Low pileup run (CMS)

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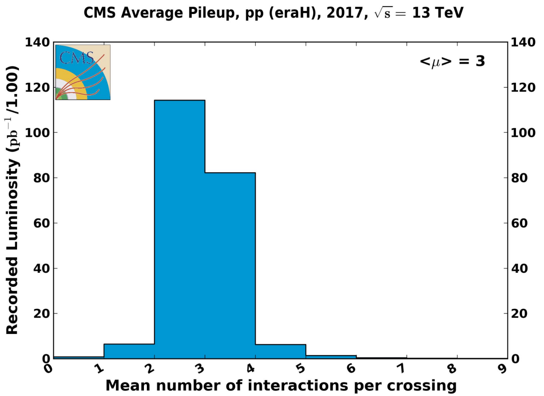
LHC EW WG General Meeting – July 10, 2024

Outline

- **Overview low-pileup data taking in 2017**
- **Projections for W mass measurement using transverse mass**
- **Considerations for a future low-pileup run**
- **Expanding physics program to other measurements**
- **Conclusions**

Low pileup run in 2017



Dedicated low pileup run taken at the end of 2017 (together with ATLAS)

- ~ 5 days of collisions, in total ~ 2 x 10^{12} proton-proton collisions

  → **200 /pb recorded and useful, about 1.6 M reconstructed leptonic W's**
- Average pile up measured to be around ⟨PU⟩ = 3

Runs, fills and machine availability during that time:

Fill	Stable beams Start	Stable beams End	Delivered lumi	Recorded lumi	Recording efficiency	Fill duration (min)	Interfill duration (min)
6404	11/21/2017 17:05	11/21/2017 19:14	13.607	6.41	47	129	0
6405	11/21/2017 21:36	11/22/2017 8:01	45.699	43.893	96	625	142
6411	11/22/2017 21:45	11/23/2017 14:53	52.752	50.907	97	1028	824
6413	11/23/2017 19:37	11/25/2017 0:14	84.303	79.013	94	1717	283
6415	11/25/2017 4:26	11/25/2017 21:43	50.773	48.443	95	1038	252
6417	11/26/2017 1:57	11/26/2017 10:31	25.153	23.856	95	514	254

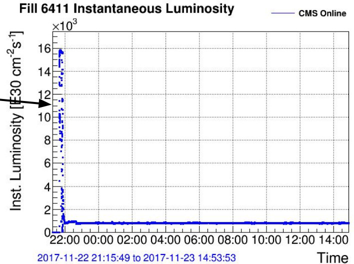
Total lumi delivered/recorded: 272/252 /pb (eff. 92%)

Used for analysis (with HLT trigger): 200 /pb → lower due to high lumi LS at fill start

Total SB time: 84 hours

Total interfill time: 30 hours (25% of total) – 75% time efficiency

Delivered(useful) lumi rate: 60(40) /pb per day



Low pileup run in 2017

CMS W and Z inclusive cross-section measurement

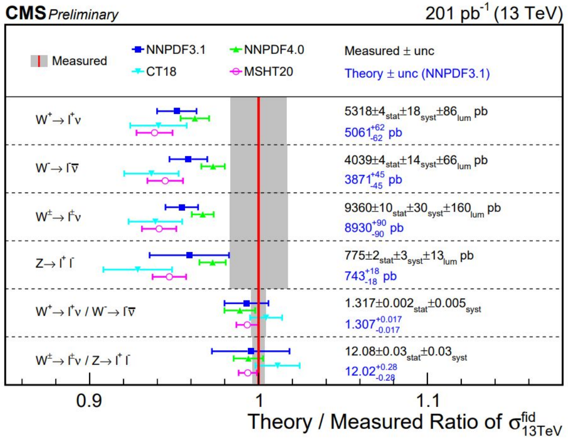
- Both at 13 and 5.02 TeV (HI reference run)
- https://cds.cern.ch/record/2868090

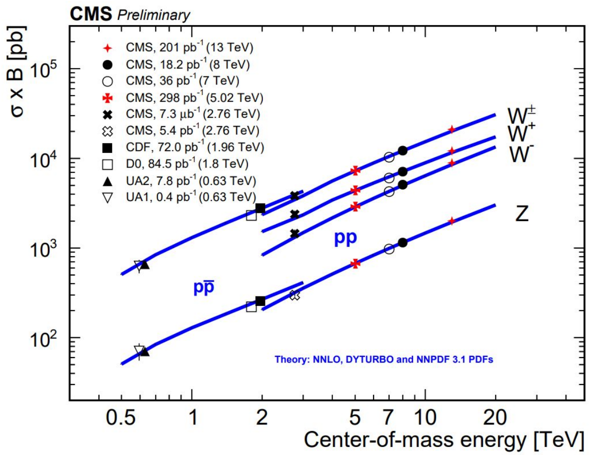
W Differential measurement in progress on the same datasets

Inclusive Top cross-sections using lepton+jets

- Only at 5.02 TeV
- https://cds.cern.ch/record/2895219

Other potential analyses can be done (see later for an overview)

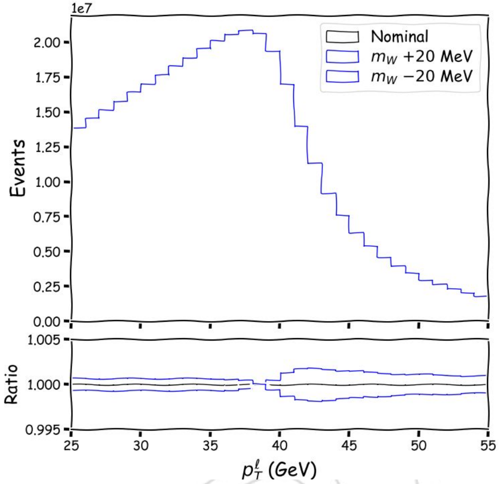


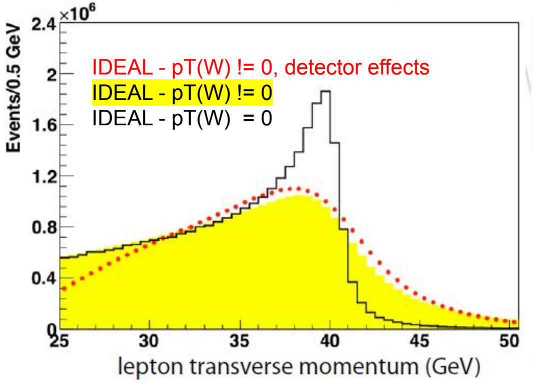


W mass using lepton kinematics

Leptonic channel most promising in LHC environment by precisely measuring the lepton p_T

- Very mild dependency on pileup
- Maximal sensitivity to the lepton momentum scale
  - 10^{-4} relative precision required for a 4 MeV impact on m_W
  - Muons are ideal – fully tracker-based momentum scale
  - More challenging for electrons due to material budget in CMS
- Maximal sensitivity to theory
  - Lepton p_T directly related to boost of W boson
  - QCD modelling crucial
  - PDFs → in-situ constraints
- Can probe large datasets delivered by LHC so far
  - Promising to constrain the theoretical uncertainties, given a well-defined uncertainty model

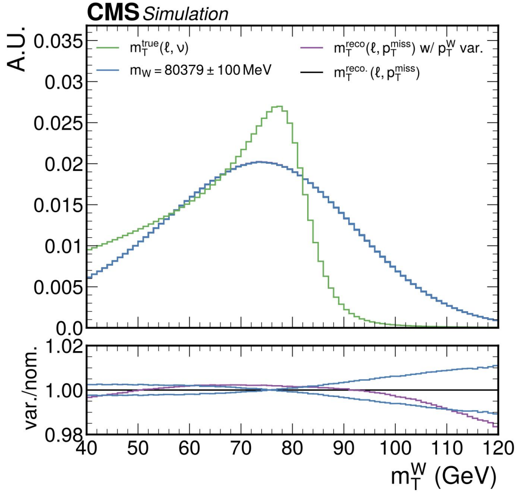




W mass using transverse mass

The transverse mass as an orthogonal measurement of m_W to lepton kinematics

- Different experimental signature: lepton + missing transverse energy (MET)
- More challenging in LHC environment as recoil highly depends on pileup
- Weaker dependency on lepton momentum scale and theory
    - Not negligible, but also less constraining power
- Trade off: MET and recoil calibration enter into the analysis



Transverse mass requires a good MET resolution and excellent control of the recoil calibration and uncertainties

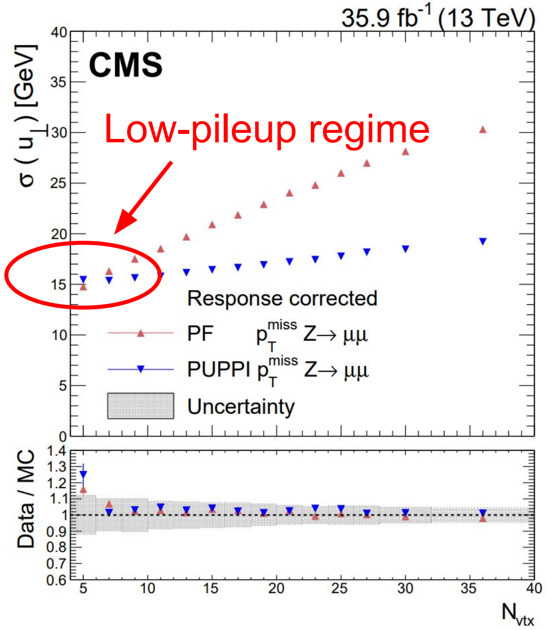
- Resolution dominantly driven by pileup, but also
    - Detector effects (ageing, radiation, holes)
    - Underlying event – scales with center-of-mass
- Excellent recoil calibration procedure is crucial
    - Recoil is a complex object and difficult to model in Monte Carlo
    - Goal to calibrate recoil to 10^{-3} relative precision
    - Sophisticated MC→data calibration needed based on Z→ll events

$$m_T = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\phi)}.$$

MET performance

Low pileup environment provides naturally good MET resolution

- Low pileup means average ⟨PU⟩ < 10
- MET resolution dominated by detector effects and UE
- Mild optimization possible using more sophisticated techniques (e.g. ML)

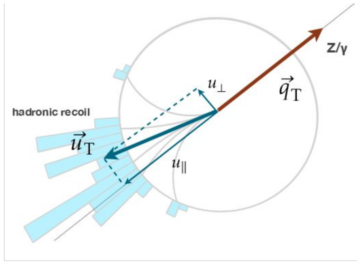


What about high pileup?

- Using machine learning and/or pileup mitigation techniques to separate pileup from hard scatter and define MET accordingly
- Promising resolutions similar to low pileup regime

Regardless of the potential use of transverse mass in high pileup, a measurement of m_W in an independent low pileup dataset is beneficial

- It is based on particle-flow MET in a “clean” environment
- The result can be used to validate the usage of more sophisticated MET estimators in high pileup



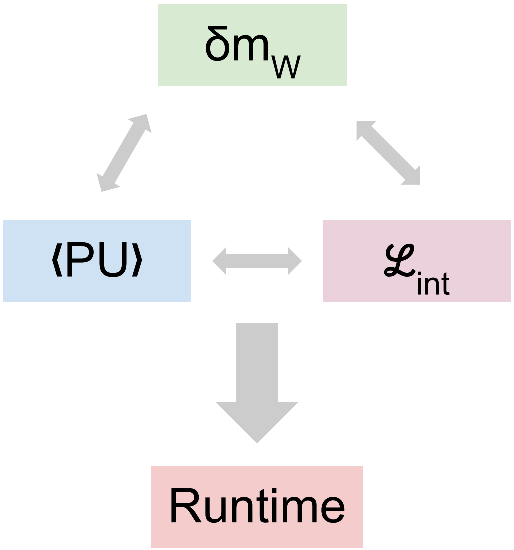
Projection studies

Ideally, aim for a competitive as standalone measurement targeting ~ 15 MeV uncertainty

- Based on a dedicated low-pileup dataset to be take next year (?)
- Bonus: can measure precisely the W width in the tails of m_T
- Resulting in a rich and well-scrutinized dataset that can be used for other measurements (see later)

Detailed projection studies ongoing based on 2017 low pileup dataset

- Estimate the necessary run time, integrated luminosity and under what pileup conditions we need to take data to reach a given uncertainty on m_W
- Projection studies also used to understand the interplay of theoretical uncertainties and PDFs, which can become dominant
- Combination with high pileup W mass analysis

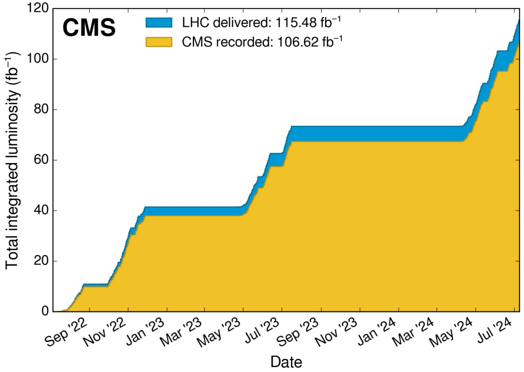


Preliminary results show 15 MeV is achievable, collecting 1 fb^{-1} under the 2017 pileup conditions

Timeline and constraints

Based on the 2017 lowPU run and conditions, it takes 20–30 machine days to take 1 fb^{-1}

- As a consequence, roughly 20–30 fb^{-1} highPU data “lost” during nominal operation
- Corresponds to 5–9% reduction in Run 3 luminosity



Current Run-3 integrated luminosity

Potential low pileup run to be taken next year in 2025

- No beam foreseen in 2026 (?)
- Can take the run independently of ATLAS (and other LHC experiments)
  - Beam separation (already done in 2018 between ATLAS-CMS)
  - Though it seems more difficult to control the luminosity

Considerations of when to take the run in 2025

- Ideally during the first part of 2025 to minimize ageing/radiation damages
  - Can take at the early beginning of the 2025 run during ramp-up phase to reduce the highPU data loss
- Desired to have highPU runs before or after
  - For alignment, lepton calibration (also cosmics during lowPU), efficiencies
  - Avoid Technical stops, magnet ramps, machine interruptions, etc.
- Desired to have VdM before and/or after the run

What else can we do with low pileup data?

Necessary to optimize the data-taking conditions for maximal profit

- A dedicated dataset of 1 fb^{-1} provides various opportunities for other physics
- Well understood dataset in terms of leptons, MET and other objects

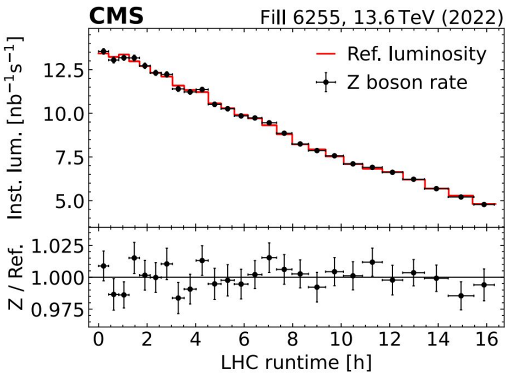
Events produced for 1 fb^{-1}	
W^+	10^8
W^-	$8x10^7$
Z	$5x10^7$
ttbar	$8x10^5$
Higgs (gluon fusion)	$5x10^4$
Higgs (VBF)	$4e10^3$
J/Psi	$6e10^{10}$

Almost direct by-products of measuring m_W using transverse mass

- Inclusive cross-sections
- Competitive differential measurement (W boson p_T) → direct test of theory predictions and models developed and used in m_W measurements

Need to have excellent control of the integrated luminosity

- Apart from traditional luminosity measurements, rely on Z(ll) counting
- Collect as many J/Psi's: complement luminosity measurement, but also heavily used for muon momentum scale calibration



Triggers?

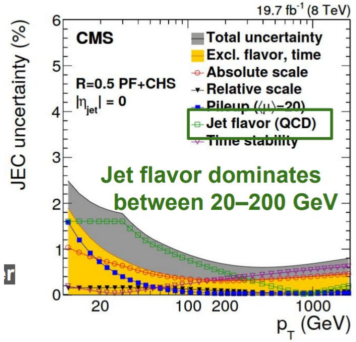
- Bandwidth allows to design exotic triggers or (drastically) lower trigger thresholds

Jet and QCD physics using low pileup data

Large benefit for QCD and jet analyses

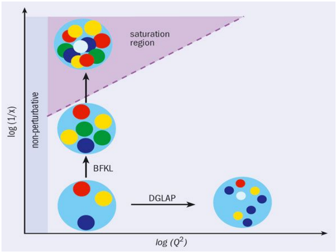
- Possibility for exclusive jet clustering
- Measuring the neutrals becomes possible

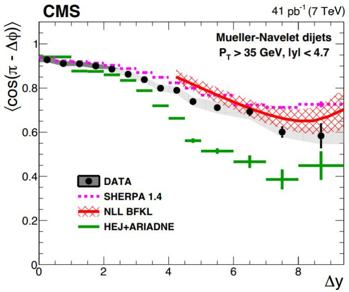
Dataset can become competitive with LEP?



Examples of potential/ongoing analyses

- Inclusive jet cross section towards lower jet p_T
- Dedicated Jet Energy Corrections and jet reconstruction techniques
  - JEC uncertainty driven by jet flavor in low jet p_T regime
- Lund jet plane measurements using Z+jets events
  - Useful to study gluon jets which are not well constrained by LEP measurements
  - Potential improvement to isolate gluon jets from quark jets → reduction in JEC uncertainty
- Study BFKL parton evolution scheme opposed to DGLAP
  - Using e.g. Mueller-Navelet jets with a wide rapidity separation
- Heavy flavor jet observables (e.g. b-jet fraction)





Conclusion

Presented the CMS point-of-view for a *potential* low pileup run to be taken next year

- Motivation to have a standalone and independent measurement of the W mass with a competitive ~ 15 MeV uncertainty
- Projection studies ongoing, but 1 fb^{-1} using ⟨PU⟩ = 3 is reasonable
- Exact data taking conditions are being studied and optimized
- A successful low pileup run will result in a rich and well-scrutinized dataset with various opportunities for other physics analyses

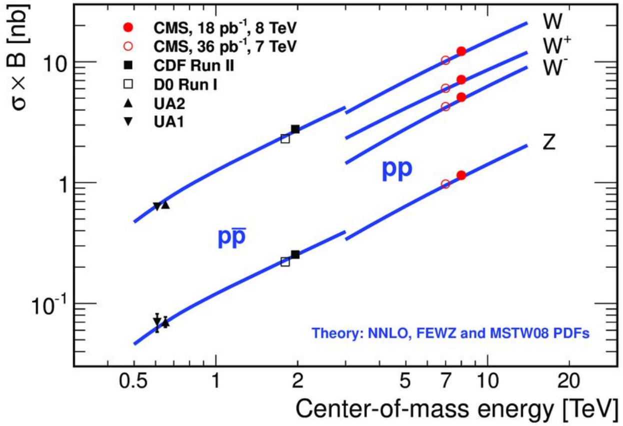
Backup

W mass measurements at hadron colliders

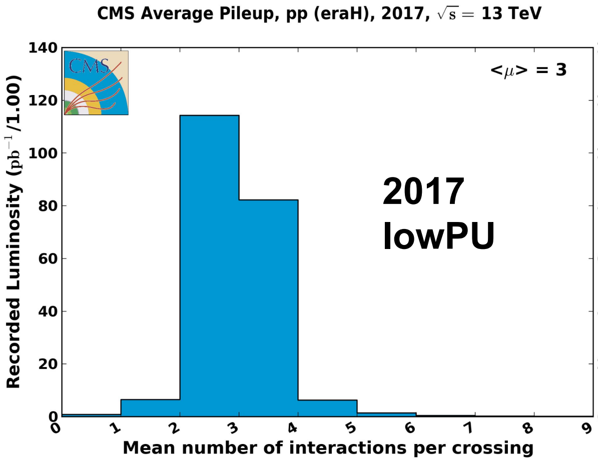
Exp.	Final states	Lumi /fb	W produced (M)	W reconstructed (M)	Stat. Unc. (MeV)	Syst. Unc. (MeV)	Total unc. (Mev)
D0	W → eν (m_T, p_T)	4.3 (1.96 TeV)	120	1.7(e)	13	22	23
ATLAS	W → μ(e)ν (p_T)	4.6 (7 TeV)	450	7.8(e), 5.9(μ), 13.7(tot)	7.0	17.8	19.0
LHCb	W → μν (p_T)	1.7 (13 TeV)	35	2.5(μ)	23.0	21.7	31.6
CDF II	W → μ(e)ν (m_T, p_T, MET)	8.8 (1.96 TeV)	224	1.8(e), 2.4(μ), 4.2(tot)	6.4	6.9	9.4
CMS	W → μν (p_T)	16.8 (13 TeV)	3400	100 (μ)	??	??	??

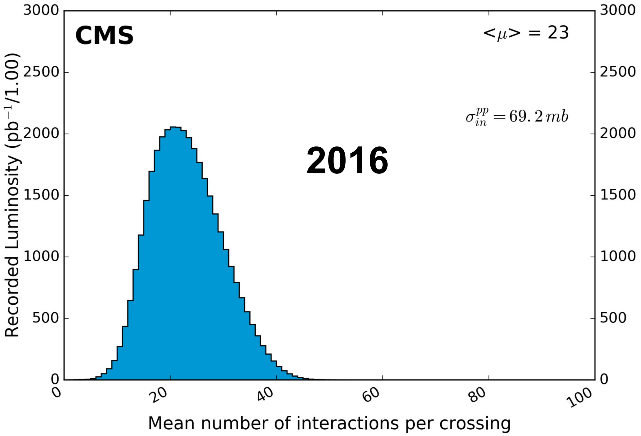
LHC W mass programme at TeV scale proton-proton:

- Profit from larger boson production cross sections
- Drawback at 13.6 TeV is the increase of underlying event activity (~ √s)
- PDFs more challenging than p–pbar → in situ constraints



LowPU vs highPU





CDF and ATLAS mW

Distribution	W boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80\ 429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^{\ell}(e)$	$80\ 411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^{\nu}(e)$	$80\ 426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu,\nu)$	$80\ 446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^{\ell}(\mu)$	$80\ 428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^{\nu}(\mu)$	$80\ 428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80\ 433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

Unc. [MeV]	Total	Stat.	Syst.
p_T^{ℓ}	16.2	11.1	11.8
m_T	24.4	11.4	21.6
Combined	15.9	9.8	12.5