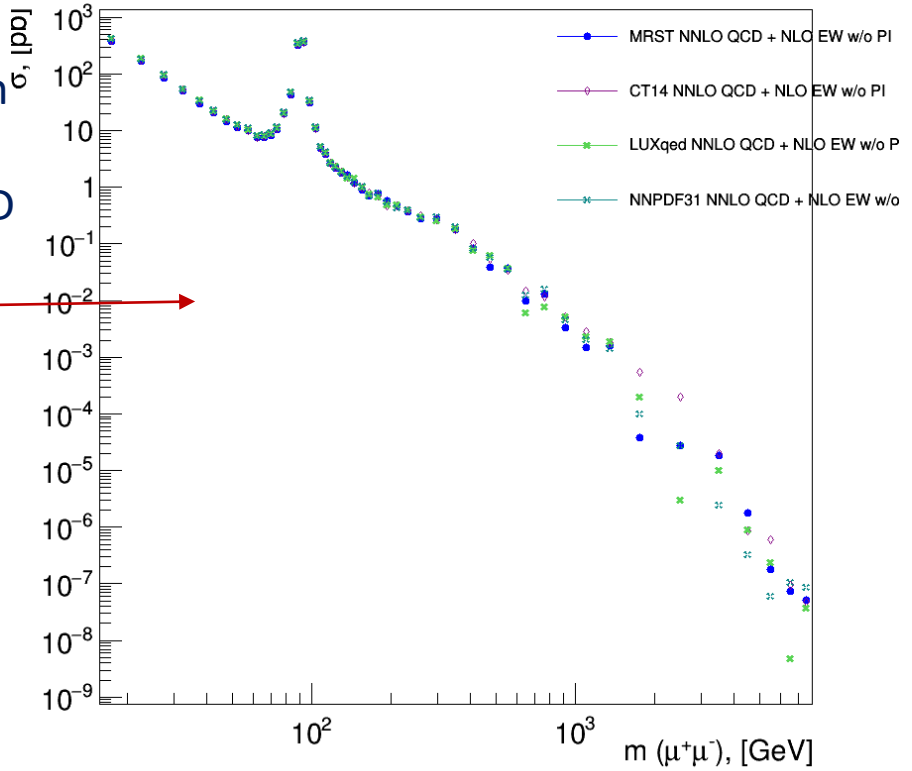


FEWZ NNLO QCD results



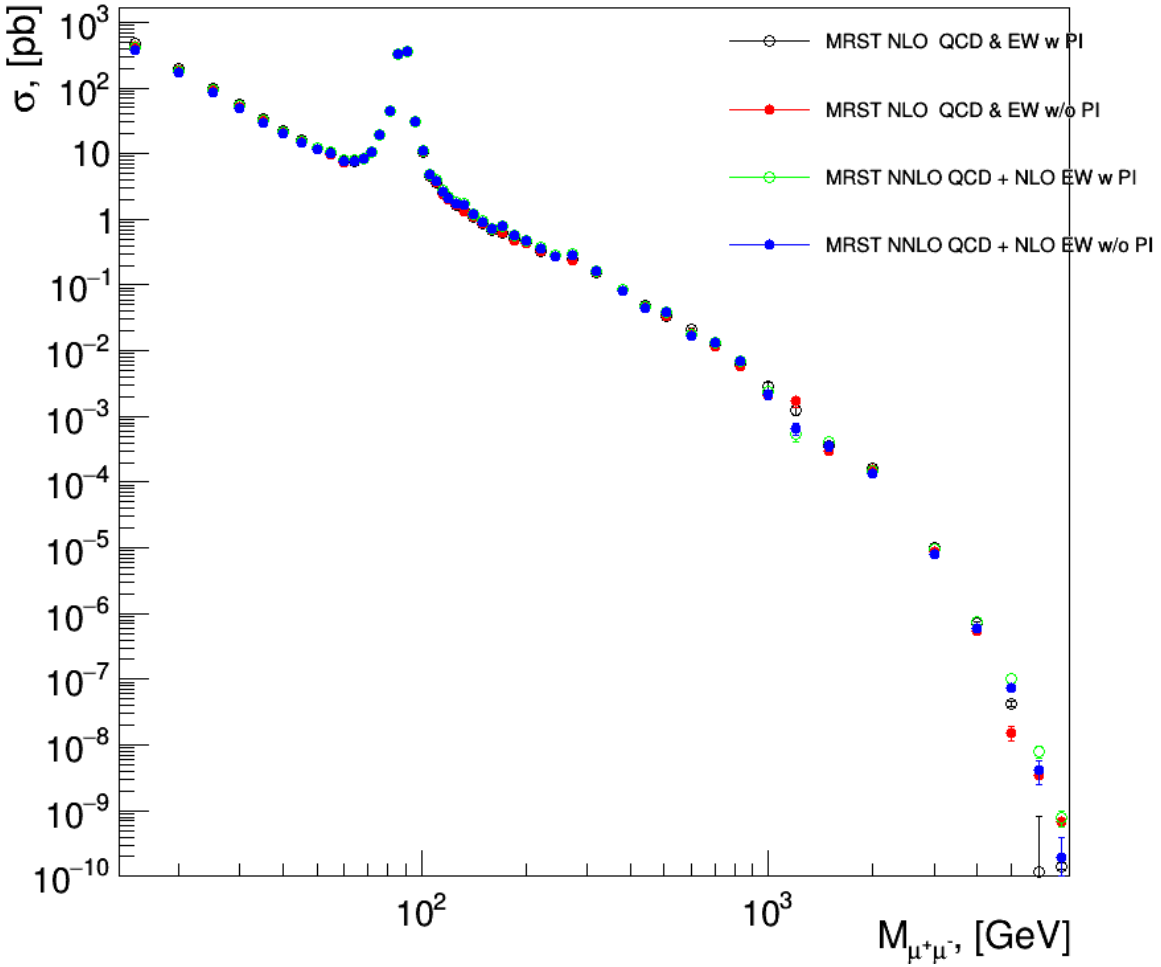
Comparison of cross section distributions of different PDFs in the order NNLO QCD with and without PI contribution

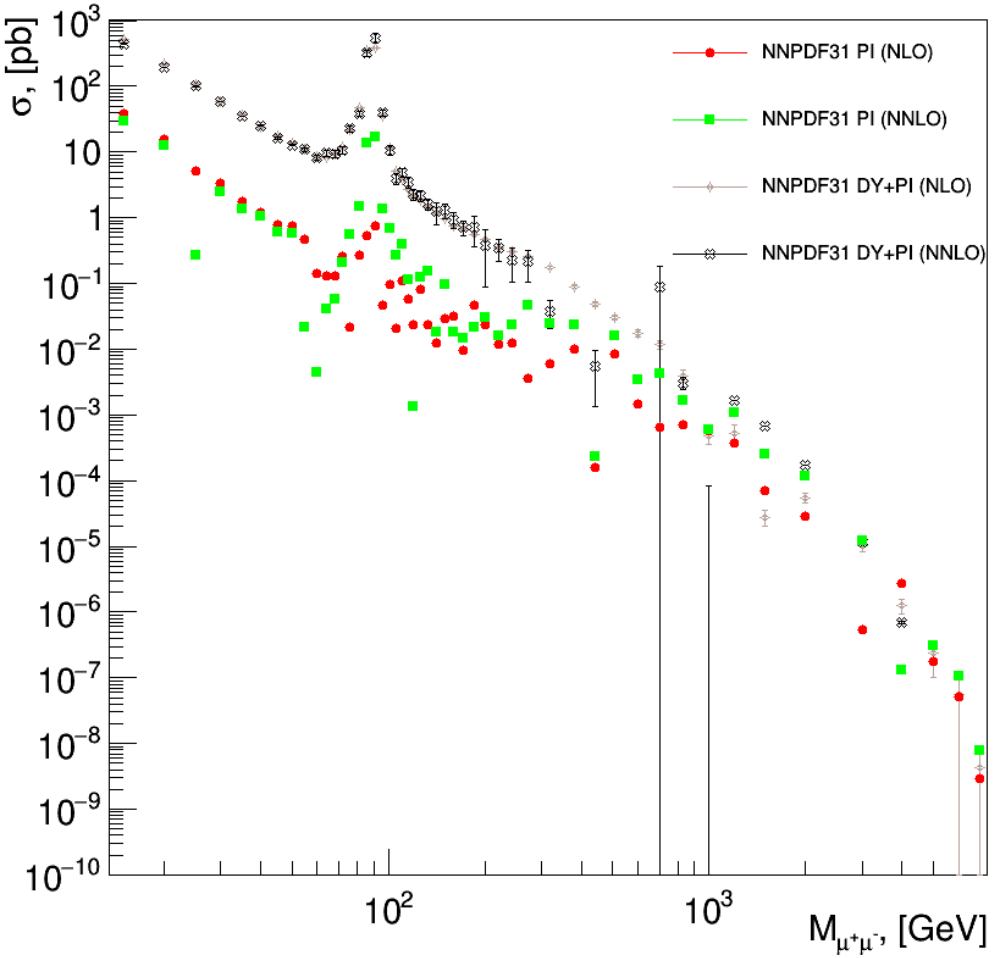
Cut: $|\eta| < 2.4$



NLO v. NNLO compare

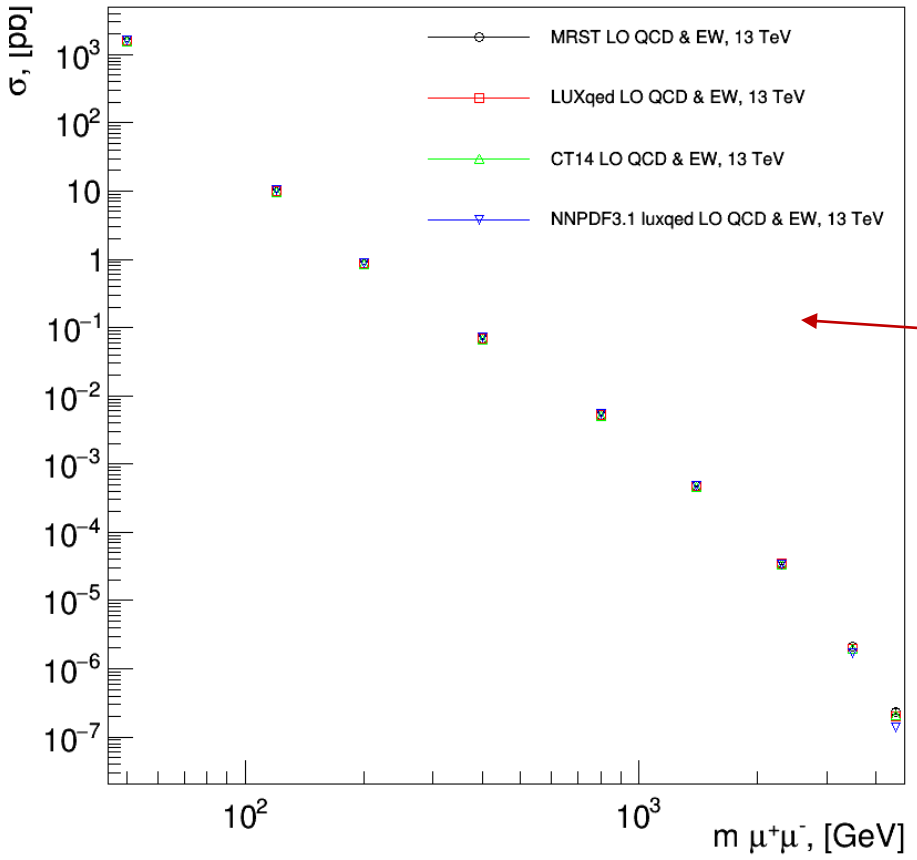
Comparison of cross section distributions of MRST PDF in the NLO and NNLO orders QCD with and without PI contribution. Cut: $|\eta| < 2.4$



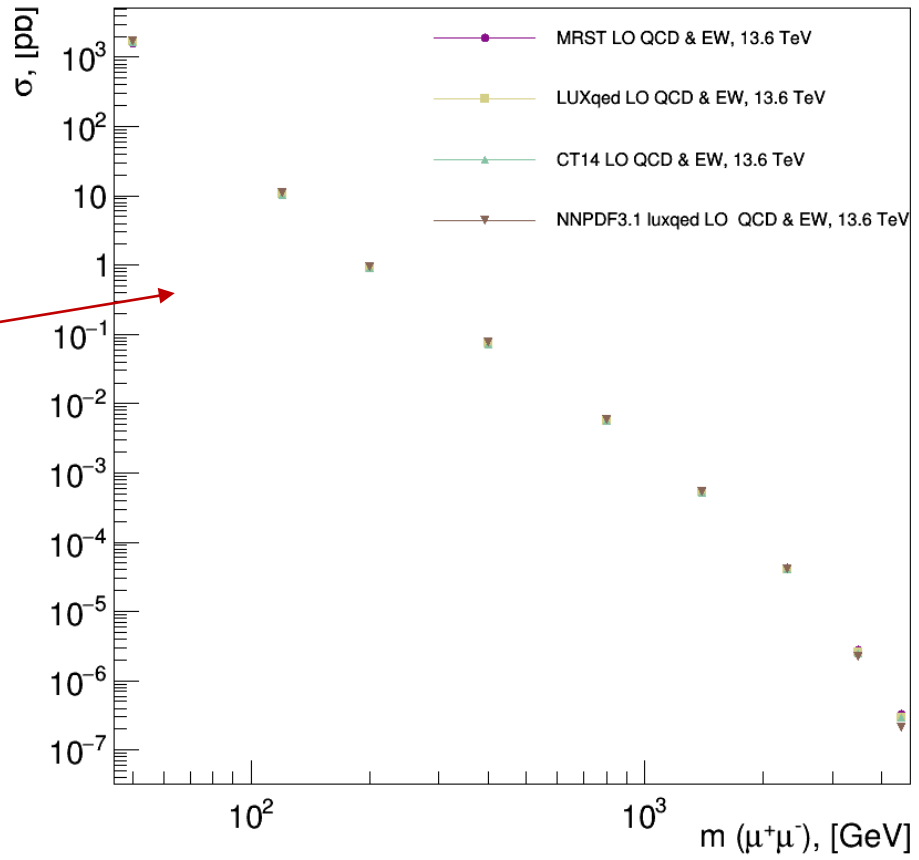


Drell-Yan: FEWZ LO results 13 & 13.6 TeV

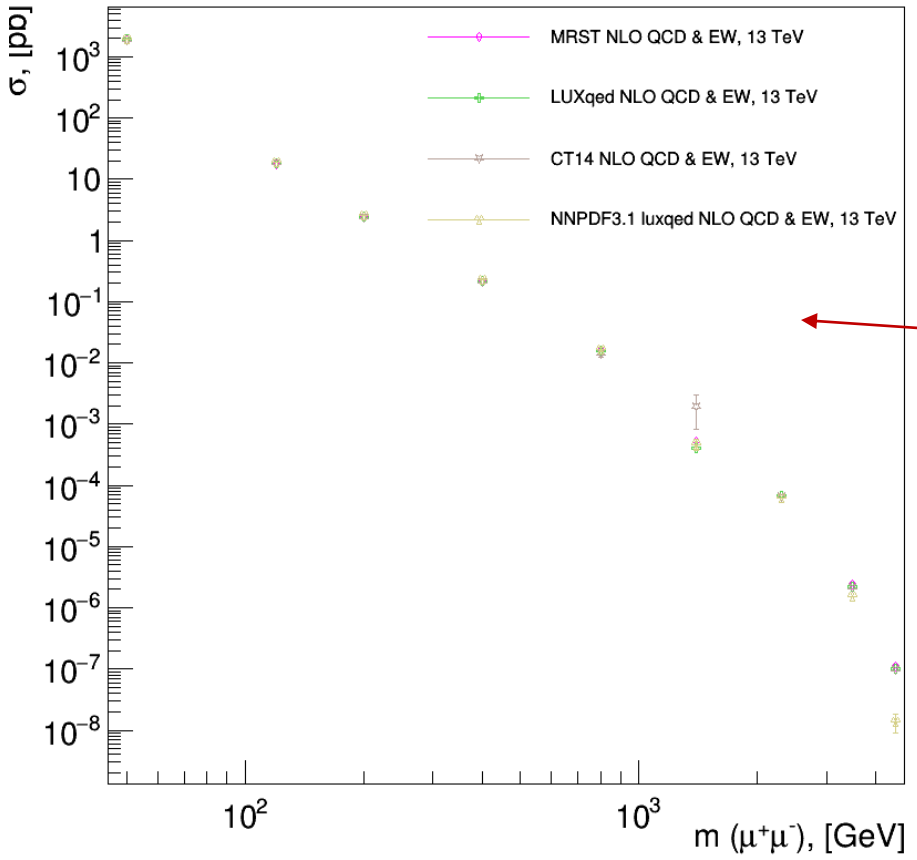
Using the same PDFs sets were simulated Drell-Yan cross sections in FEWZ
in the orders NLO QCD + NLO EWK and NNLO QCD + NLO EW in the interval from 15 to 6000 GeV



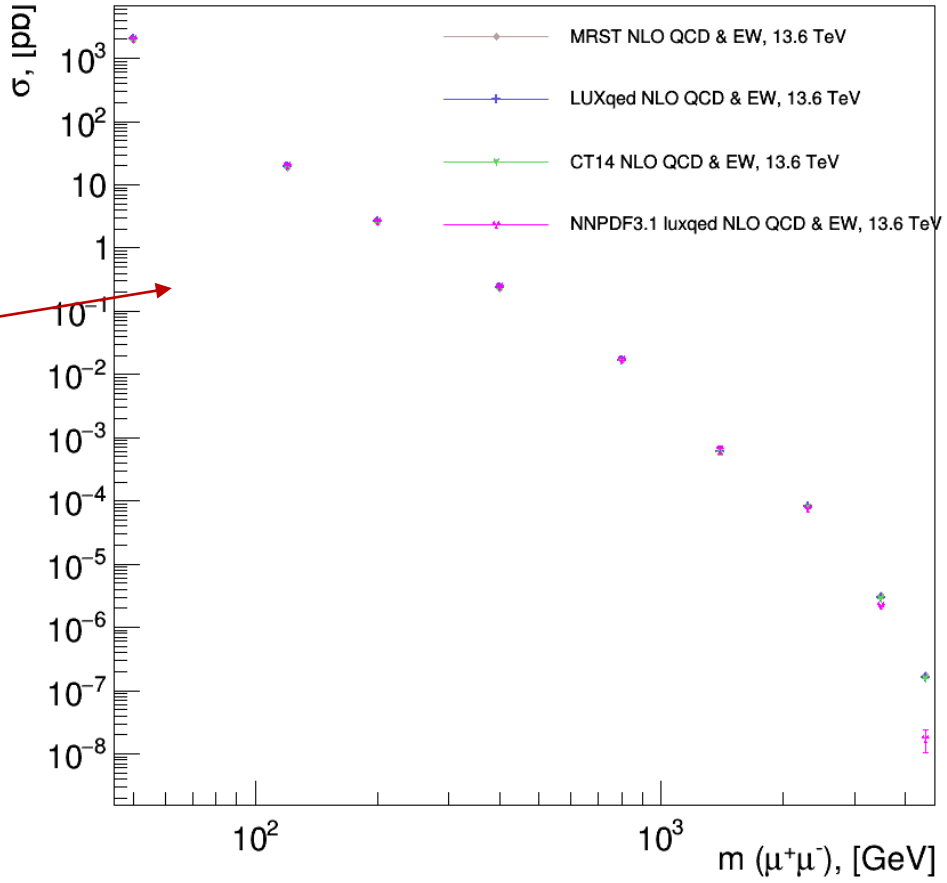
Comparison of distributions
cross sections
of different PDFs
in the order LO QCD
over the whole phase space



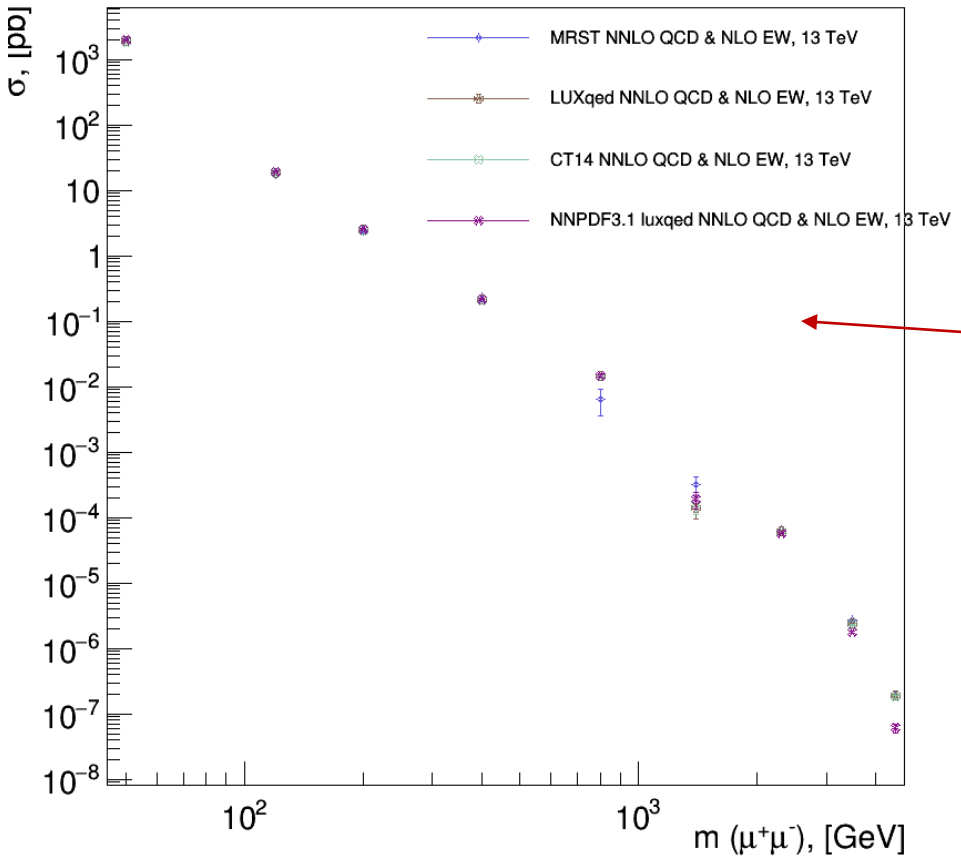
Drell-Yan: FEWZ NLO results 13 & 13.6 TeV



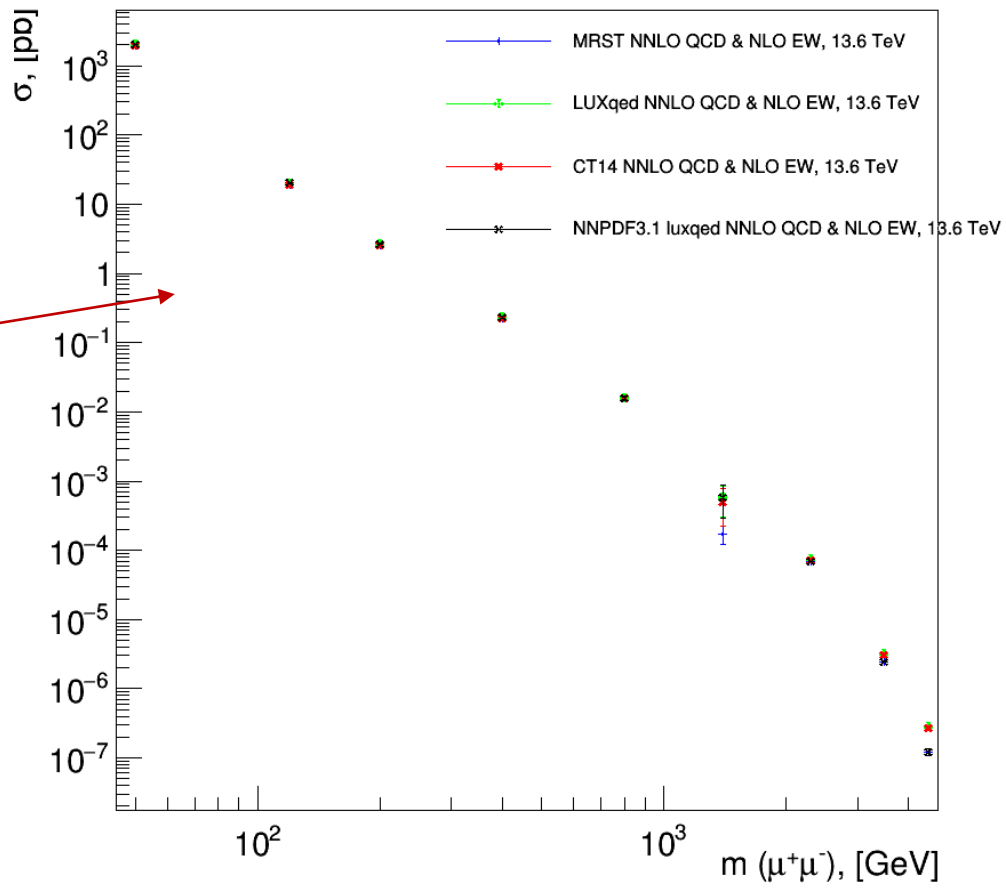
Comparison of distributions
cross sections
of different PDFs
in the order NLO QCD
over the whole phase space



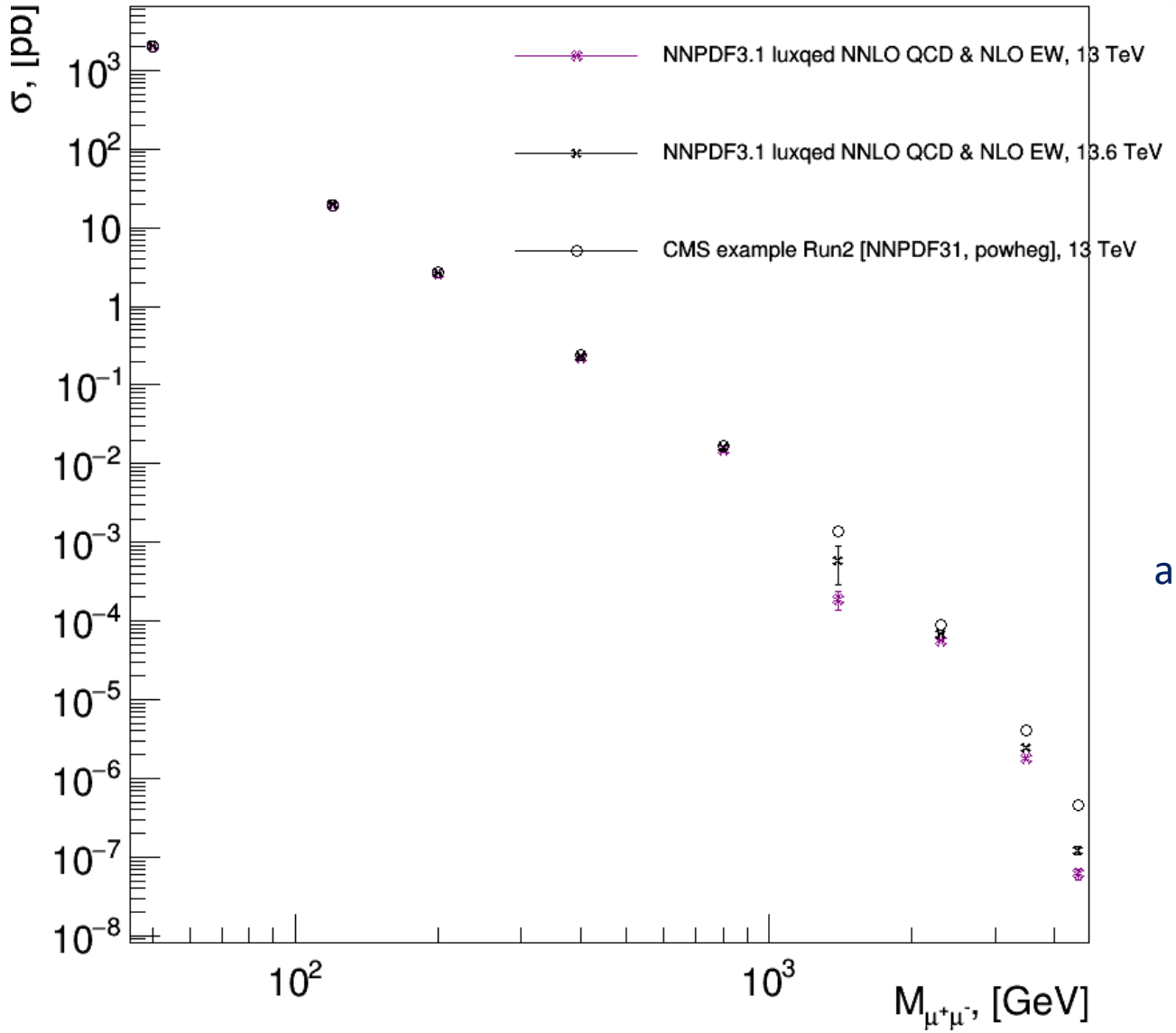
Drell-Yan: FEWZ NNLO QCD results 13 & 13.6 TeV



Comparison of distributions
cross sections
of different PDFs
in the order NNLO QCD
over the whole phase space



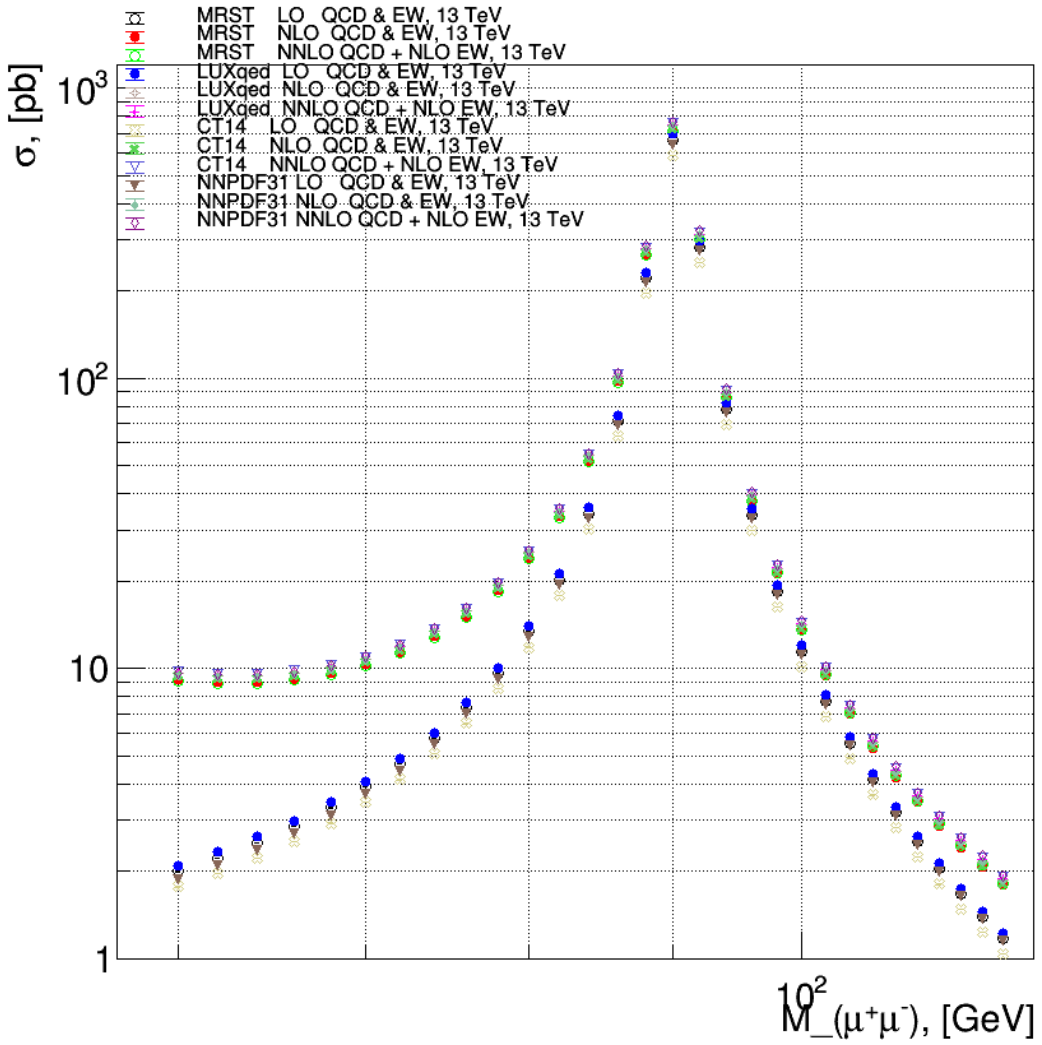
Drell-Yan: FEWZ NNLO QCD results 13 & 13.6 TeV + CMS

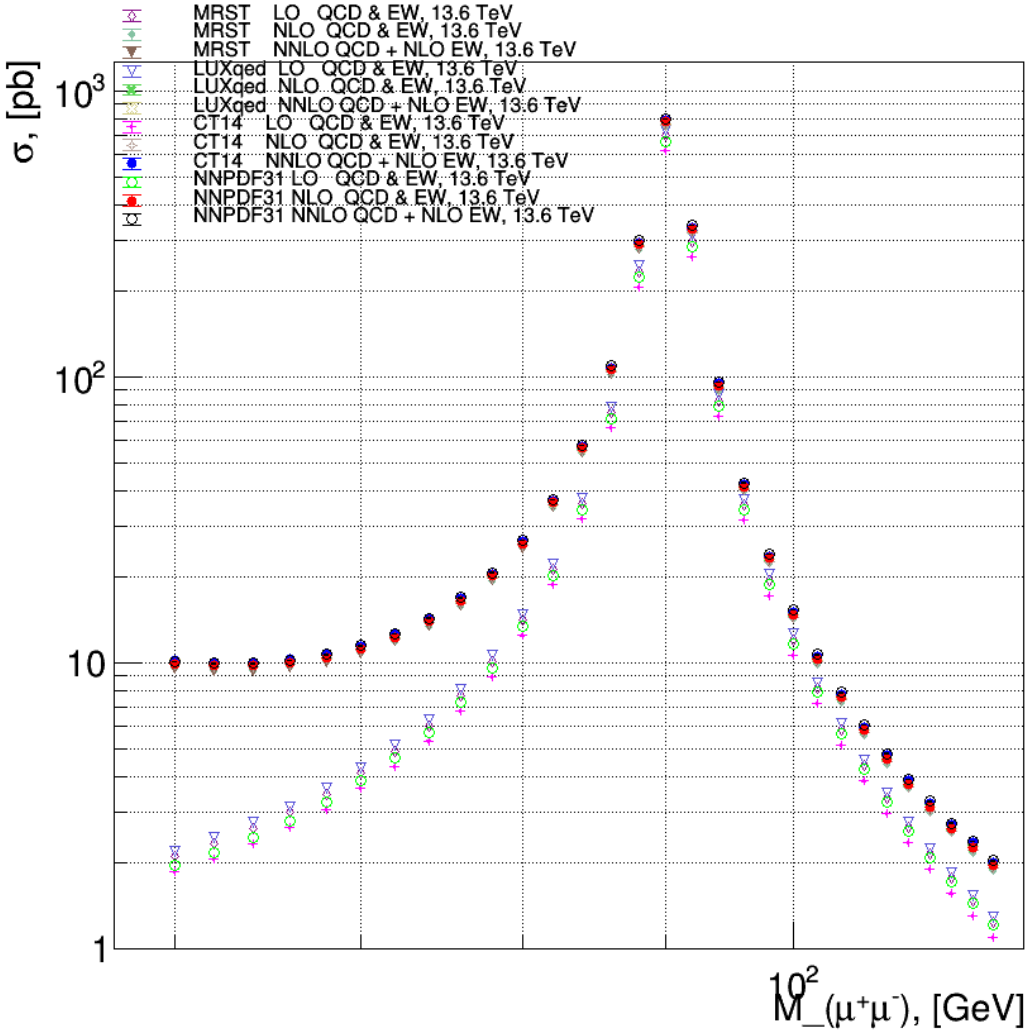


Comparison of distributions
cross sections of NNPDF3.1
in the order NNLO QCD
over the whole phase space
and compare with CMS Run2 examples

Z^0 peak

Calculation of cross sections in the Z^0 peak region M = 60-120 GeV

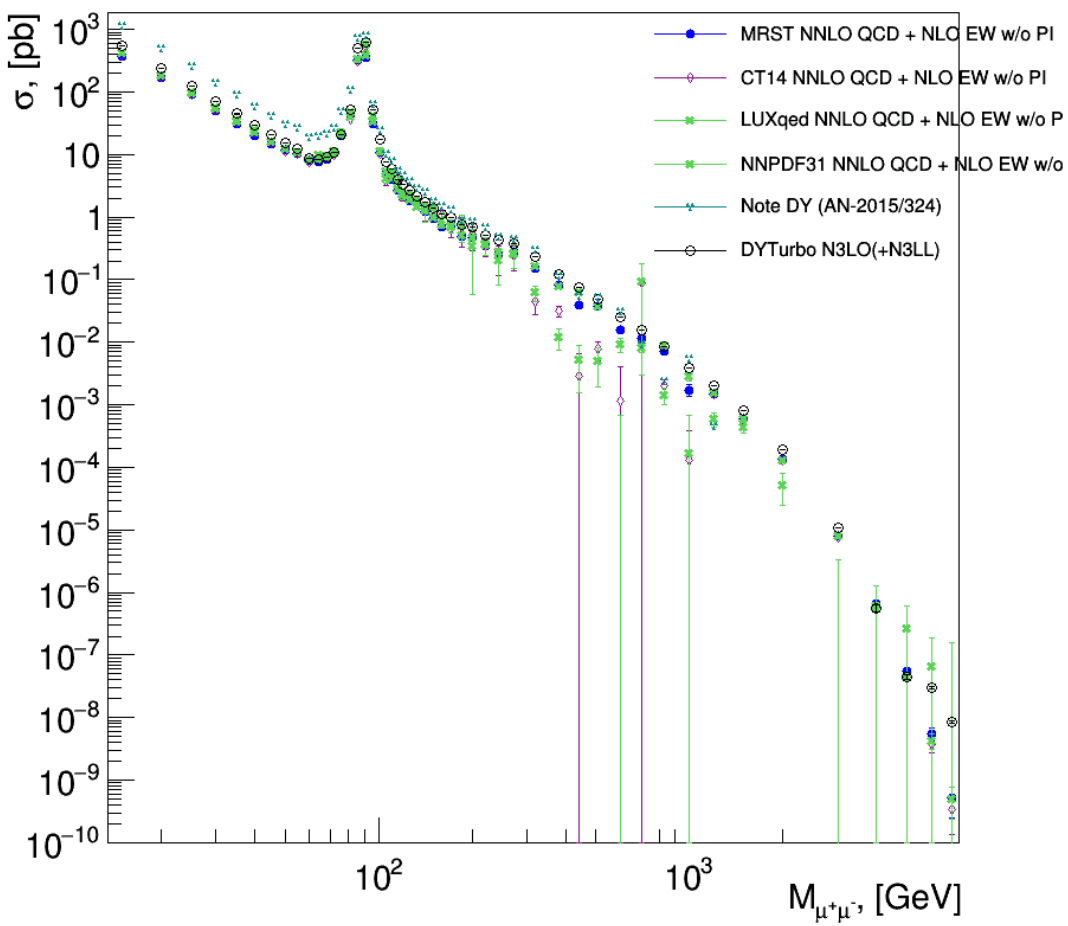


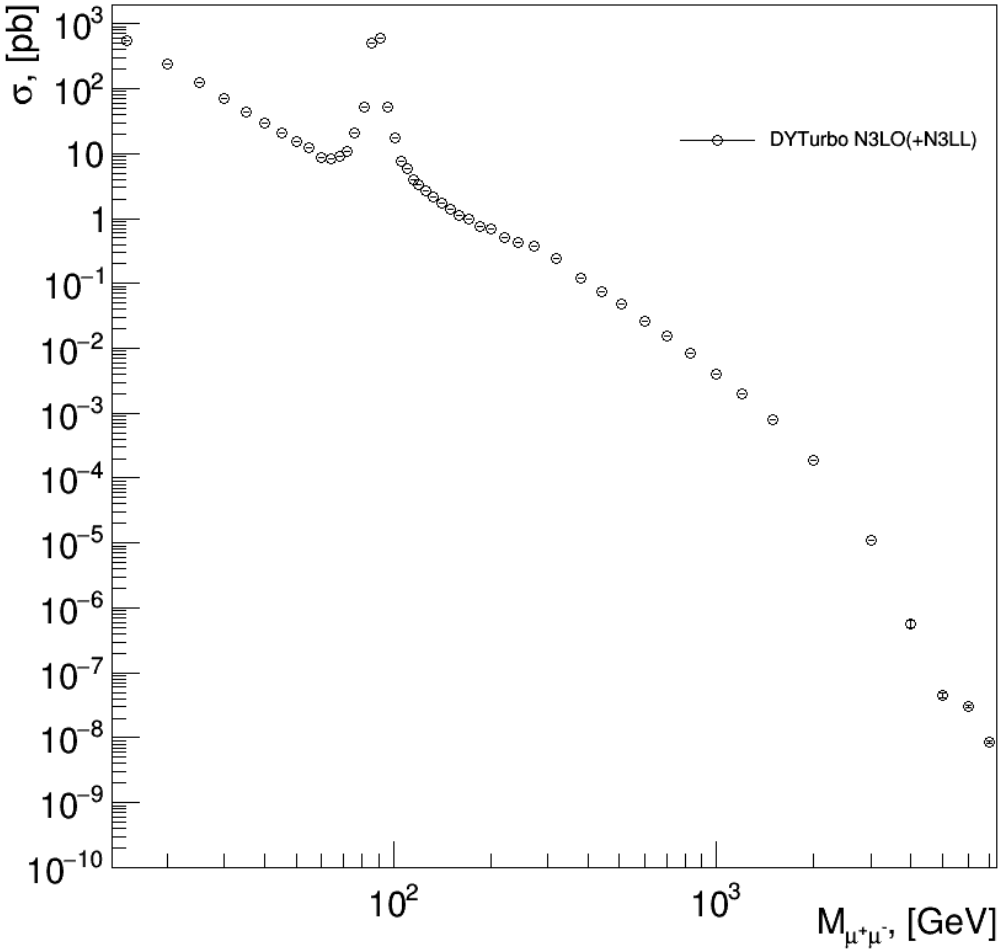


«*DYTurbo*»

arXiv:1910.07049v2

DYTurbo is Monte-Carlo program which provides fast and numerically precise predictions including the full kinematical dependence of the decaying lepton pair at final state and the finite value of the *W* and *Z/γ** - boson width at the N^{3}LO in QCD





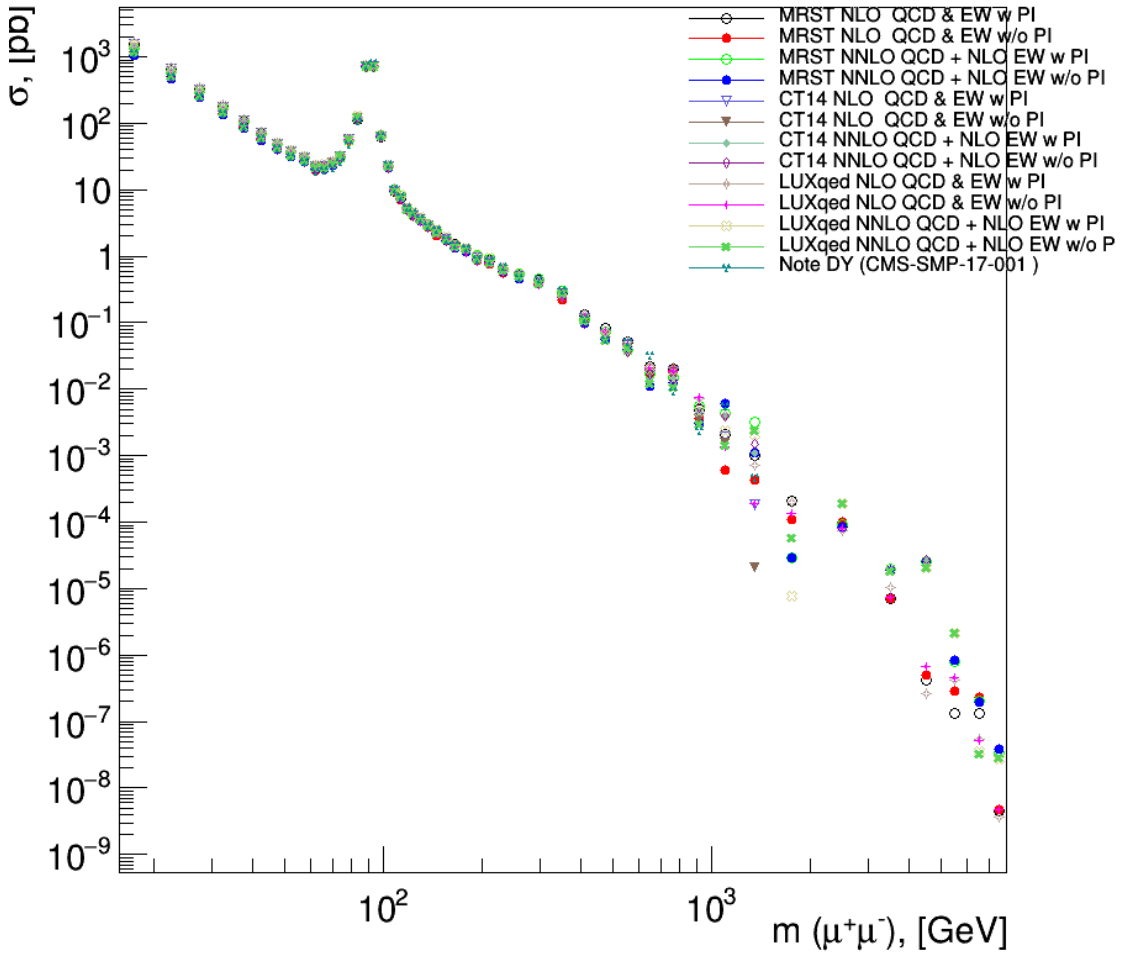
Conclusion

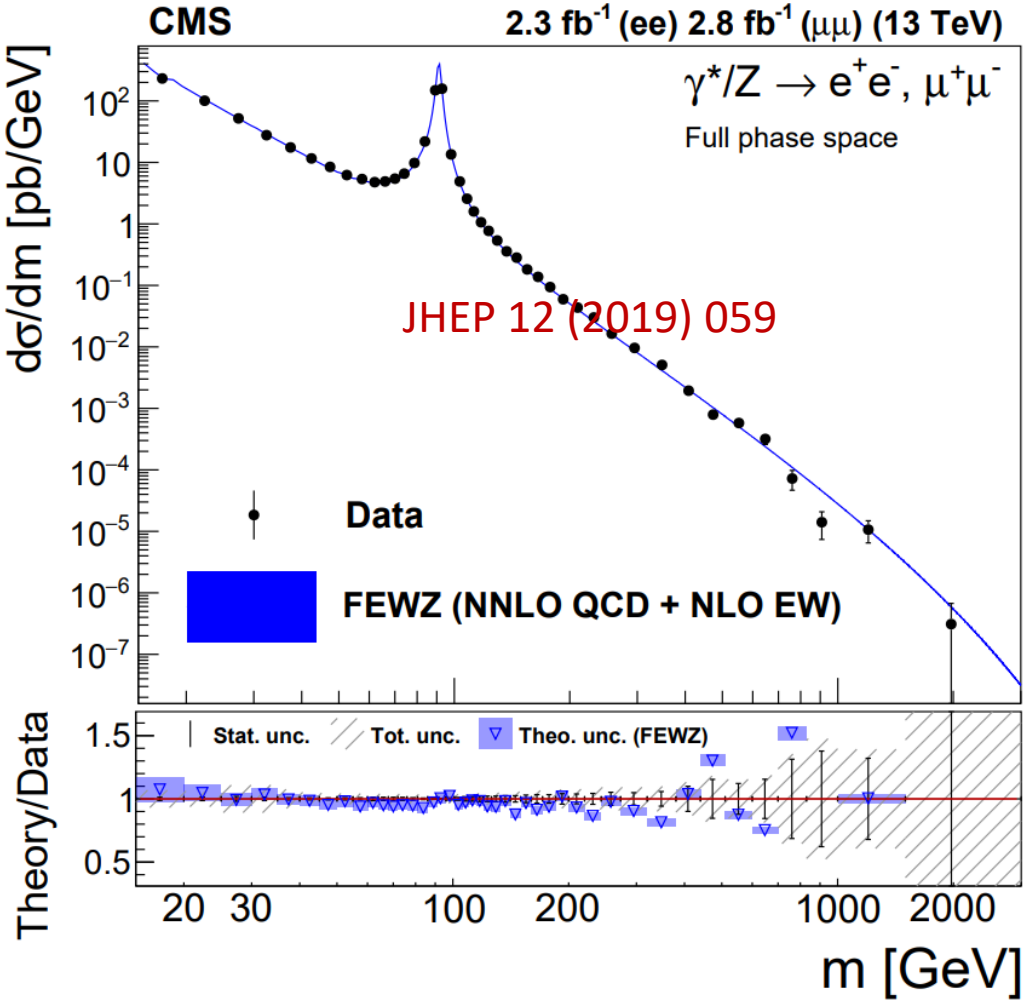
- ✓ Run2 complete 2016-2018 statistics has been processed;
- ✓ Development of methods for the separation of muon pairs in events with more than 2 muons;
- ✓ The selection of same-sign pairs of muons has been made and the first results of the analysis have been obtained;
- ✓ Modeling of photon backgrounds by the FEWZ generator in the order NNLO QCD + NLO EW was carried out. The cross section distributions for various PDFs were obtained;
- ✓ Calculations of Drell-Yan cross sections for various PDF at √s=13 and 13.6 TeV.

Thanks for your attention!

FEWZ NLO + NNLO + DY paper w & w/o PI

Comparison of the cross section distributions as a function of the invariant mass of different PDFs at NLO and NNLO orders, as well as a comparison with cross sections for DY from JHEP 12 (2019) 059 over the entire phase space.





Drell-Yan: NLO/LO & NNLO/NLO results 13 & 13.6 TeV