Brandeis University

Electroweak precision measurements at hadron colliders

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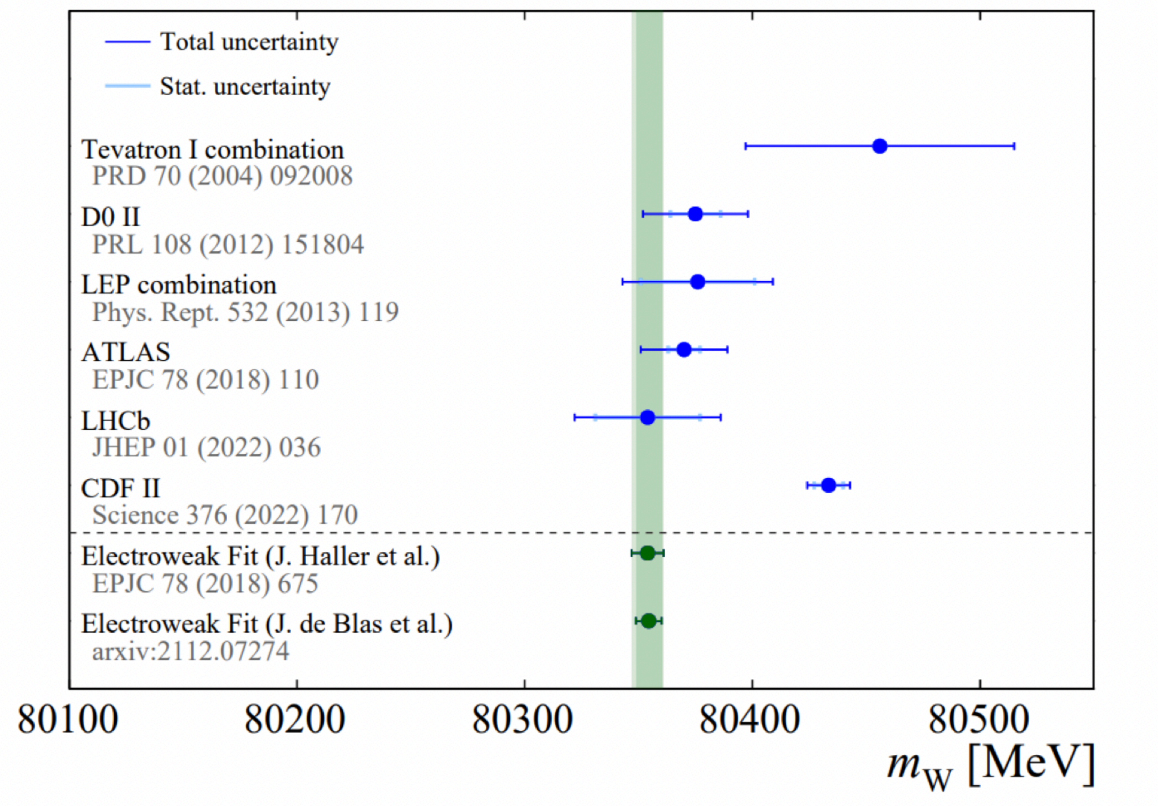
May, 2022

LoopFest XX, University of Pittsburgh

W mass excitement!

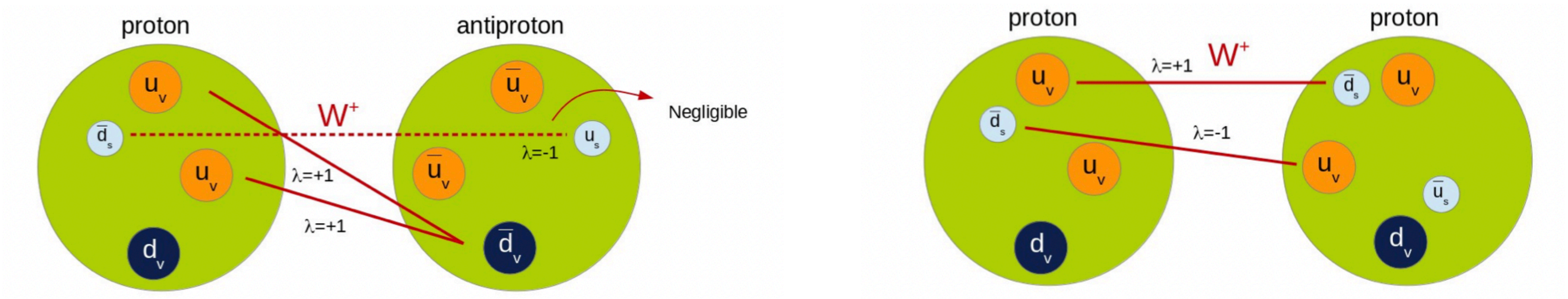
- Impressive precision achieved by CDF (Science 376 (2022) 170)
  - The result is in tension with the SM and other experiments



  - Complex measurements requiring O(5-10) years

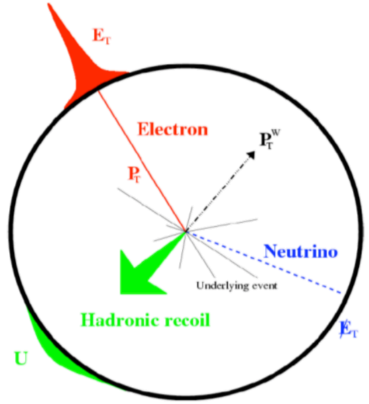
W mass at hadron colliders

- Extremely challenging environment and prone to biases due to QCD effects
  - Proton-proton collider is more challenging compared to proton-antiproton



- QCD complications at LHC:
  - Larger role for heavy flavor induced processes
  - W polarization uncertainty affecting the lepton pT
  - Larger gluon induced W production,
  - W+,W-, and Z produced by different light flavor fractions,
  - …

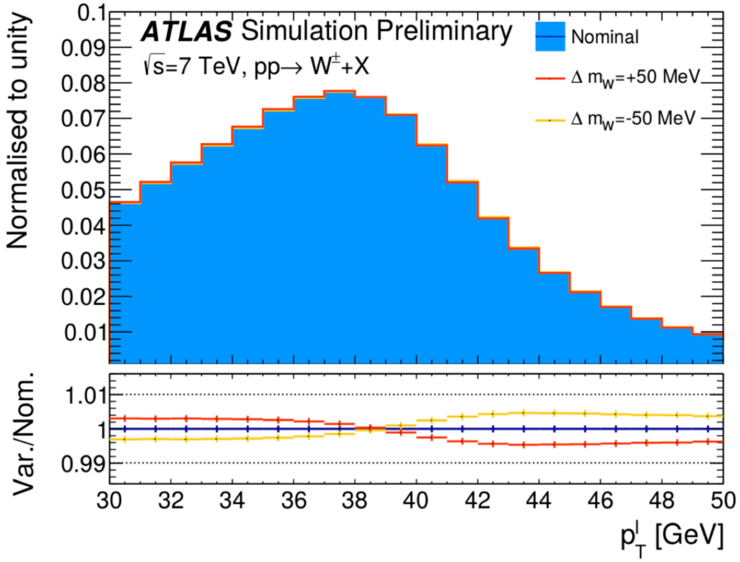
How do we measure W mass?

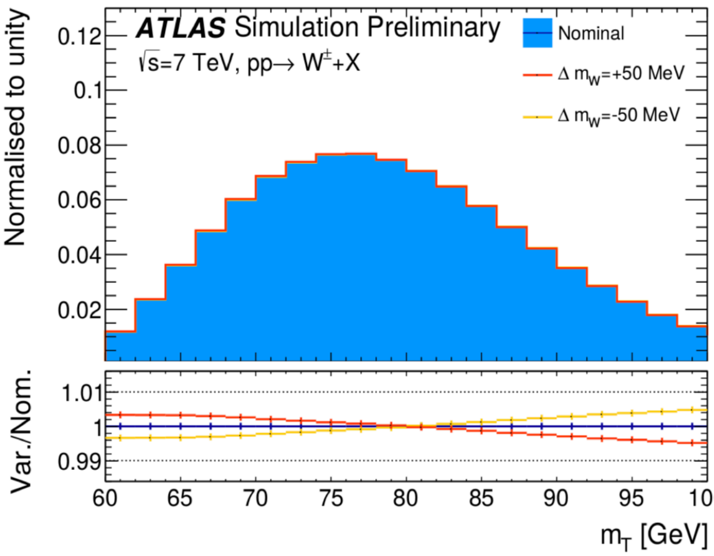


- Main signature is a final state lepton (electron or muon)
- Neutrino escapes detection-> missing energy

$$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\left(\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{u}_{\mathrm{T}}\right) \qquad m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi)}$$

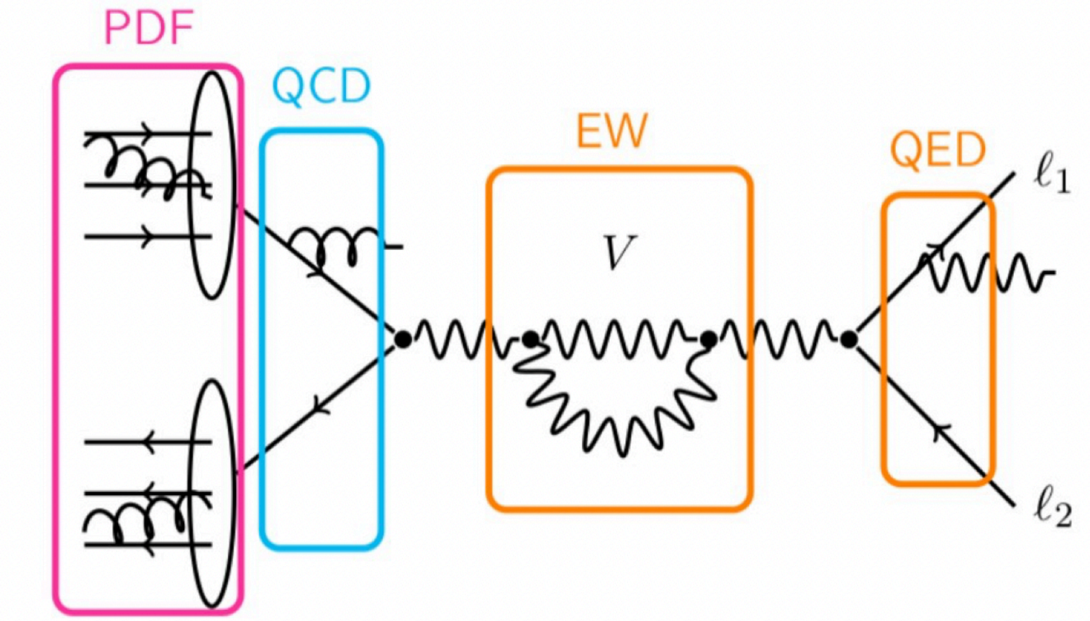
- Lepton p_T has a Jacobian edge at $m_W/2$
- m_T has a Jacobian edge at m_W
- Fit the distributions of p_T and m_T (also p_T^{miss}) to determine W mass





W mass measurement ingredients

- Precise momentum calibrations (not discussed here)
  - Requires huge amount of work
- Physics modeling (experimental and theoretical challenges)
  - Parton distribution functions (PDFs)
  - Measurements of pT W, pT W/Z
  - Electroweak corrections
  - Measurements and predictions of angular coefficients



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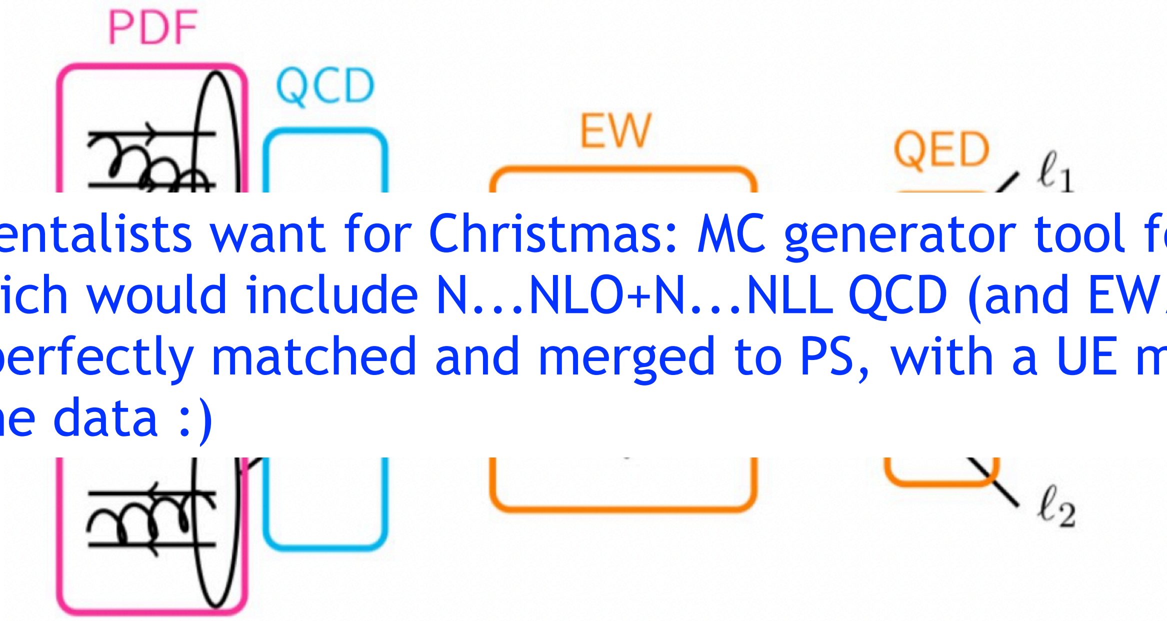
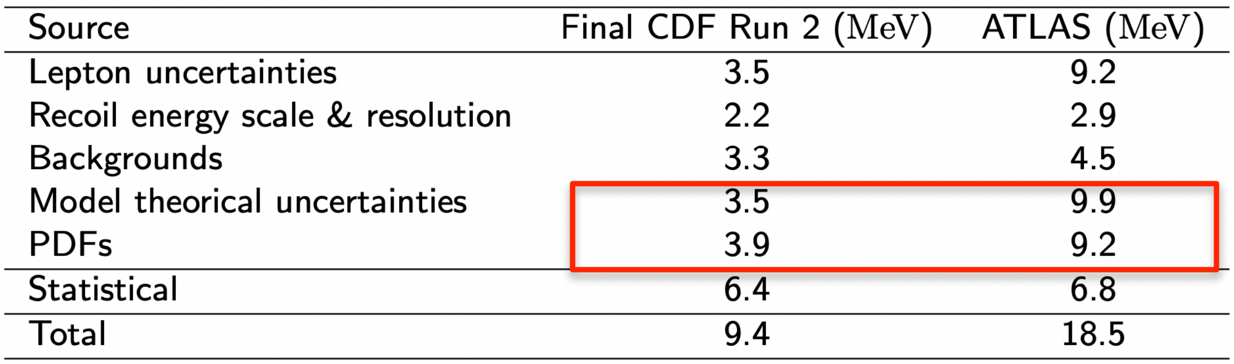


What experimentalists want for Christmas: MC generator tool for DY production which would include N...NLO+N...NLL QCD (and EW/QED) calculations, perfectly matched and merged to PS, with a UE model reproducing the data :)

Systematic uncertainties

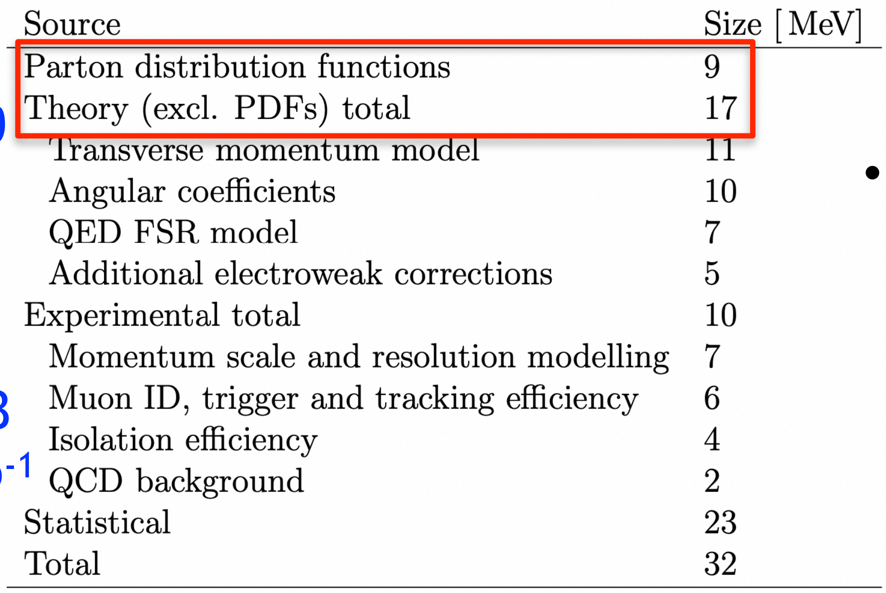
- Focus on 3 recent measurements: CDF2, ATLAS, and LHCb



Source	Final CDF Run 2 (MeV)	ATLAS (MeV)
Lepton uncertainties	3.5	9.2
Recoil energy scale & resolution	2.2	2.9
Backgrounds	3.3	4.5
Model theorical uncertainties	3.5	9.9
PDFs	3.9	9.2
Statistical	6.4	6.8
Total	9.4	18.5

CDF:
Science 376 (2022) 170
$\sqrt{s}$=1.96 TeV, 8.8 fb^{-1}

ATLAS:
arXiv:1701.07240
$\sqrt{s}$=7 TeV, 4.6 fb^{-1}



Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

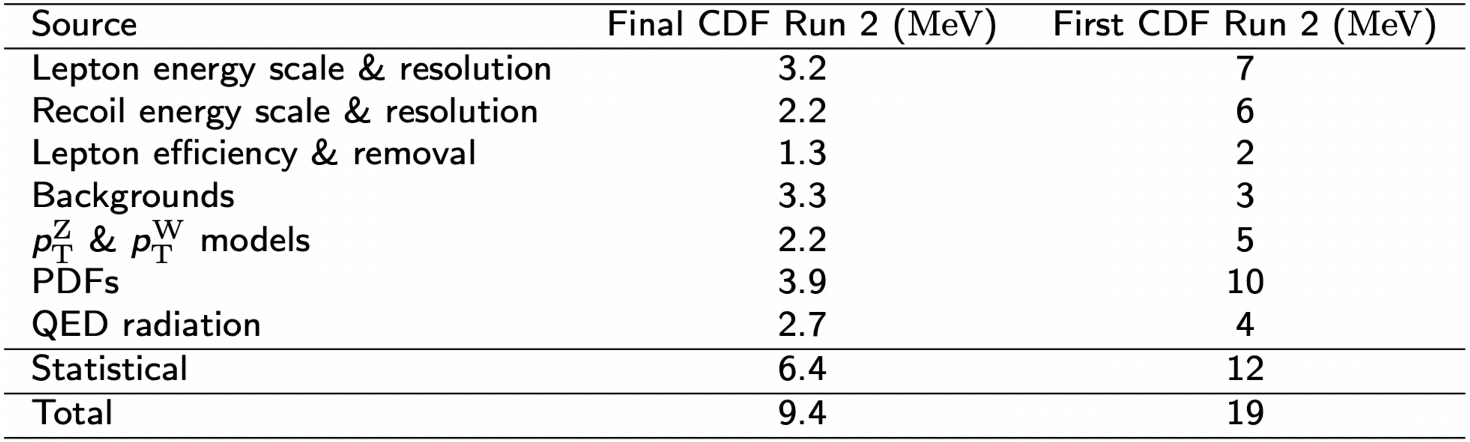
LHCb:
arXiv:2109.01113
$\sqrt{s}$=13 TeV, 1.7 fb^{-1}

- Similar statistical precision between ATLAS and CDF
- Larger theoretical uncertainties in ATLAS and LHCb results

- Larger datasets at the LHC yet to be explored
  - Larger Z samples for detector calibration
  - Possible in-situ theory constrains
  - Larger detector coverage

CDF PDF uncertainties

- W asymmetry and Z rapidity measurements directly constrain the valence and sea PDFs in the x,Q region relevant for W mass measurements
- CDF reduced the PDF uncertainty with respect to the previous measurement by using newer PDF sets at NNLO (NNPDF 3.1)
  - Uncertainty reduced from 10 MeV to 3.9 MeV
  - Moves the central value of W mass by +3.5 MeV

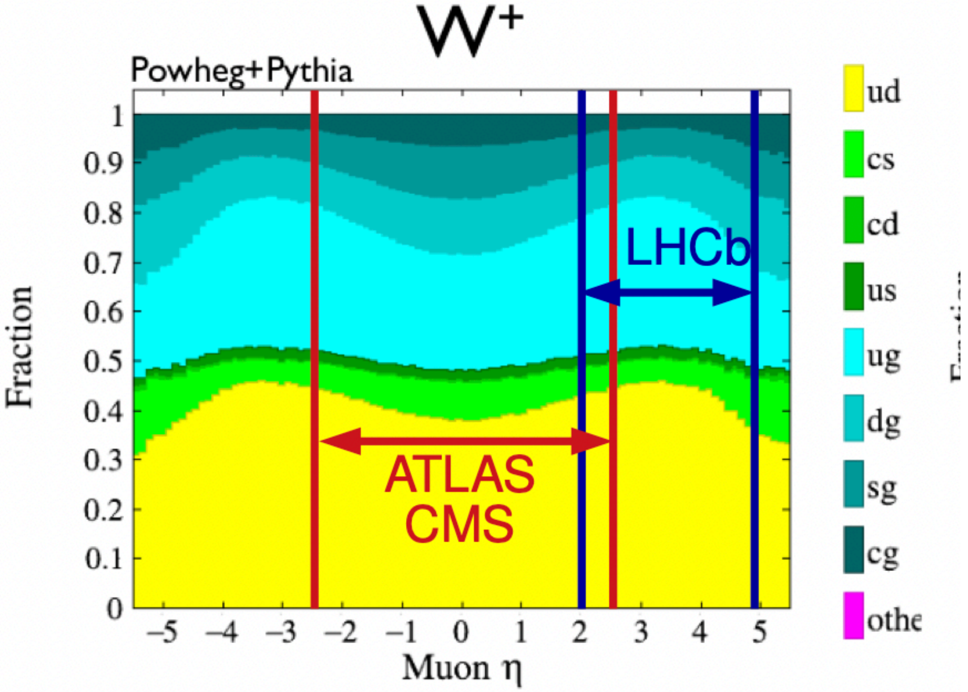


Source	Final CDF Run 2 (MeV)	First CDF Run 2 (MeV)
Lepton energy scale & resolution	3.2	7
Recoil energy scale & resolution	2.2	6
Lepton efficiency & removal	1.3	2
Backgrounds	3.3	3
p_T^Z & p_T^W models	2.2	5
PDFs	3.9	10
QED radiation	2.7	4
Statistical	6.4	12
Total	9.4	19

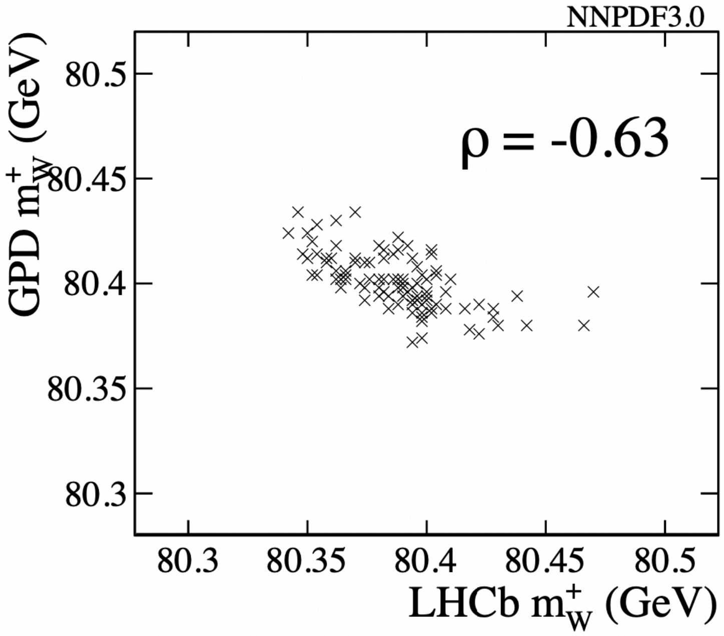
- Previous measurement should change by +13.5 MeV after the analysis improvements (calibrations, PDF, etc.)

LHCb measurement

- LHCb fiducial region is highly complementary to ATLAS/CMS at the LHC
- W production at the LHCb has a different flavor decomposition with respect to ATLAS and CMS
- PDF uncertainty are uncorrelated or anti-correlated between ATLAS/CMS and LHCb, and the corresponding uncertainty will reduce in the combination



Taken from slides by S. Camarda



arXiv:1508.06954

W mass and W pT

- W pT distribution must be known to very good precision for the W mass measurement, especially when fitting the lepton pT distribution
  - Roughly: O(%) uncertainty in W pT translates to O(10) MeV uncertainty
- Approach is based on very precise measurement of Z pT and accurate predictions of W/Z pT ratio

$$\frac{\mathrm{d}\sigma(W)}{\mathrm{d}p_T} = \left[\frac{\mathrm{d}\sigma(W)/\mathrm{d}p_T}{\mathrm{d}\sigma(Z)/\mathrm{d}p_T}\right]_{\text{theory}} \times \left[\frac{\mathrm{d}\sigma(Z)}{\mathrm{d}p_T}\right]_{\text{measured}}$$

- Require great understanding of:
  - Non-perturbative QCD effects
  - qT Resummation
  - Heavy flavor initiated production

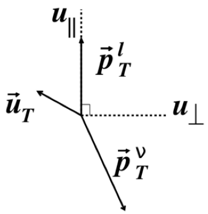
- Different approaches for the measurements:
  - ATLAS uses Pythia8 predictions tuned on Z pT
  - LHCb uses Powheg+Pythia8 predictions tuned on Z pT
  - CDF uses Resbos (NNLL + NLO)

CDF W pT

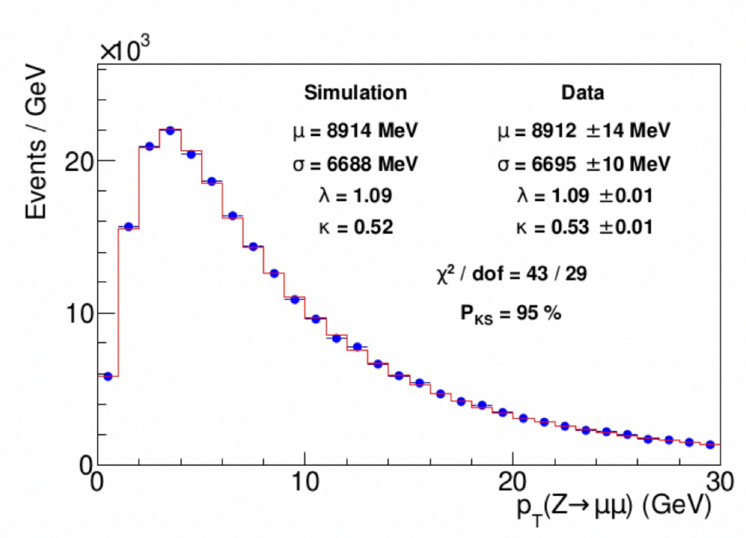
- Fitting the non-perturbative g_2 parameter in Resbos using the dilepton pT
- α_s is also tuned using dilepton pT
  - 1.8 MeV uncertainty from pT Z

$$S = \left[g_1 - g_2 \log \left(\frac{\sqrt{\hat{s}}}{2Q_0} \right) - g_1 g_3 \log \left(\frac{100 \hat{s}}{s} \right) \right] b^2,$$

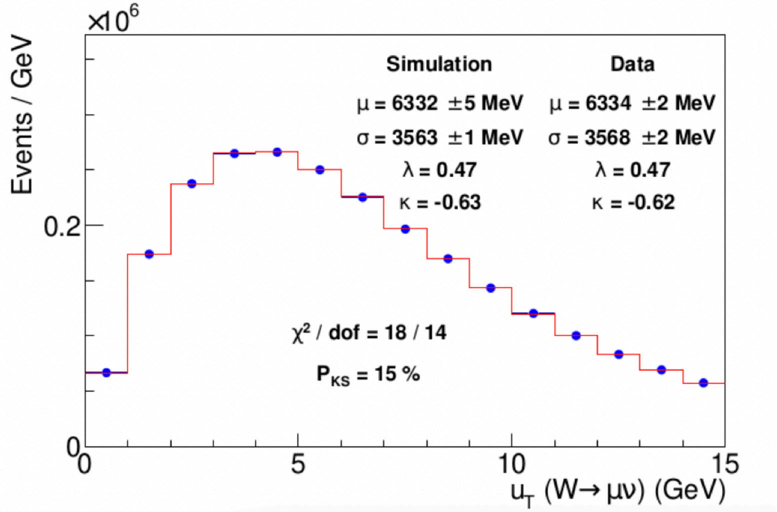
- New feature in the analysis: Use the recoil pT distribution to constrain the scale uncertainties in the pTW/pTZ ratio (evaluated with DYQT)
  - Impressive recoil resolution (low √s) and agreement with data
  - 1.3 MeV uncertainty from pTW/pTZ



$$|\vec{u}| = |\textstyle\sum_i E_i sin\theta_i|$$



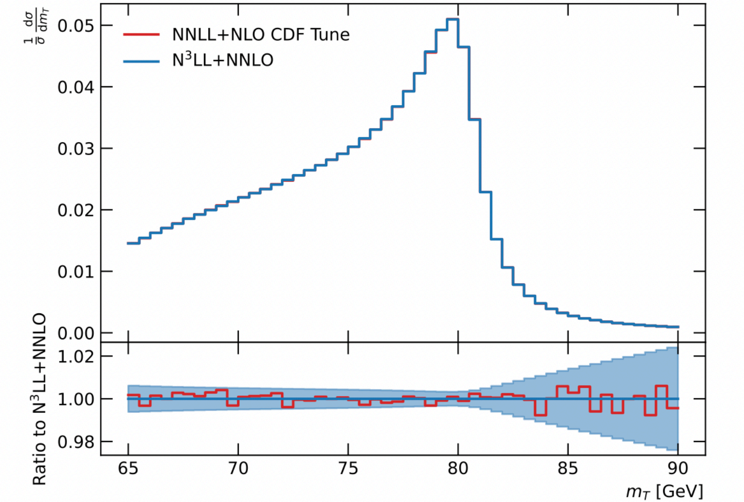
Z pT



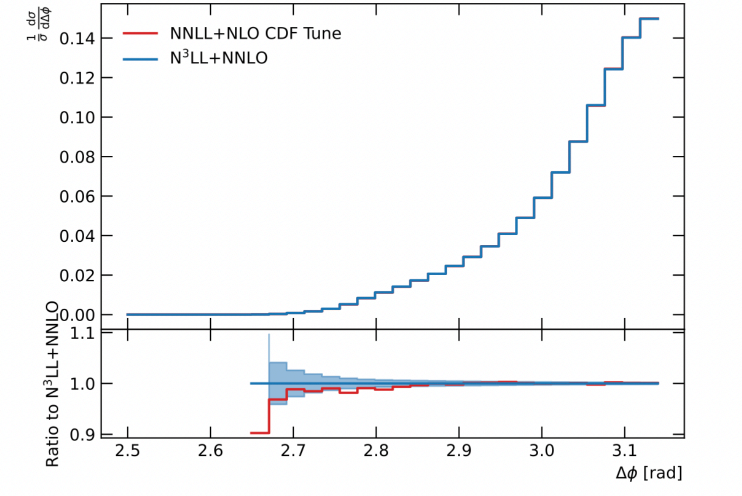
Recoil u_T

Resbos2 and W mass

- Interesting recent paper by Resbos authors to study the impact of Resbos2 with N^{3}LL+NNLO accuracy compared to the older version of Resbos used in CDF measurement
  - Arxiv: 2205.02788. The data-driven approach perhaps captures most of the higher order corrections.
- Issue with angular coefficients with Resbos version used by CDF
  - It appears the impact of the angular coefficients is small. Tight requirement with recoil |u| < 15 GeV.



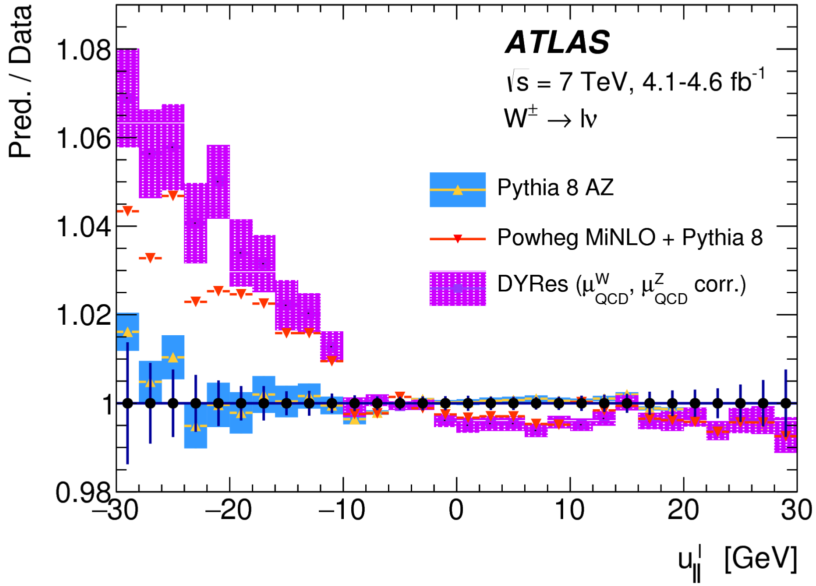
Transverse mass

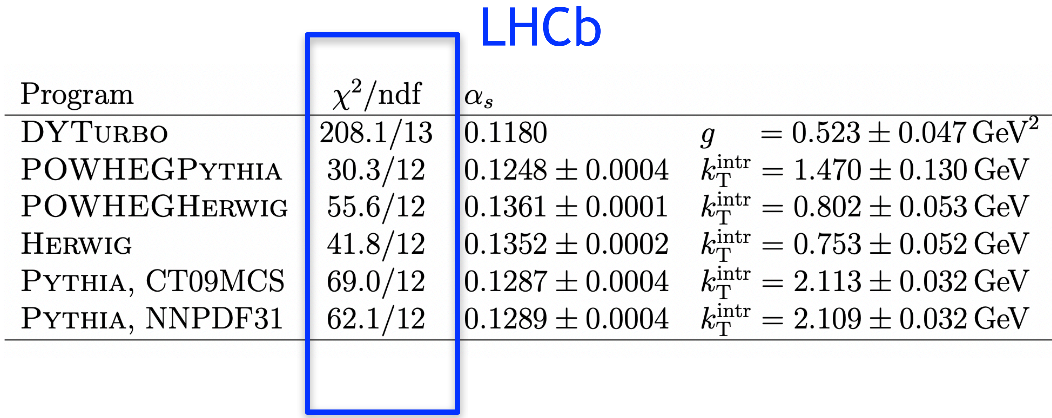


Δϕ

ATLAS/LHCb W pT modeling

- ATLAS and LHCb find better agreement with data by tuning Pythia8 instead of higher order resummed calculations
  - α_s and intrinsic kT are mainly used to tune to Z pT
- DYTurbo is used to compute the angular coefficients at (α_s^2)
  - Good agreement with ATLAS measurements of angular coefficients
  - LHCb uses a scaling factor for A_3 in the W mass fit to reduce the uncertainties by factor of three (10 MeV uncertainty)




LHCb

Program	χ^2/ndf	α_s	
DYTurbo	208.1/13	0.1180	$g = 0.523 \pm 0.047\,\mathrm{GeV}^2$
POWHEGPythia	30.3/12	0.1248 ± 0.0004	$k_T^{\rm intr} = 1.470 \pm 0.130\,\mathrm{GeV}$
POWHEGHerwig	55.6/12	0.1361 ± 0.0001	$k_T^{\rm intr} = 0.802 \pm 0.053\,\mathrm{GeV}$
Herwig	41.8/12	0.1352 ± 0.0002	$k_T^{\rm intr} = 0.753 \pm 0.052\,\mathrm{GeV}$
Pythia, CT09MCS	69.0/12	0.1287 ± 0.0004	$k_T^{\rm intr} = 2.113 \pm 0.032\,\mathrm{GeV}$
Pythia, NNPDF31	62.1/12	0.1289 ± 0.0004	$k_T^{\rm intr} = 2.109 \pm 0.032\,\mathrm{GeV}$

Resummation benchmarking studies

- Resummation benchmarking for DY production at LHC
  - Has never been done before
  - Step by step: start with pT Z
- Work is done in the context of the wider LHC precision EW working group, which itself is a sub-group of the LPCC SM WG
  - Many theorists working on resummation calculations together with a few experimentalists
  - Huge thanks to all theory colleagues for answering our questions over the last three years
- Compare predictions and understand their differences, uncertainties, and accuracy
  - One theorist's implicit assumption is another theorist's uncertainty
- The effort started in 2018 and we have now produced enough interesting results that it is hoped to publish this by the end of this year
  - Comprehensive summary by Johannes:
    - https://indico.cern.ch/event/1108518/

Participating codes

TMD global fit tools (Collins/Soper/Sterman formalism):

`artemide`	Scimemi, Vladimirov ’17, ’19
`NangaParbat`	Bacchetta et al. ’19
`ResBos2`	Isaacson ’17

Direct QCD (Catani/de Florian/Grazzini formalism):

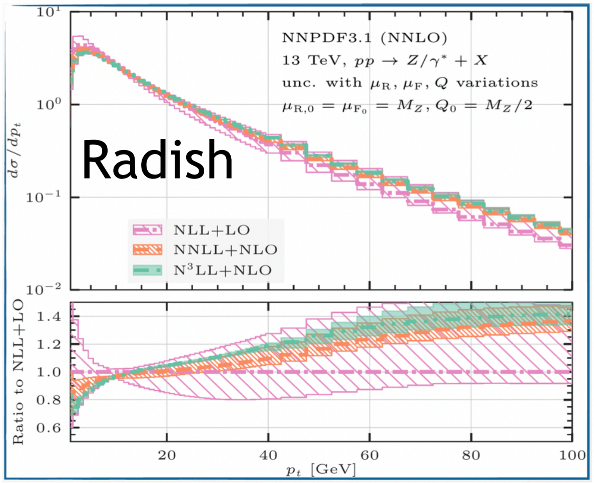
`DYRes/DYTurbo`	Camarda et al. ’15, ’19, ’21
`reSolve`	Coradeschi, Cridge ’17

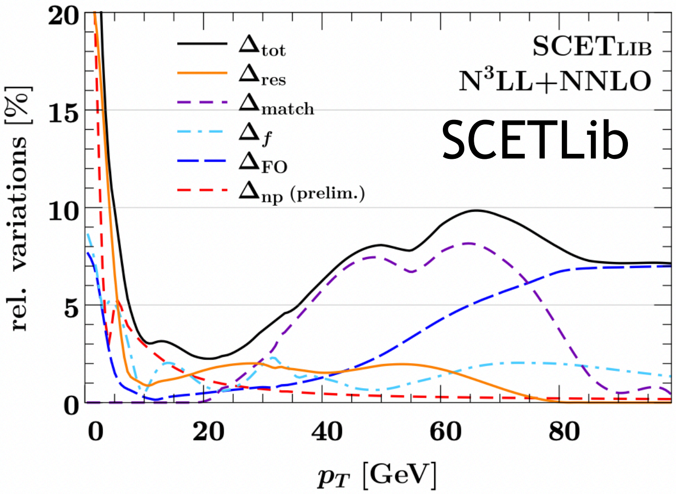
SCET-based tools:

`CuTe-MCFM`	Becher, Neumann ’11, ’20
`SCETlib`	Billis, Ebert, JM, Tackmann ’17, ’20

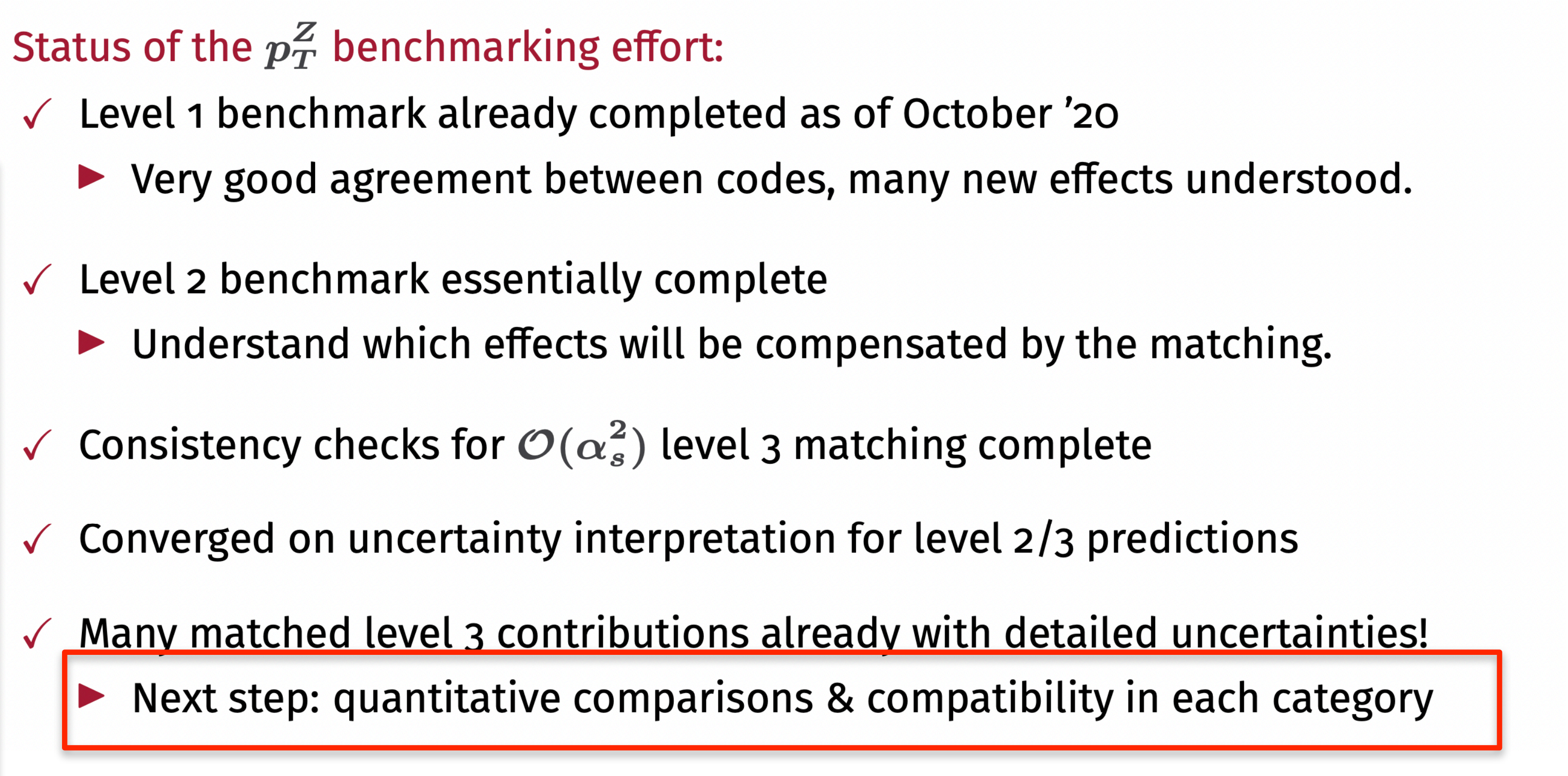
Coherent branching/momentum-space resummation:

`RadISH`	Monni, Re, Rottoli, Torrielli ’16, ’17, ’19, ’21





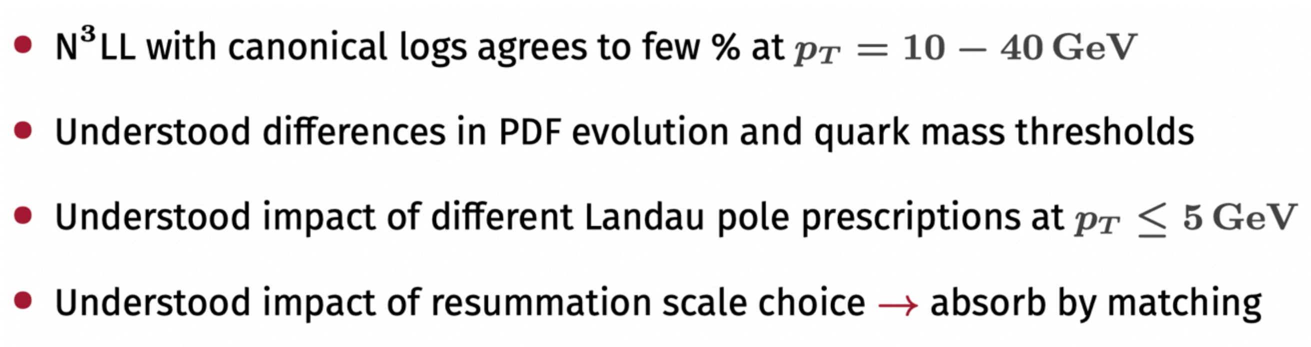
Benchmarking status



Status of the p_T^Z benchmarking effort:

- ✓ Level 1 benchmark already completed as of October ’20
  - ▶ Very good agreement between codes, many new effects understood.
- ✓ Level 2 benchmark essentially complete
  - ▶ Understand which effects will be compensated by the matching.
- ✓ Consistency checks for $\mathcal{O}(\alpha_s^2)$ level 3 matching complete
- ✓ Converged on uncertainty interpretation for level 2/3 predictions
- ✓ Many matched level 3 contributions already with detailed uncertainties!
  - ▶ Next step: quantitative comparisons & compatibility in each category

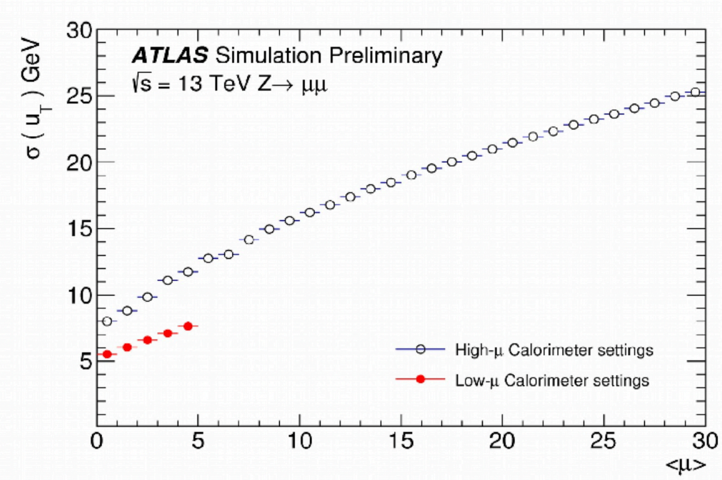
Level 1,2

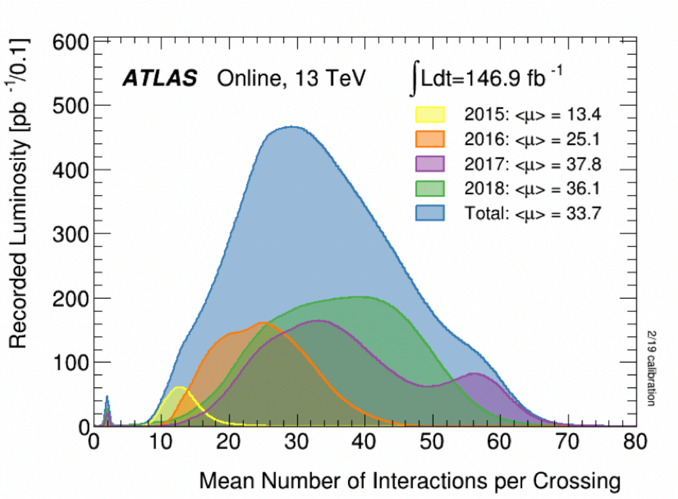


- N^{3}LL with canonical logs agrees to few % at $p_T = 10 - 40\,\mathrm{GeV}$
- Understood differences in PDF evolution and quark mass thresholds
- Understood impact of different Landau pole prescriptions at $p_T \leq 5\,\mathrm{GeV}$
- Understood impact of resummation scale choice → absorb by matching

LHC W mass measurements

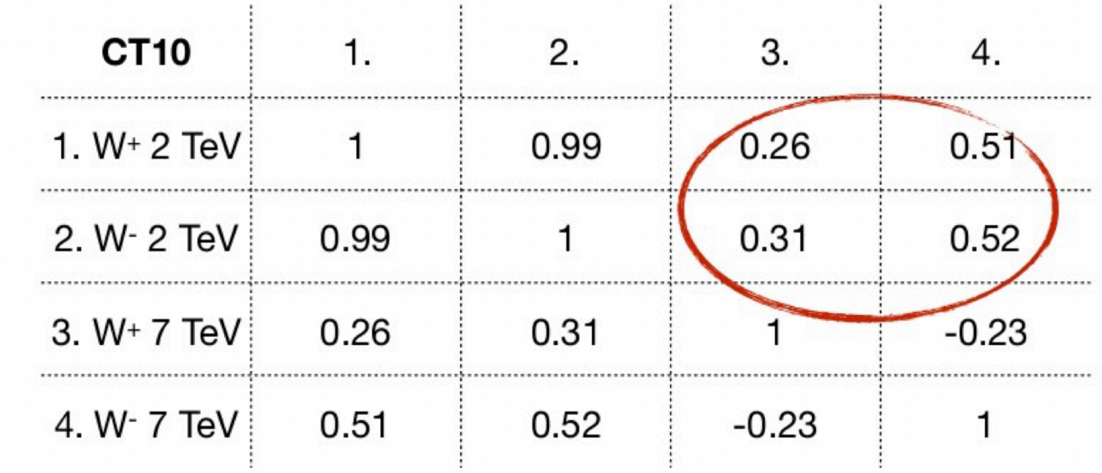
- Much harder data taking conditions at LHC due to ~10 times more pileup events
  - Degradation of the recoil resolution with pileup (lepton pT becomes dominant compared to mT)
- For the same integrated luminosity the number of W bosons events at the LHC is about 10 times larger than Tevatron
  - Factor of ~5 larger cross section,Factor of ~2 larger detector coverage
- Dedicated low pileup runs at the LHC are important for mT based W mass measurements as well as for W pT measurements to constrain theory modeling and uncertainties for lepton pT based W mass measurements
  - Orthogonal approaches with high and low pileup measurements





LHC and Tevatron combinations

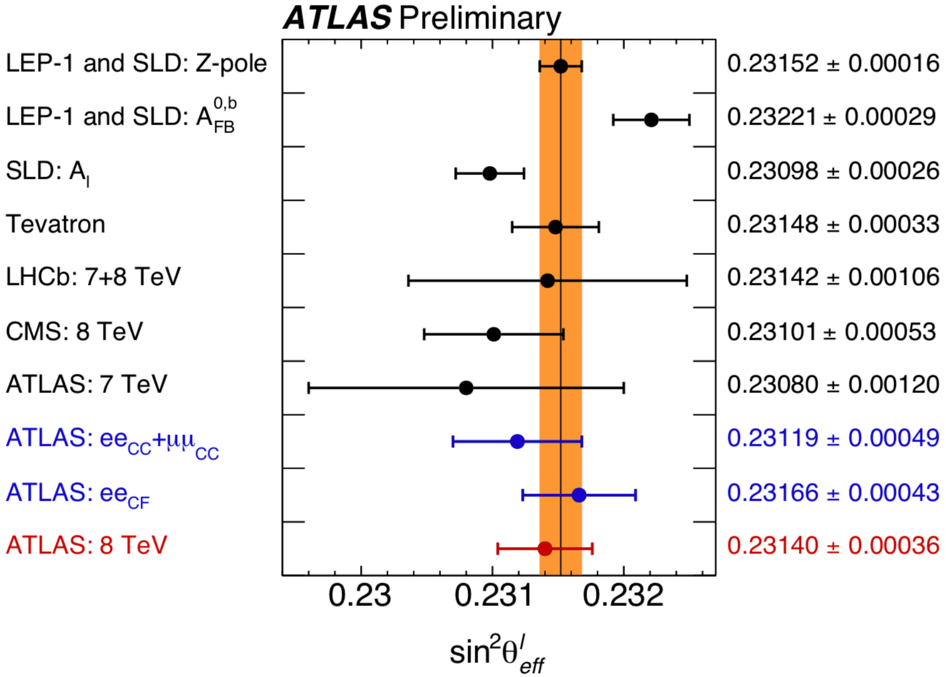
- Work within the LHC-Tevatron-Wmass combination WG under the umbrella of LHC EW WG
  - Establish a methodology to combine present and future measurements
  - Enable physics-modeling updates of past measurements (e.g. PDFs)
- Lot of progress with interesting results using the previous CDF measurement. Final prescriptions for the combination for the central values and uncertainties to be decided. What is the strategy for including the new CDF result in the combination?
  - Summary by Maarten: https://indico.cern.ch/event/1108518/
- PDF uncertainties and correlations between Tevatron and ATLAS (7TeV)



CT10	1.	2.	3.	4.
1. W^+ 2 TeV	1	0.99	0.26	0.51
2. W^- 2 TeV	0.99	1	0.31	0.52
3. W^+ 7 TeV	0.26	0.31	1	-0.23
4. W^- 7 TeV	0.51	0.52	-0.23	1

Measurement of $\sin^2\theta_{\text{eff}}$

- Comparable precision at LHC and Tevatron
- Uncertainties in knowledge of the Parton Distribution Functions (PDFs) dominate
- Important that experiments use same (equivalent models) to interpret data and treat common uncertainty sources consistently to produce final combined measurement



$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

F: cosθ>0
B: cosθ<0

QED/EW effects at the Z pole

- Detailed studies of QED/EW effects at the Z pole for $\sin^2\theta_{eff}$ measurement
    - Has never been done before
- Work is done in the context of the wider LHC precision EW working group
- Benchmark different aspects of the interpretation framework
    - Cross sections and A_{fb}
    - Part 1: Virtual EW corrections (NLO, NLO+HO)
    - Part 2: QED ISR and IFI
- Work done considering:
    - different EW input parameter schemes
    - different width schemes
- Results are basically completed
    - Documentation in progress
- Comprehensive summary by Fulvio:
    - https://indico.cern.ch/event/1108518/

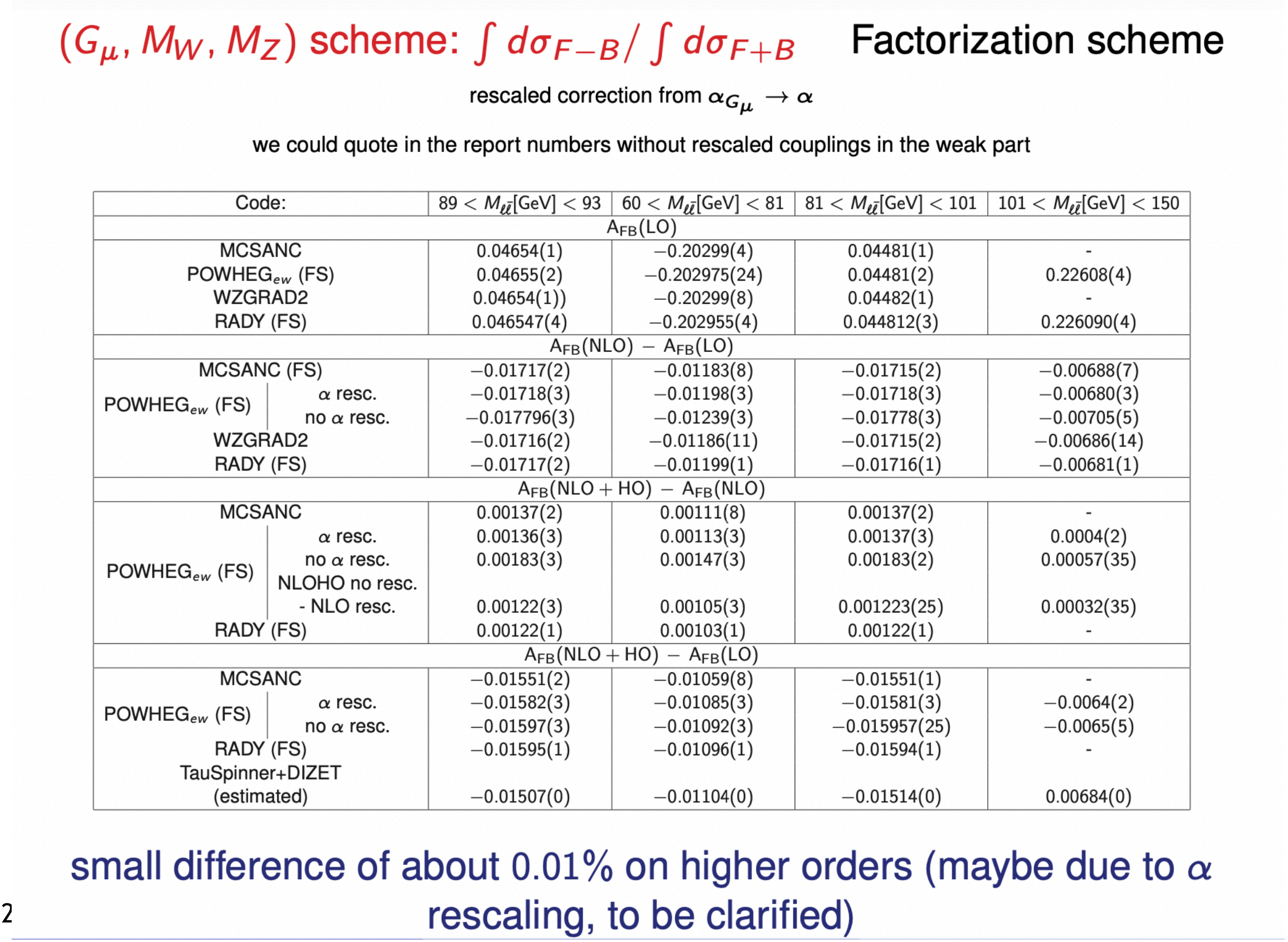
Programs/groups involved

- KKMC_hh
- MCSANC
- POWHEG_ew
- RADY
- WZGRAD2
- DIZET/TauSpinner

Adopted input parameter schemes

- (G_μ, M_W, M_Z)
  - MCSANC, POWHEG_EW, RADY, WZGRAD2
- $(\alpha(0), M_W, M_Z)$
  - MCSANC, POWHEG_EW, RADY, WZGRAD2
- $(G_\mu, \sin^2\vartheta^\ell_{\mathrm{eff}}, M_Z)$, $(\alpha(0), \sin^2\vartheta^\ell_{\mathrm{eff}}, M_Z)$
  - POWHEG_EW, RADY
- $(\alpha(0), G_\mu, M_Z)$
  - DIZET

Virtual corrections



(G_μ, M_W, M_Z) scheme: $\int d\sigma_{F-B} / \int d\sigma_{F+B}$ Factorization scheme

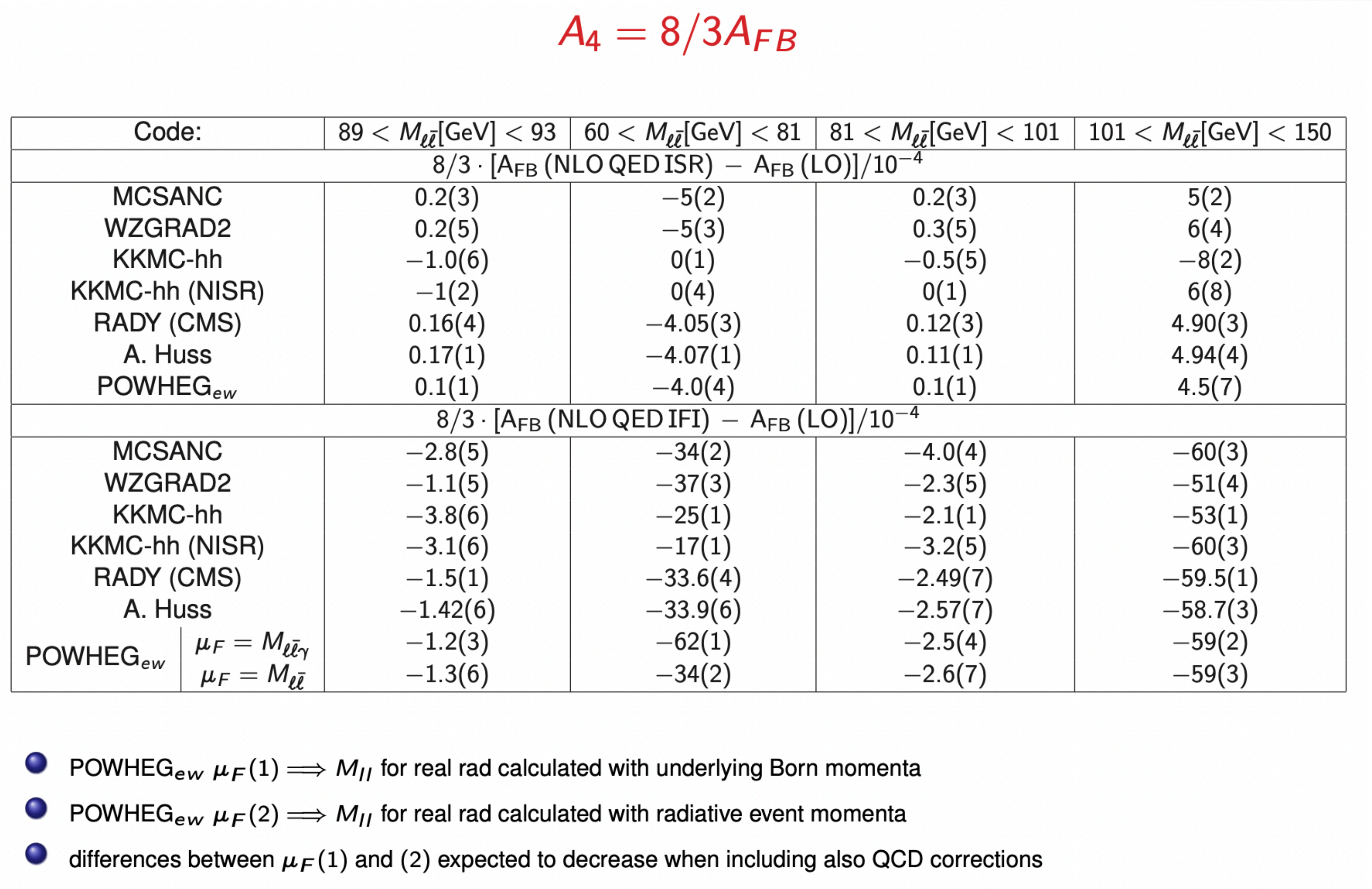
rescaled correction from $\alpha_{G_\mu} \to \alpha$

we could quote in the report numbers without rescaled couplings in the weak part

Code:		$89 < M_{l\bar{l}}$[GeV] < 93	$60 < M_{l\bar{l}}$[GeV] < 81	$81 < M_{l\bar{l}}$[GeV] < 101	$101 < M_{l\bar{l}}$[GeV] < 150
A_{FB}(LO)					
MCSANC		0.04654(1)	−0.20299(4)	0.04481(1)	-
POWHEG$_{ew}$ (FS)		0.04655(2)	−0.202975(24)	0.04481(2)	0.22608(4)
WZGRAD2		0.04654(1))	−0.20299(8)	0.04482(1)	-
RADY (FS)		0.046547(4)	−0.202955(4)	0.044812(3)	0.226090(4)
A_{FB}(NLO) − A_{FB}(LO)					
MCSANC (FS)		−0.01717(2)	−0.01183(8)	−0.01715(2)	−0.00688(7)
POWHEG$_{ew}$ (FS)	α resc.	−0.01718(3)	−0.01198(3)	−0.01718(3)	−0.00680(3)
	no α resc.	−0.017796(3)	−0.01239(3)	−0.01778(3)	−0.00705(5)
WZGRAD2		−0.01716(2)	−0.01186(11)	−0.01715(2)	−0.00686(14)
RADY (FS)		−0.01717(2)	−0.01199(1)	−0.01716(1)	−0.00681(1)
A_{FB}(NLO + HO) − A_{FB}(NLO)					
MCSANC		0.00137(2)	0.00111(8)	0.00137(2)	-
POWHEG$_{ew}$ (FS)	α resc.	0.00136(3)	0.00113(3)	0.00137(3)	0.0004(2)
	no α resc.	0.00183(3)	0.00147(3)	0.00183(2)	0.00057(35)
	NLOHO no resc. - NLO resc.	0.00122(3)	0.00105(3)	0.001223(25)	0.00032(35)
RADY (FS)		0.00122(1)	0.00103(1)	0.00122(1)	-
A_{FB}(NLO + HO) − A_{FB}(LO)					
MCSANC		−0.01551(2)	−0.01059(8)	−0.01551(1)	-
POWHEG$_{ew}$ (FS)	α resc.	−0.01582(3)	−0.01085(3)	−0.01581(3)	−0.0064(2)
	no α resc.	−0.01597(3)	−0.01092(3)	−0.015957(25)	−0.0065(5)
RADY (FS)		−0.01595(1)	−0.01096(1)	−0.01594(1)	-
TauSpinner+DIZET (estimated)		−0.01507(0)	−0.01104(0)	−0.01514(0)	0.00684(0)

small difference of about 0.01% on higher orders (maybe due to α rescaling, to be clarified)

ISR/IFI effects



$$A_4 = 8/3 A_{FB}$$

Code:		$89 < M_{\ell\bar\ell}$[GeV] < 93	$60 < M_{\ell\bar\ell}$[GeV] < 81	$81 < M_{\ell\bar\ell}$[GeV] < 101	$101 < M_{\ell\bar\ell}$[GeV] < 150
$8/3 \cdot [\mathrm{A_{FB}}$ (NLO QED ISR) $- \mathrm{A_{FB}}$ (LO)$]/10^{-4}$					
MCSANC		0.2(3)	−5(2)	0.2(3)	5(2)
WZGRAD2		0.2(5)	−5(3)	0.3(5)	6(4)
KKMC-hh		−1.0(6)	0(1)	−0.5(5)	−8(2)
KKMC-hh (NISR)		−1(2)	0(4)	0(1)	6(8)
RADY (CMS)		0.16(4)	−4.05(3)	0.12(3)	4.90(3)
A. Huss		0.17(1)	−4.07(1)	0.11(1)	4.94(4)
POWHEG$_{ew}$		0.1(1)	−4.0(4)	0.1(1)	4.5(7)
$8/3 \cdot [\mathrm{A_{FB}}$ (NLO QED IFI) $- \mathrm{A_{FB}}$ (LO)$]/10^{-4}$					
MCSANC		−2.8(5)	−34(2)	−4.0(4)	−60(3)
WZGRAD2		−1.1(5)	−37(3)	−2.3(5)	−51(4)
KKMC-hh		−3.8(6)	−25(1)	−2.1(1)	−53(1)
KKMC-hh (NISR)		−3.1(6)	−17(1)	−3.2(5)	−60(3)
RADY (CMS)		−1.5(1)	−33.6(4)	−2.49(7)	−59.5(1)
A. Huss		−1.42(6)	−33.9(6)	−2.57(7)	−58.7(3)
POWHEG$_{ew}$	$\mu_F = M_{\ell\bar\ell\gamma}$	−1.2(3)	−62(1)	−2.5(4)	−59(2)
	$\mu_F = M_{\ell\bar\ell}$	−1.3(6)	−34(2)	−2.6(7)	−59(3)

- POWHEG$_{ew}$ $\mu_F(1) \Longrightarrow M_{ll}$ for real rad calculated with underlying Born momenta
- POWHEG$_{ew}$ $\mu_F(2) \Longrightarrow M_{ll}$ for real rad calculated with radiative event momenta
- differences between $\mu_F(1)$ and (2) expected to decrease when including also QCD corrections

Summary

- Exciting developments with impressive precision by CDF on W boson mass
  - Sizable tension with the SM EW fit predictions and other experiments
- Critical work within the LHC EW precision WG by theorists and experimentalists to study the physics modeling needed for the precision measurements (W mass and $\sin^2\theta_{eff}$)
  - Only selected highlights in this talk but other areas of work ongoing (combination of the measurements, PDFs,etc.)
- Could LHC W mass measurements reach 10 MeV precision?
  - Perhaps but it will require patience
  - Future measurements will likely follow two orthogonal paths: low pileup measurements dominated by mT, and high pileup measurements dominated by lepton pT
- Other important LHC precision measurements not discussed today:
  - W branching fraction measurements
    - Arxiv:2201.07861 and Arxiv:2007.14040