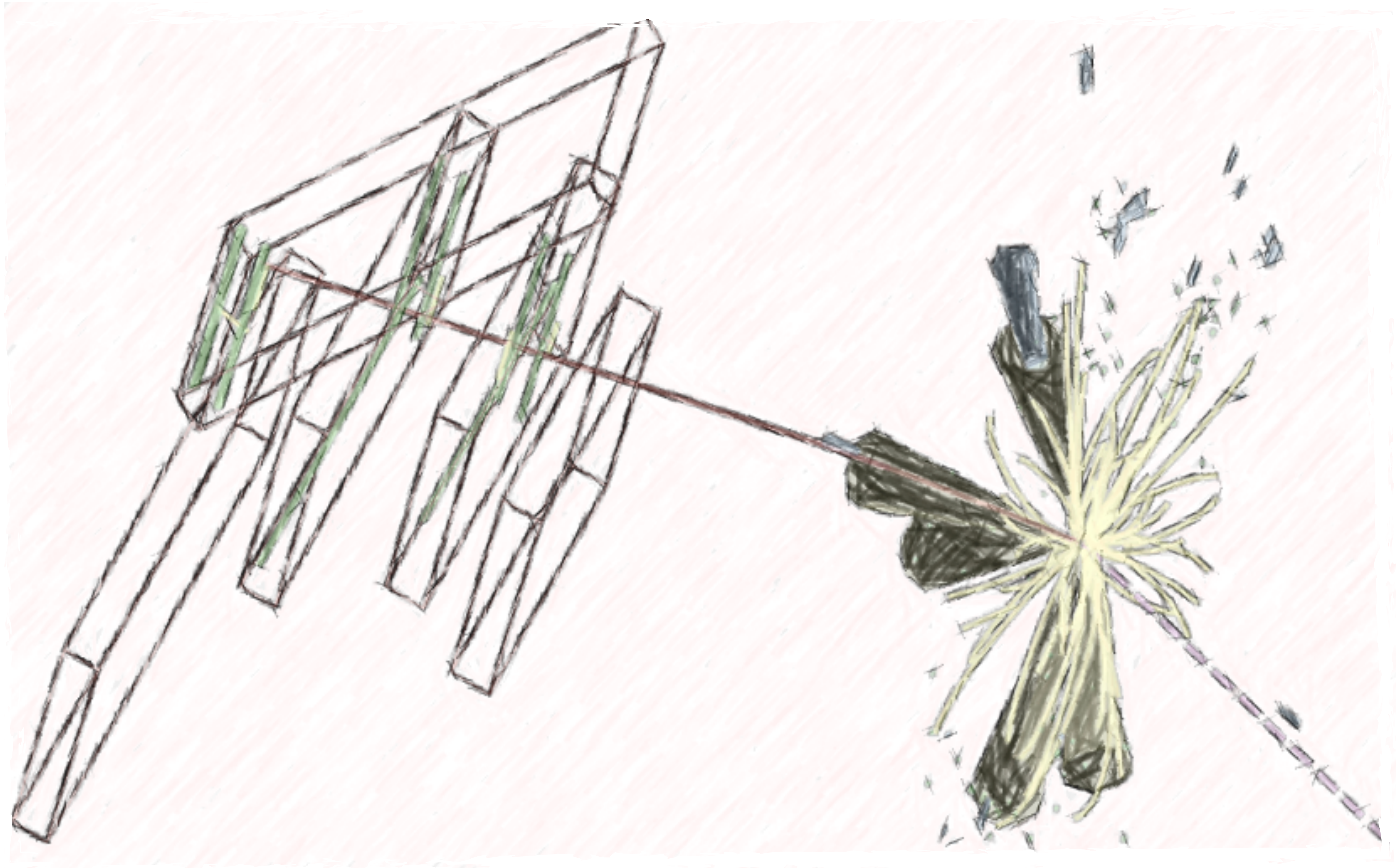
FROM PHD THESIS:

Towards a simultaneous measurement of W boson mass and production properties with CMS detector

Josh Bendavid,
Valerio Bertacchi,
Lorenzo Bianchini,
Elisabetta Manca,
Gigi Rolandi,
Suvankar Roy Chowdhury,



Milano-Pisa PRIN Meeting
5 October 2021

CMS Compact Muon Solenoid

SCUOLA NORMALE SUPERIORE

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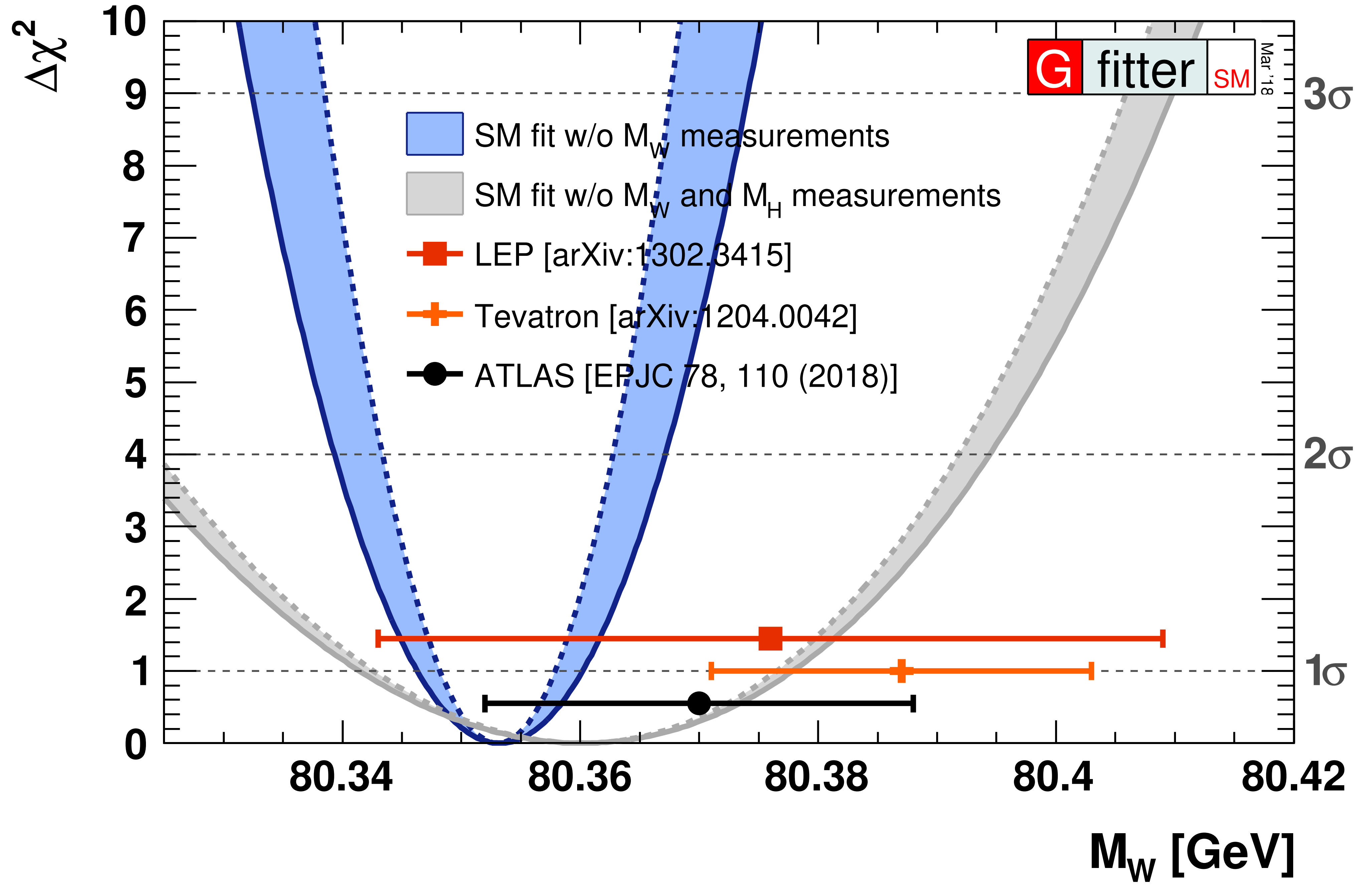
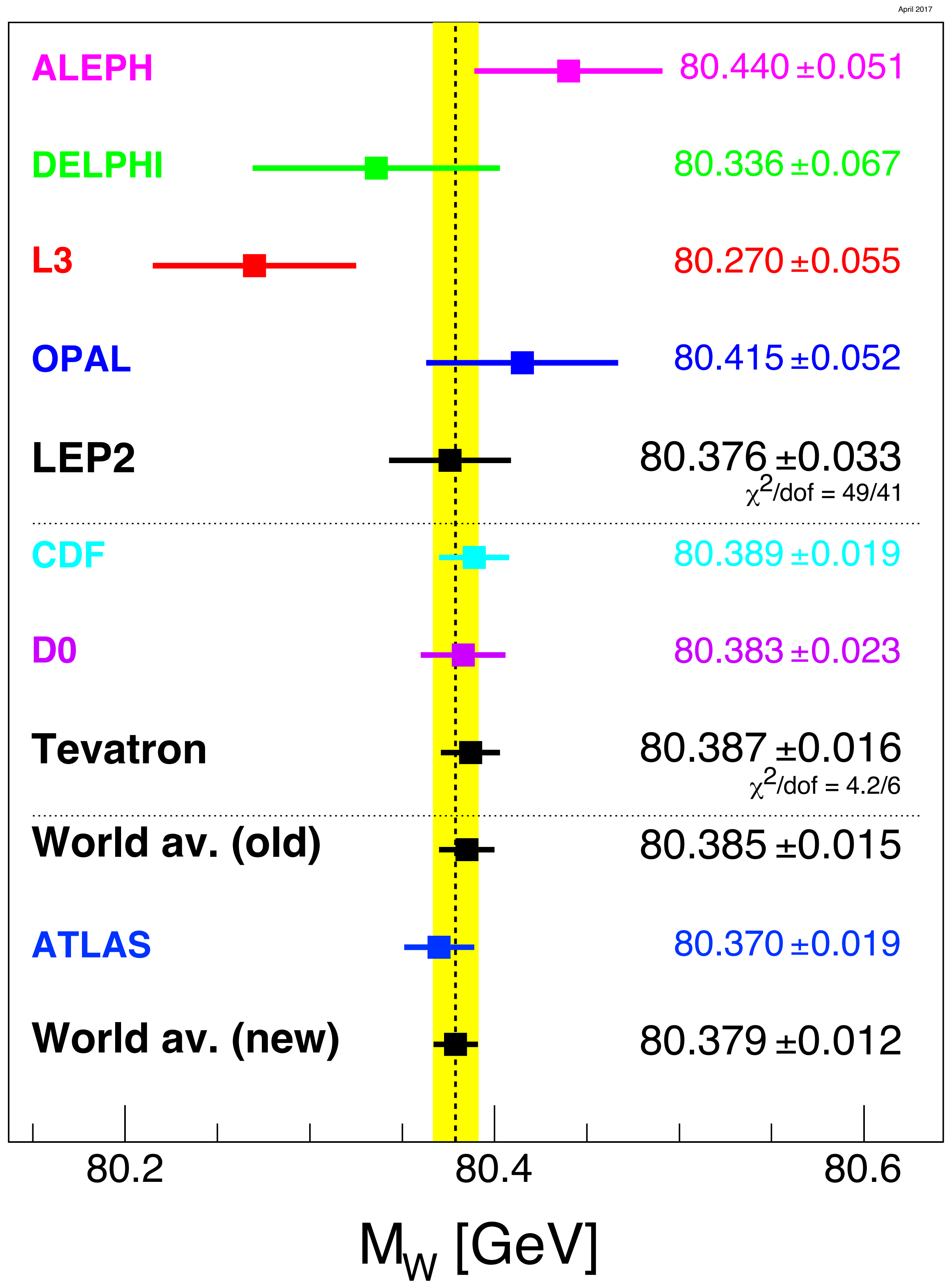
Outline

- W production mechanism systematic uncertainties
- Motivation for the a new W mass measurement
- The **W boson mass and production properties analysis**
  - Analysis strategy
  - Framework, data sample, event selection and efficiencies
  - Background measurement
  - Template Fit
- Results and interpretation

The W boson mass - electroweak fit results





LHCb: 80.364 ± 32

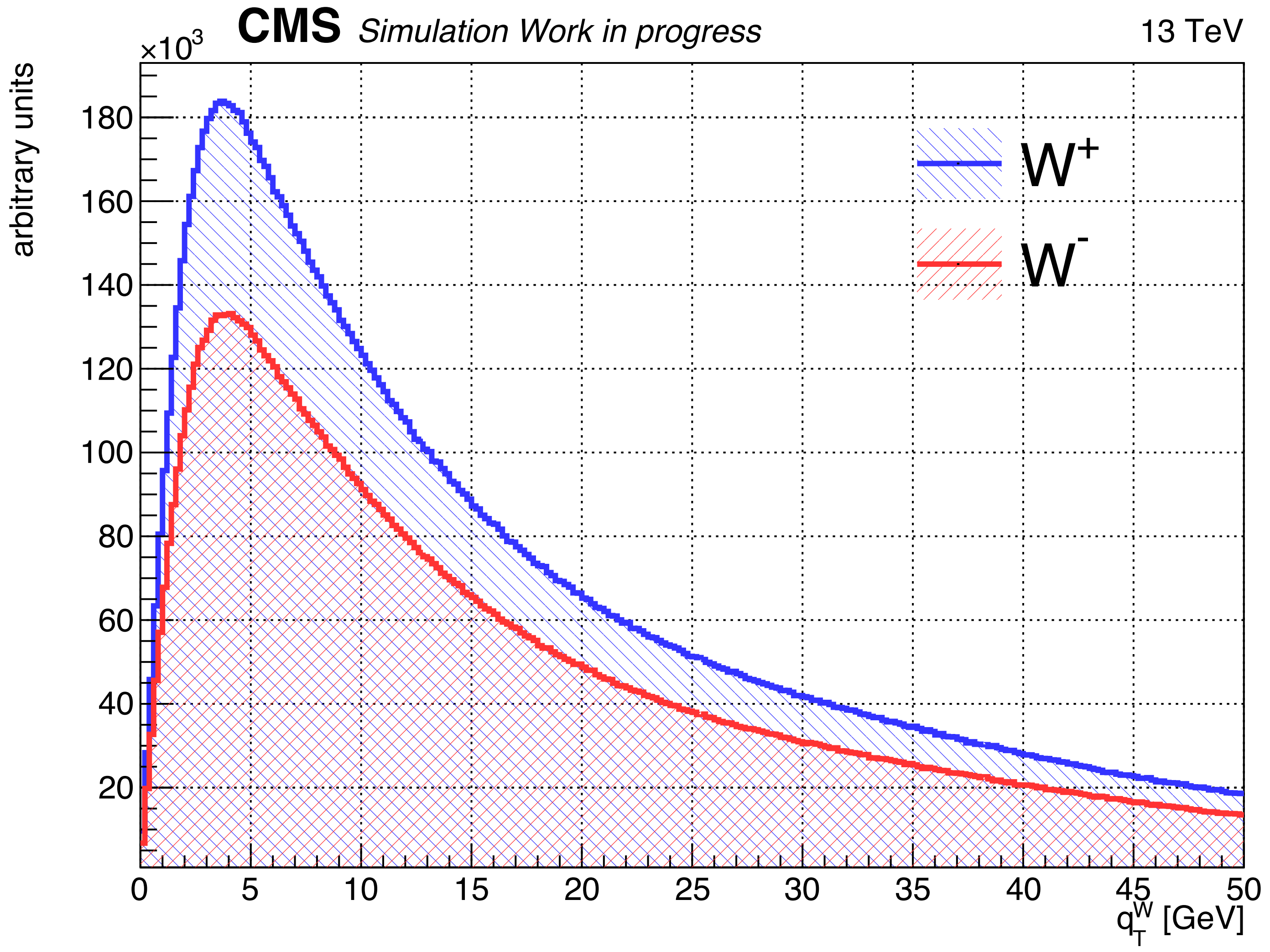
$$\begin{cases} m_W^{\text{exp}} = 80.379 \pm 0.012 \text{ GeV} \\ m_W^{\text{theo}} = 80.354 \pm 0.007 \text{ GeV} \end{cases}$$

- $\sim 1.5\sigma$ **strain**
- **prediction more precise than measurement**

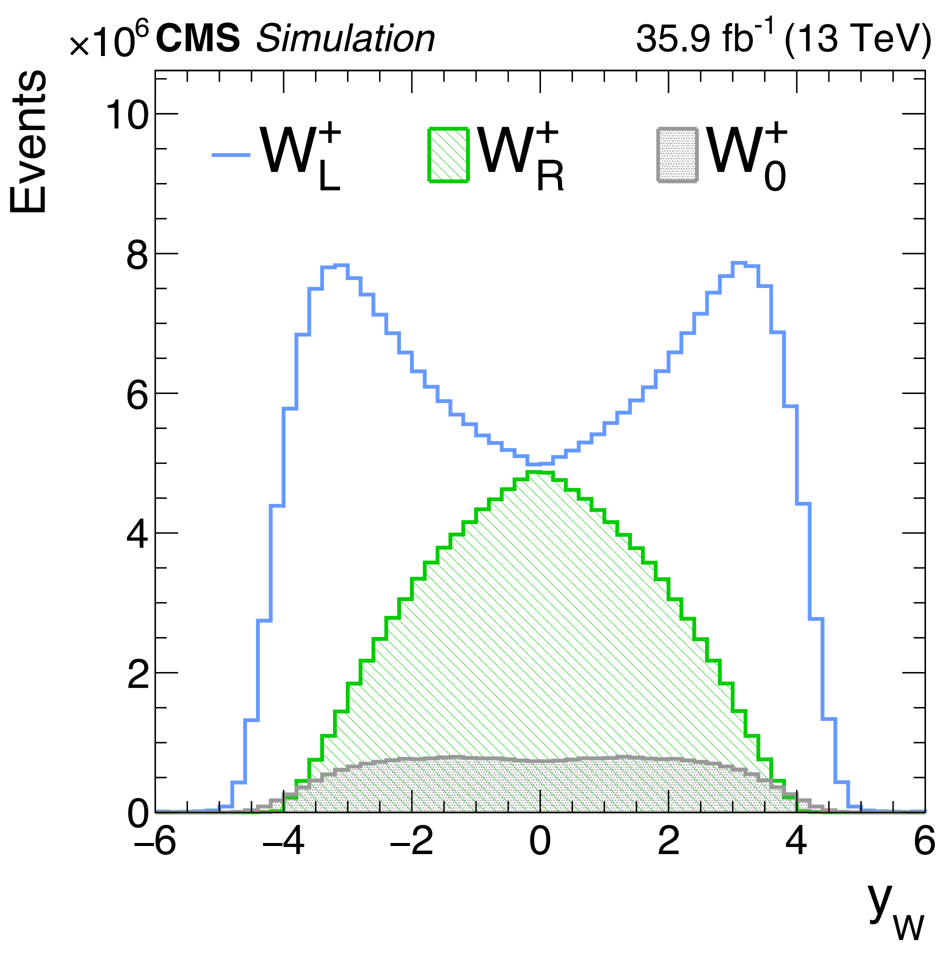
Target a new measurement with ~ 10 MeV uncertainty

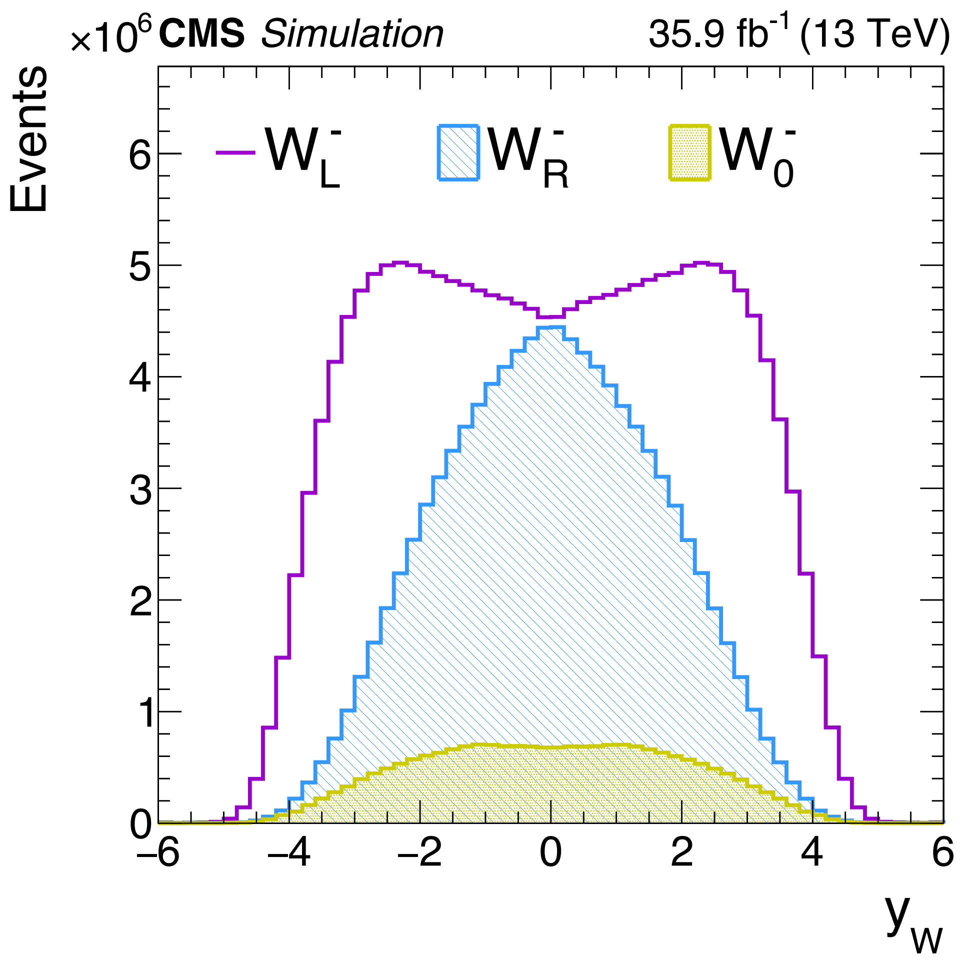
W production mechanism impact on m_W

- q_T^W: at NLO the W is produced with q_T^W spectra —> p_T^μ depends on underlying q_T^W spectrum
  - low-q_T^W region relies on resummation techniques —> large uncertainty (4-6%)
  - Syst.: 8 MeV/19 MeV (ATLAS)



- Y_W+polarization: limited acceptance—>sculpted Y_W —> sculpted p_T^μ as a function of Y_W and polarization
  - since Y_W and polarization distribution are function of parton momentum —>PDF dependence
  - Syst.: 9 MeV/19 MeV (ATLAS)





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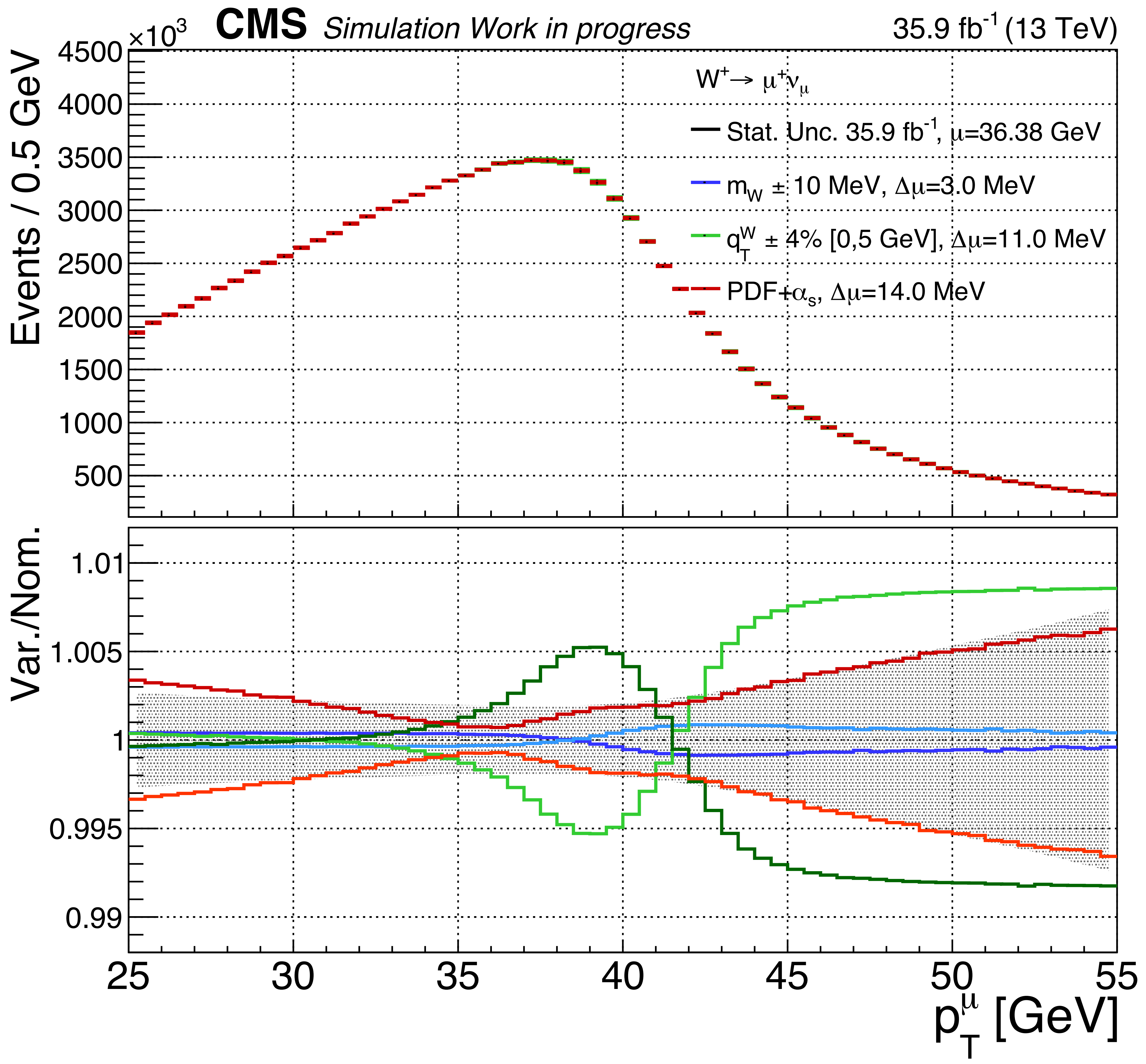

Goal of this work

1. Measurement of W boson production properties: $\frac{d\sigma}{dq_T^W dY_W d\cos\theta_\mu d\phi_u}$

   - W transverse momentum: $d\sigma/dq_T^W$
   - W rapidity: $d\sigma/dY_W$
   - 5 angular coefficients: $A_i(Y_W, q_T^W), i = 0,\ldots,4$

   Constraint for W production mechanism in a future m_W measurement

2. Simultaneous fit to the **W production properties** and **W mass**

<u>The PhD thesis content:</u>

Analysis performed on data collected in 2016 and correspondent MC, with parameter of interest blinded —> proof-of-feasibility of the measurement

Luminosity of data: 35.9 fb^{-1}

Equivalent luminosity of MC: 4.7 fb^{-1}

Analysis Strategy - theoretical foundation

** CS=Collins-Soper frame, details in the backup

$$\frac{d\sigma}{dq_{T,W}^2 dY_W d\cos\theta_\mu^* d\phi_\mu^*} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dq_{T,W}^2 dY_W}\left[(1+\cos^2\theta_\mu^*) + \sum_{i=0}^{7} A_i P_i(\cos\theta_\mu^*, \phi_\mu^*)\right].$$

W variables, lab frame

Lepton variables, CS frame **

Unpolarized cross section

«Angular coefficients»

known angular functions CS frame

[From E. Mirkes, https://doi.org/10.1016/0550-3213(92)90046-E]

$$P_0 = \frac{1}{2}(1-3\cos^2\theta^*),\quad P_1 = \sin 2\theta^*\cos\phi^*,\quad P_2 = \frac{1}{2}\sin^2\theta^*\cos 2\phi^*,\quad P_3 = \sin\theta^*\cos\phi^*,\quad P_4 = \cos\theta^*,\quad P_5 = \sin^2\theta^*\sin 2\phi^*,\quad P_6 = \sin 2\theta^*\sin\phi^*,\quad P_7 = \sin\theta^*\sin\phi^*,$$

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Model hypothesis: Massive spin 1 boson which decays in 2 fermions

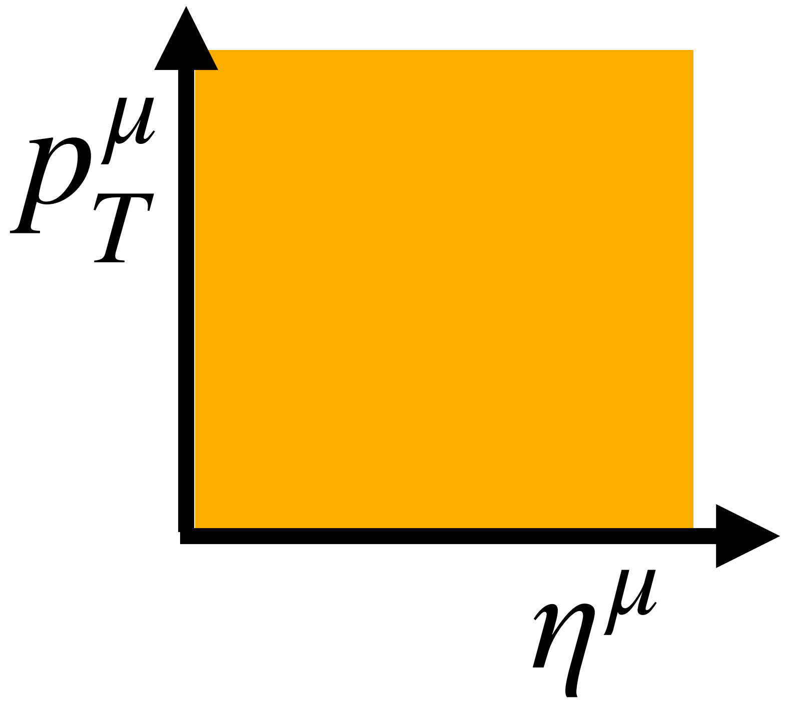
Implications: completely decouple the W boson production physics (unknown) $A_i = A_i(Y_W, q_T^W), \sigma^{U+L}(Y_W, q_T^W)$, from the W decay physics (known) $P_i = P_i(\theta^*_\mu, \phi^*_\mu)$

Analysis strategy - template fit

From muon kinematics —> $(\eta^{\mu} \times p_T^{\mu})$

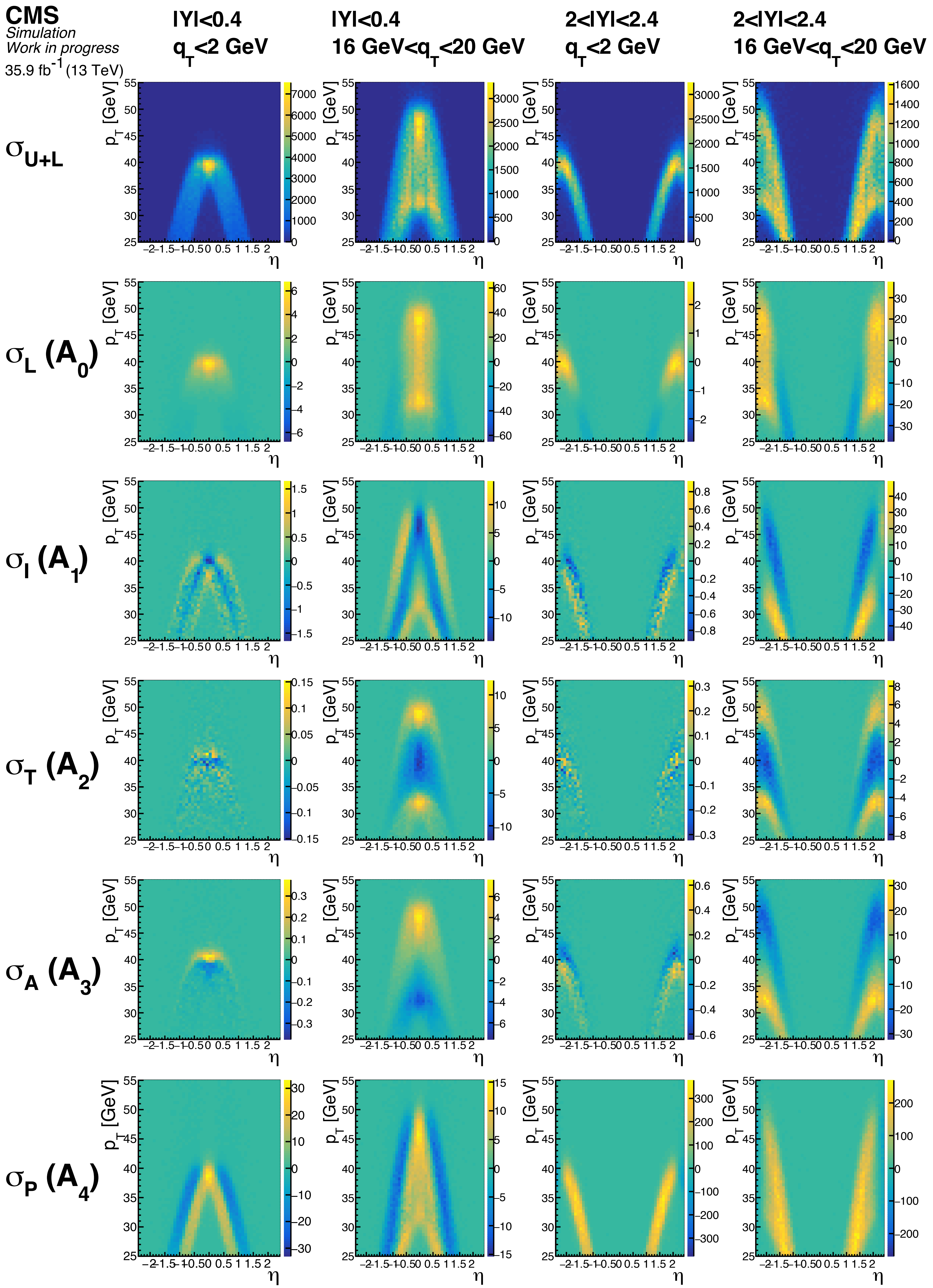
template fit, in bin of Y_W, q_T^W for each A_i

—> unfold the boson distributions



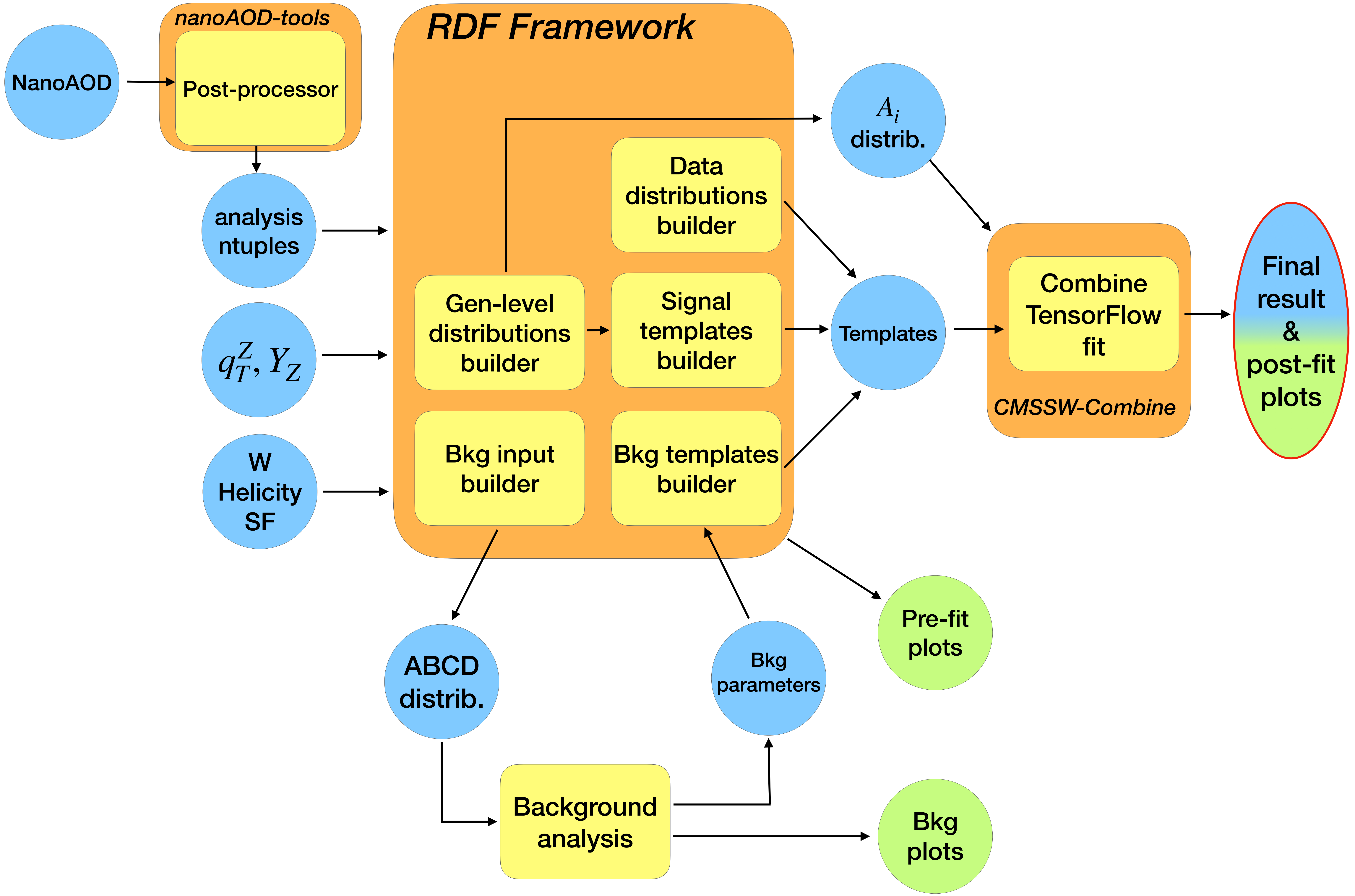
Additional requirements:

- Proper modeling of FSR of the muon
- Experimental requirements:
  - muon scale and resolution calibration
  - efficiencies
  - background estimation

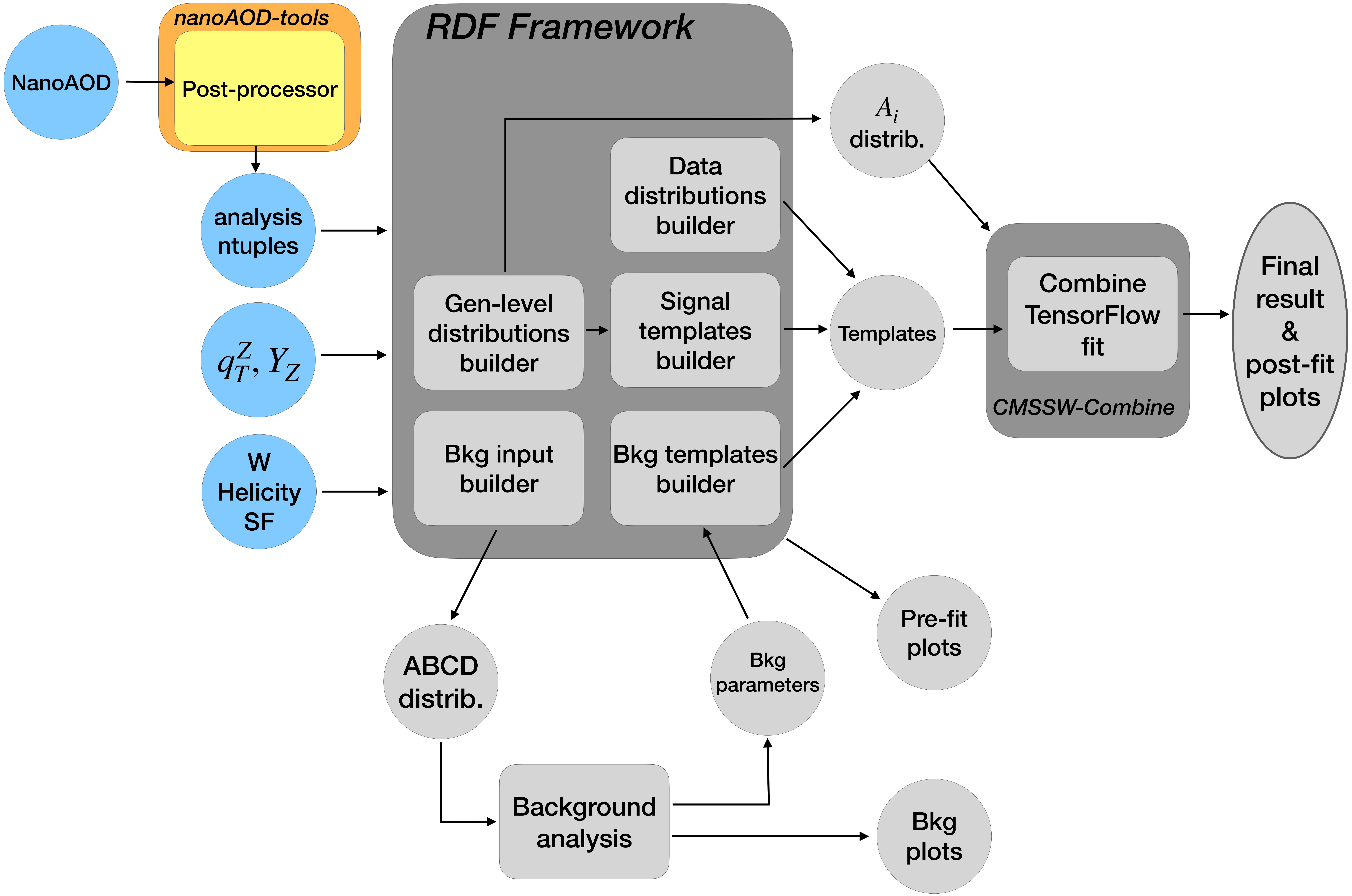


- Proof-of-concept: [E. Manca et al. JHEP, 12, (2017) 130]
- First use: [SMP-18-012, CMS Collaboration, Phys. Rev. D 102 (2020) 092012]

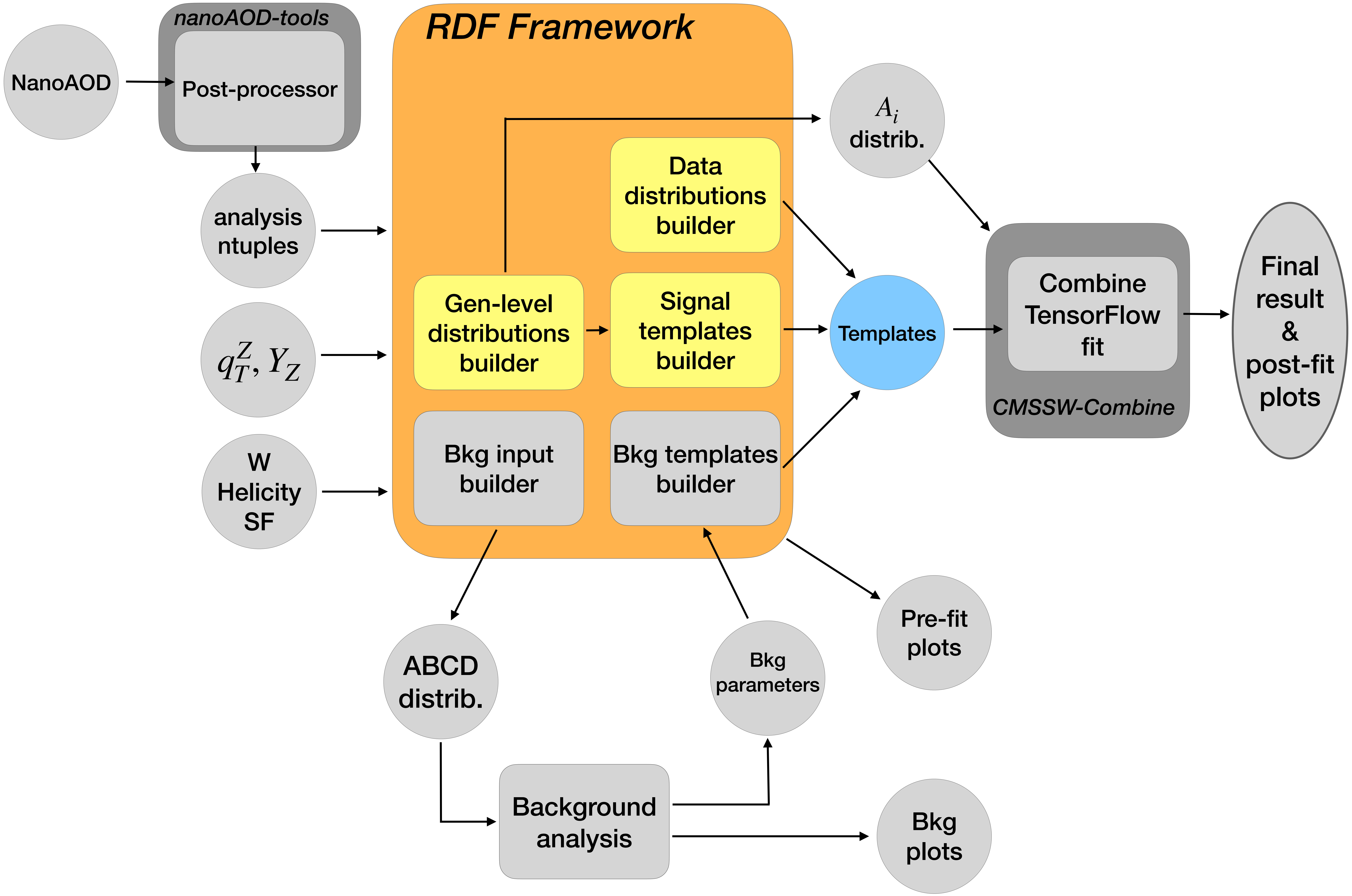
Analysis workflow



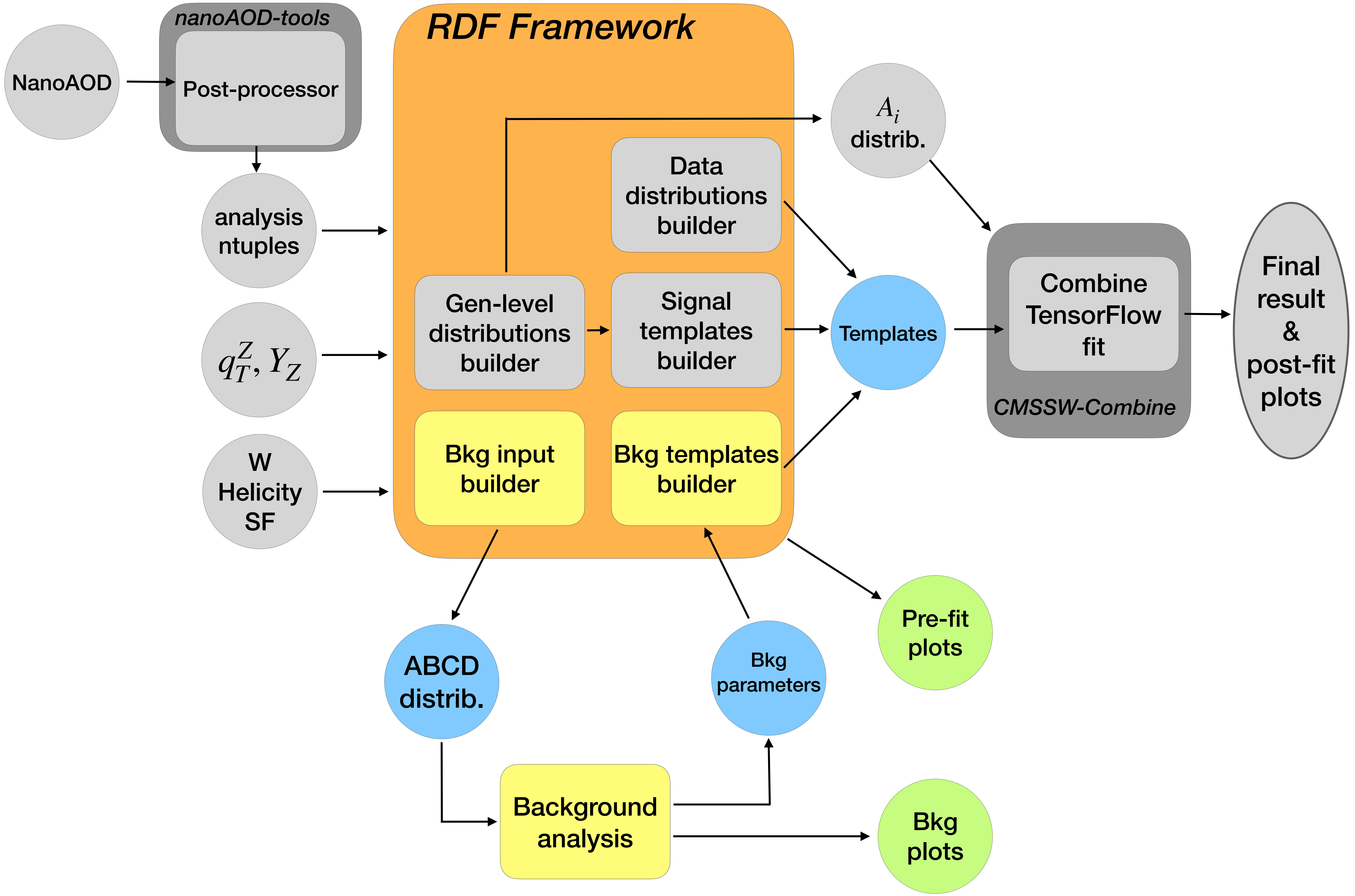
Analysis workflow: input



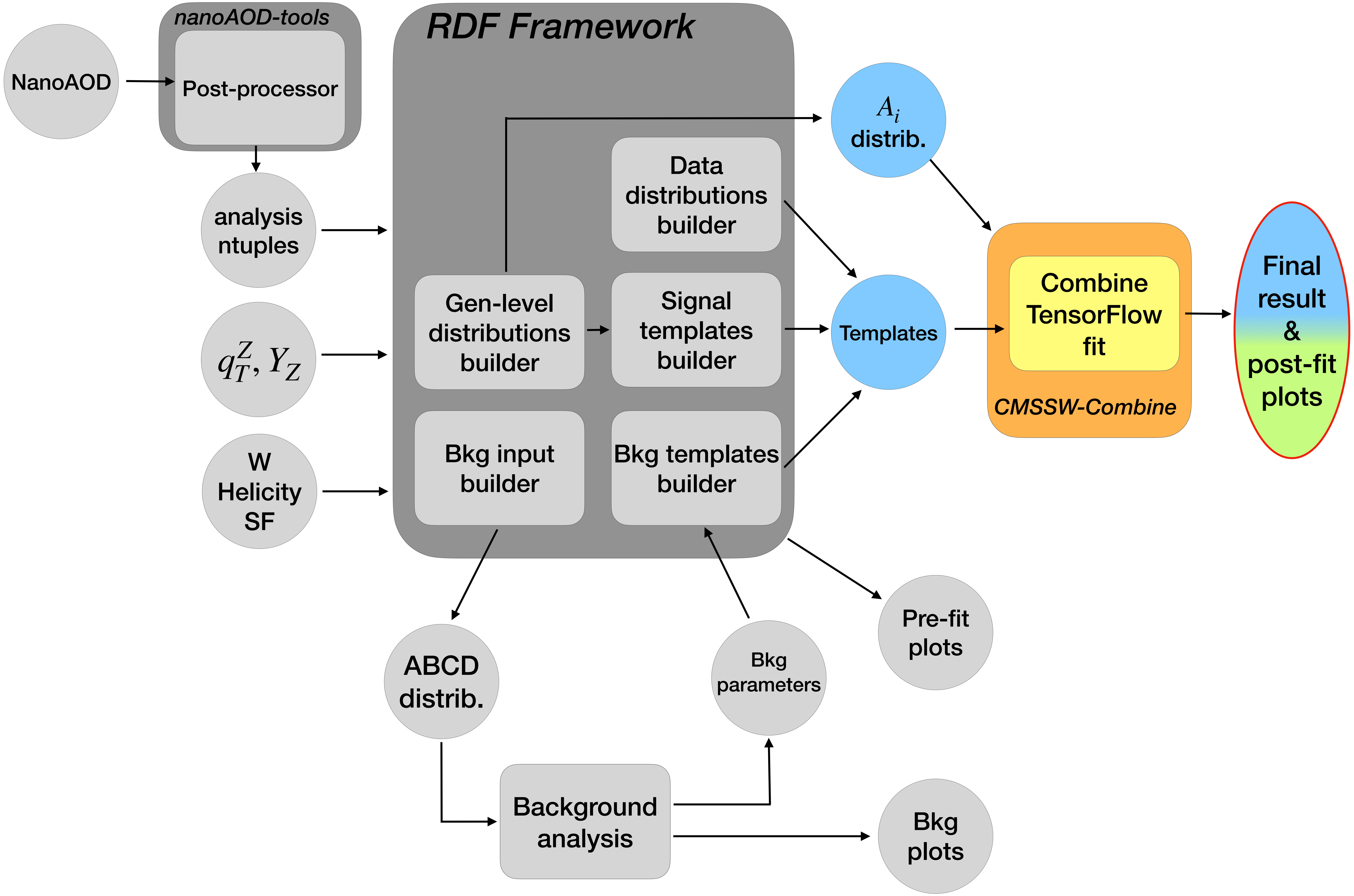
Analysis workflow: signal templates



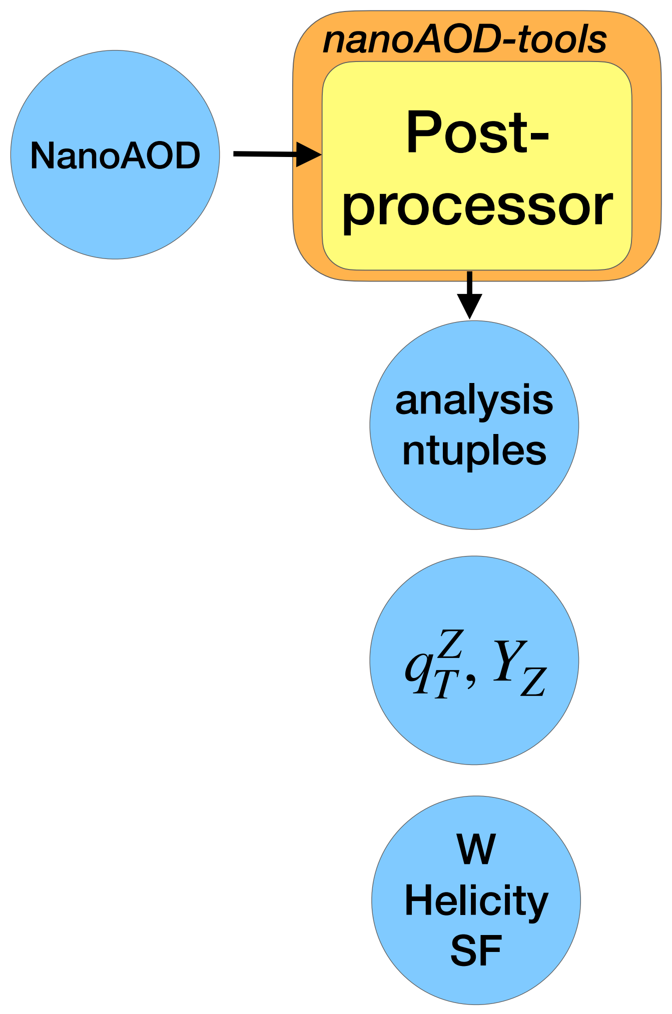
Analysis workflow: backgrounds



Analysis workflow: template fit



Input and selection



Process	σ [pb]	$\mathcal{L}_{\text{int}}^{\text{eq}}$ [fb^{-1}]	generator
$W(\to \ell\nu)$+jets	61526.70	4.7	MadGraph_aMC@NLO
$Z/\gamma^*(\to \ell\ell)$, $m_{\ell\ell} > 50$ GeV	6025.20	9.1	MadGraph_aMC@NLO
$Z/\gamma^*(\to \ell\ell)$, 10 GeV $< m_{\ell\ell} <$ 50 GeV	1093.00	29.1	MadGraph_aMC@NLO
$t\bar{t}(\ell)$	182.00	623.6	Madgraph, LO
$t\bar{t}(\ell\ell)$	95.02	319.2	Madgraph, LO
t (t-channel)	136.20	493.3	POWHEG, NLO
$\bar{t}$ (t-channel)	80.95	479.4	POWHEG, NLO
top (s-channel)	3.68	105.5	POWHEG, NLO
tW	35.60	195.3	POWHEG, NLO
WW	115.00	69.4	Madgraph, LO
WZ	47.13	84.8	Madgraph, LO
ZZ	16.50	59.9	Madgraph, LO

Data and MC samples

- CMS compressed data format: NanoAOD-V6
- Data: 2016 data taking period
- Lumi = 35.9 fb^{-1}

Selection and **(in a nutshell)**

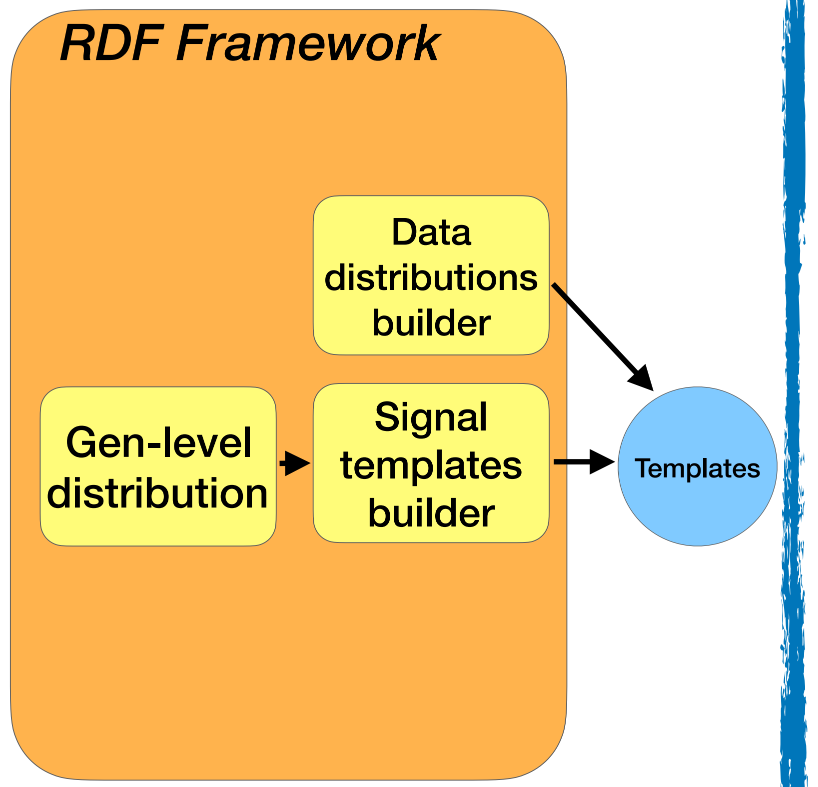
- Single Muon trigger, require exactly one muon in the event (isolated, $m_T > 40$ GeV)
- Calibration:
  - efficiency SF
  - p_T^μ calibration: Rochester corrections

Efficiency Scale Factors

- from W-Helicity CMS analysis *[https://doi.org/10.1103/PhysRevD.102.092012]*
- Standard Tag and Probe technique —-> $\text{SF} = \text{SF}_{\text{sel}} \cdot \text{SF}_{\text{trig}}$, with: $\text{SF}_\text{i} \equiv \frac{\varepsilon_\text{i}^{\text{data}}}{\varepsilon_\text{i}^{\text{MC}}}$, where sel=ID*ISO

[More details in the backup]

Signal templates - RDF



- $10^8 - 10^9$ events to analyze
- 400 nominal histograms
  - x 100 considering systematic variations

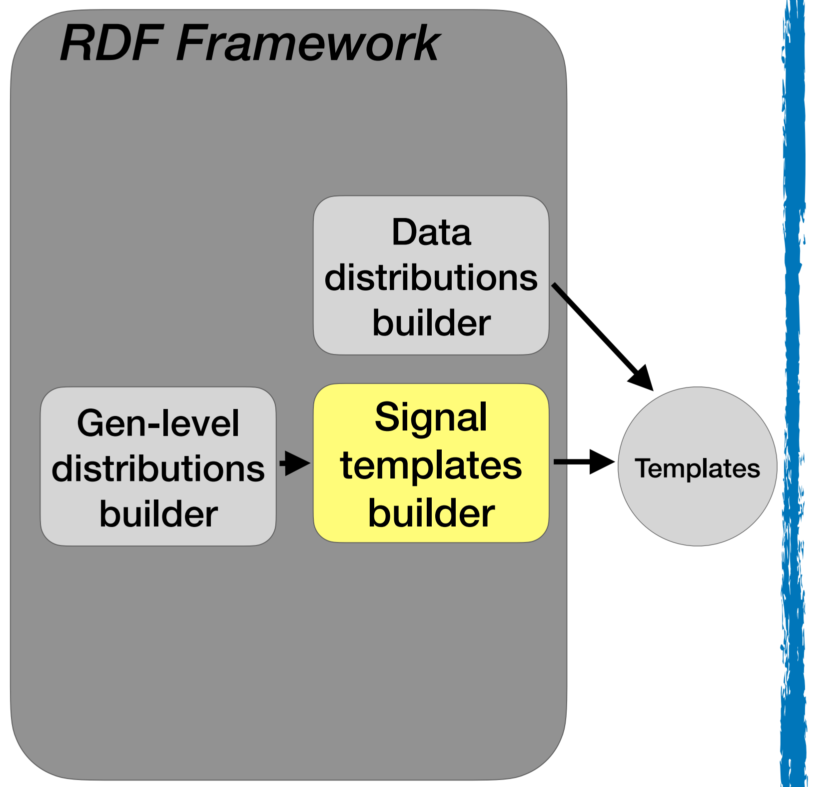
$\sim 4 \cdot 10^4$ templates to manage at each step of the analysis

- Custom RDataFrame-based framework developed for this purpose
- Allow easy parallelization, quick I/O, tidy environment —> processing frequency of 0.1-1 MHz (events/s)*

* on new Pisa server: AMD EPYC 7742 processor, 256 cores, 2TB memory (DDR4, 3200 MHz) and a SSD-nvme disk of 54 TB

[First presented version https://indico.cern.ch/event/849610/]

Signal templates - template building

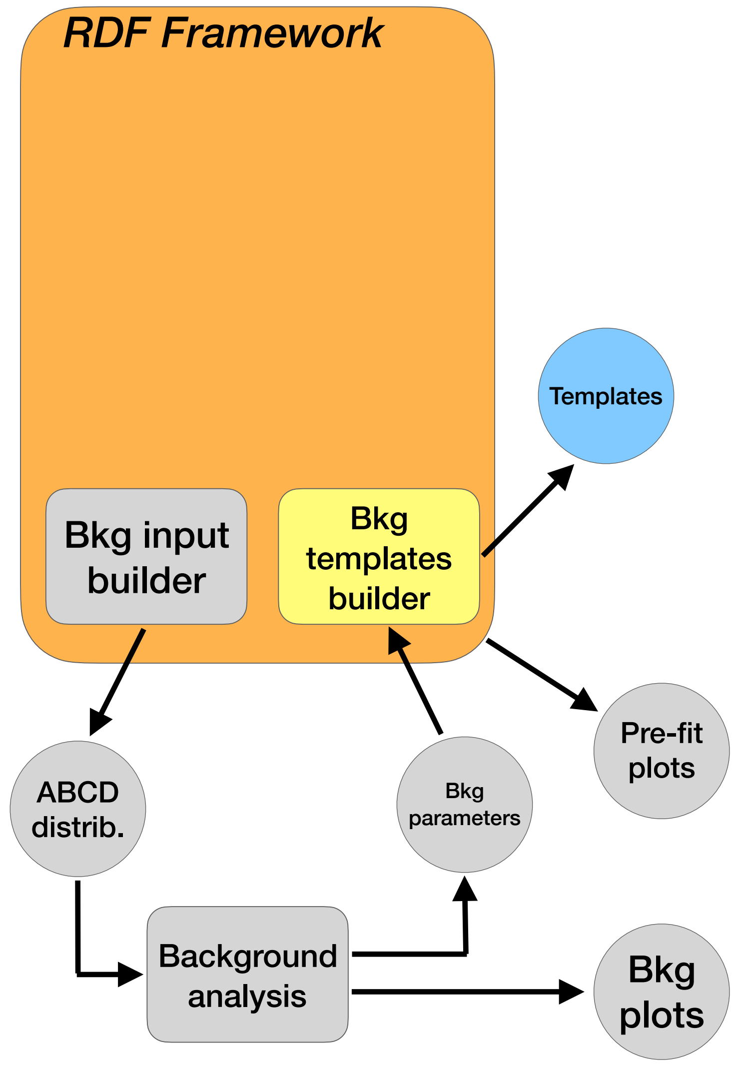


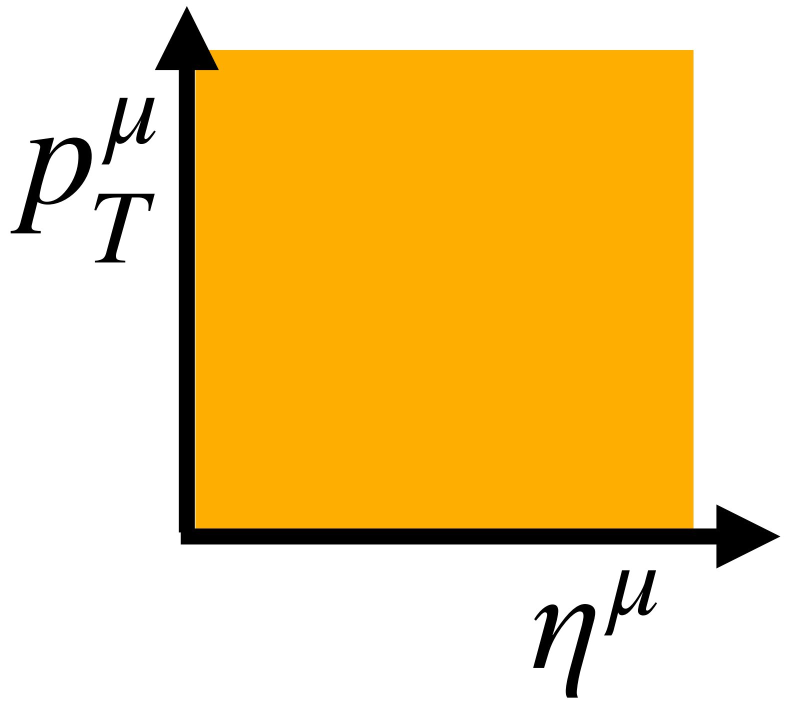
1. from W MC —> get the events in a certain bin of Y_W, q_T^W
2. Reweight the events to obtain the desired $(\cos\theta^* \times \phi^*)$ distribution
3. Fill $(\eta^\mu \times p_T^\mu)$ template

- The overall normalization of the template relies on the MC, but is left free in the fit —-> no assumption on A_i and $\sigma^{U+L}(q_T^W, Y_W)$
- The bins should be small enough to avoid strong variation of A_i within the bin
- The mapping $(\cos\theta^* \times \phi^*) \rightarrow (\eta^\mu \times p_T^\mu)$ is 2—>1:
  - $\phi^*, -\phi^*$ go in same (η, p_T) bin
  - A_5, A_6, A_7 templates mathematically 0 and they do not affect the measurement of W mass and the other properties

[More details in the backup]

Backgrounds - Electroweak

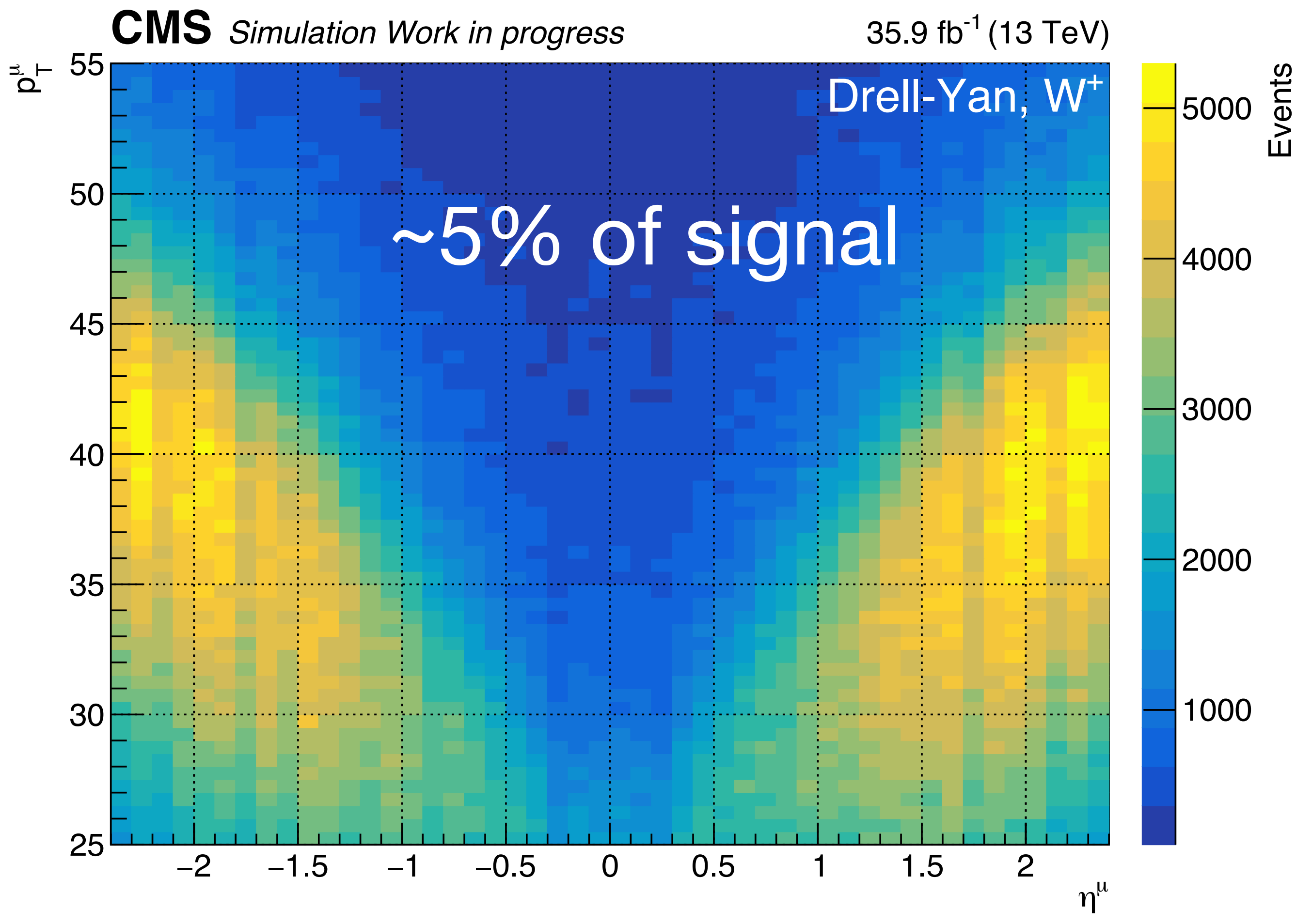


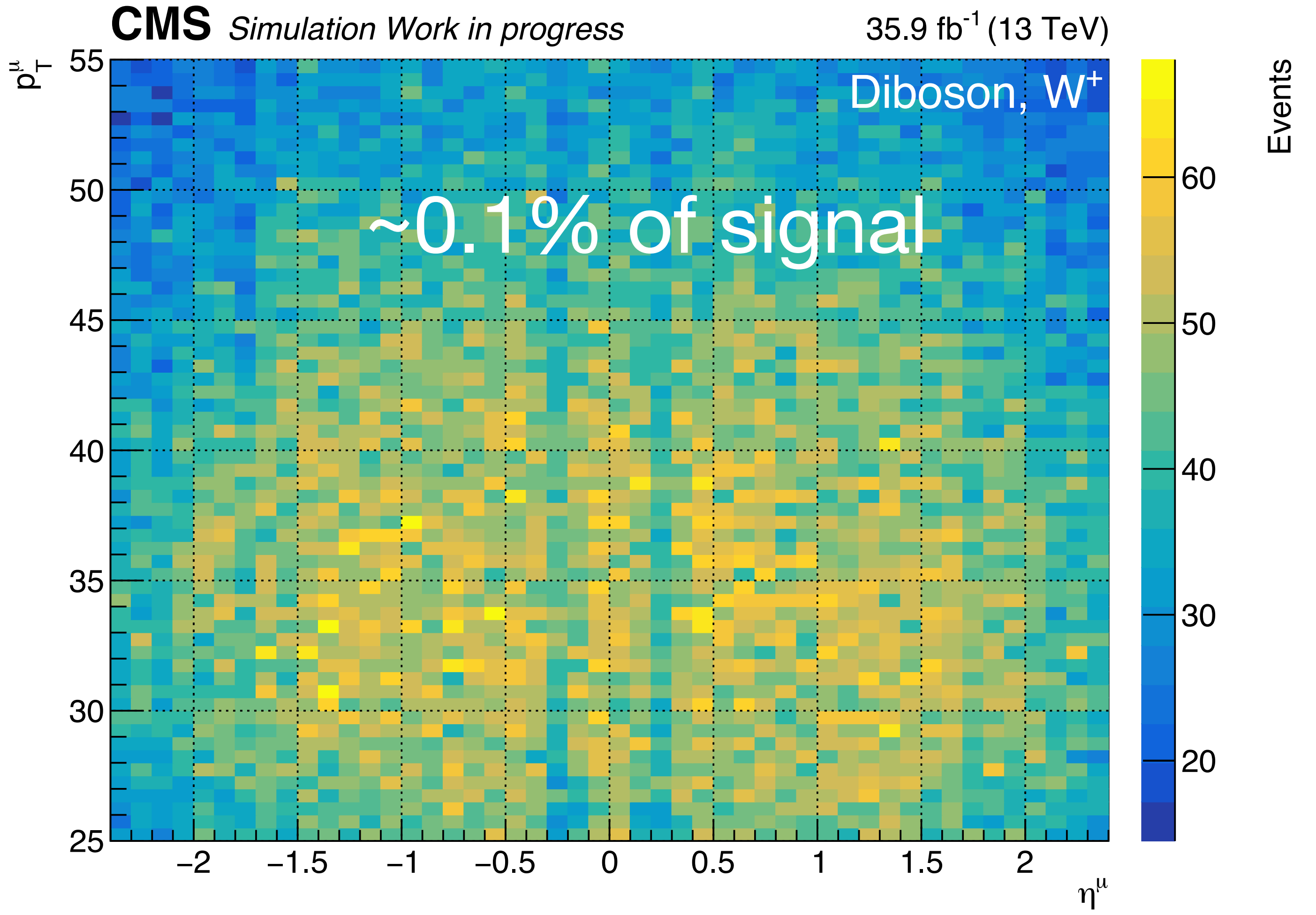


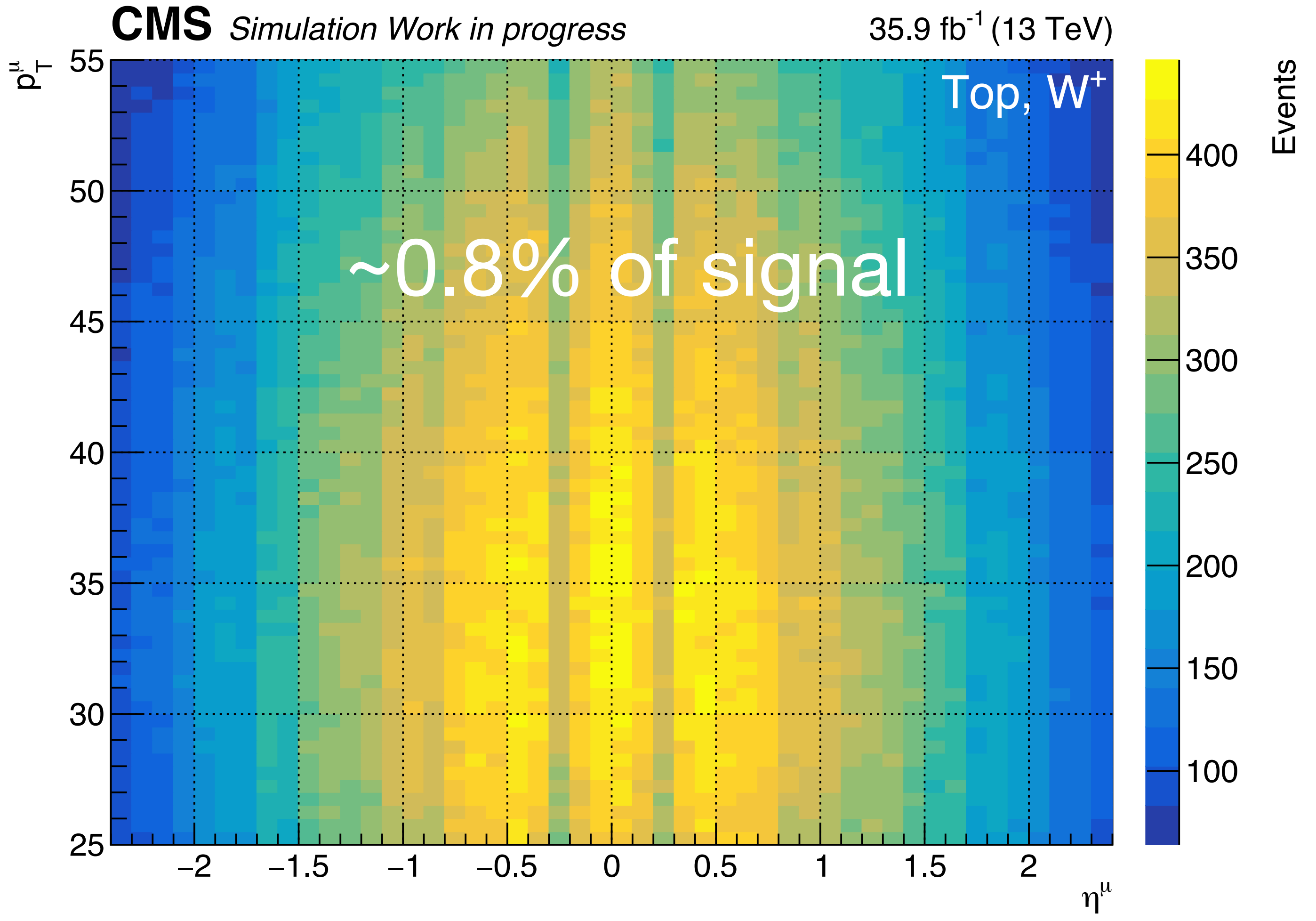
Source: prompt muons from electroweak channels which mimic the signal

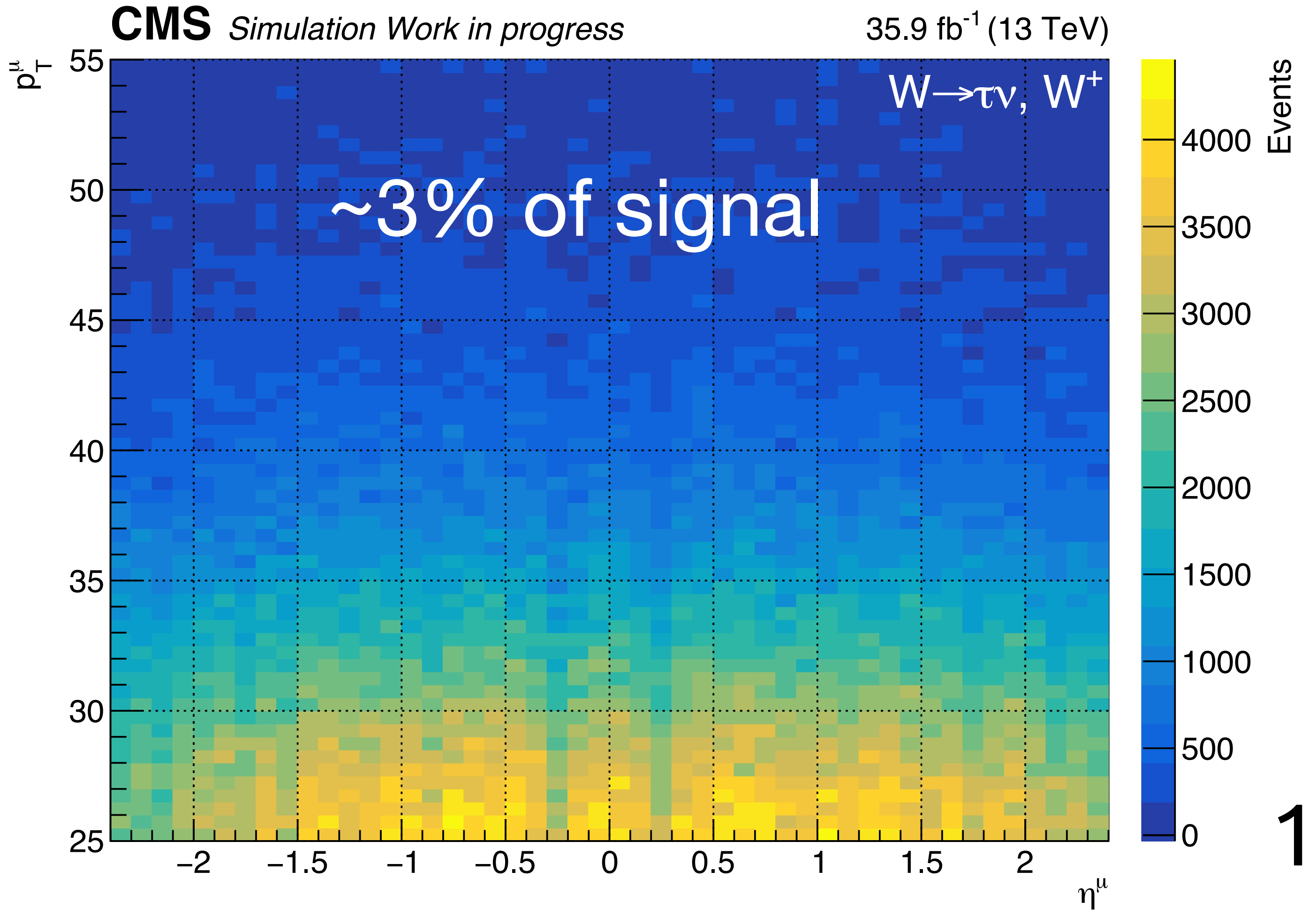
How: directly from MC samples, with the same selection of the signal

- $Z \to \mu\mu$
- Top decays (single top or ttbar)
- Diboson decays (WW, WZ, ZZ)
- $W \to \tau\nu$ decays

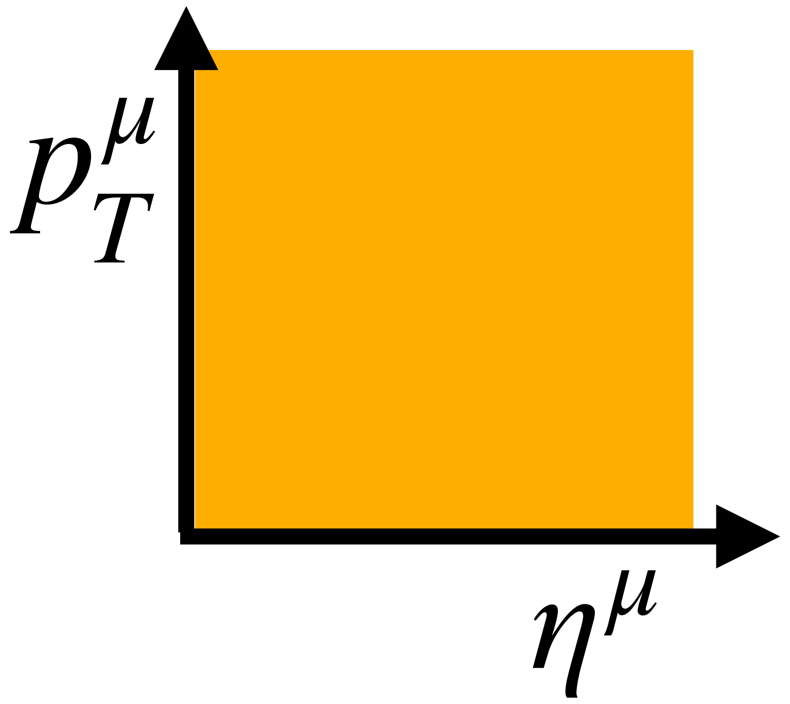


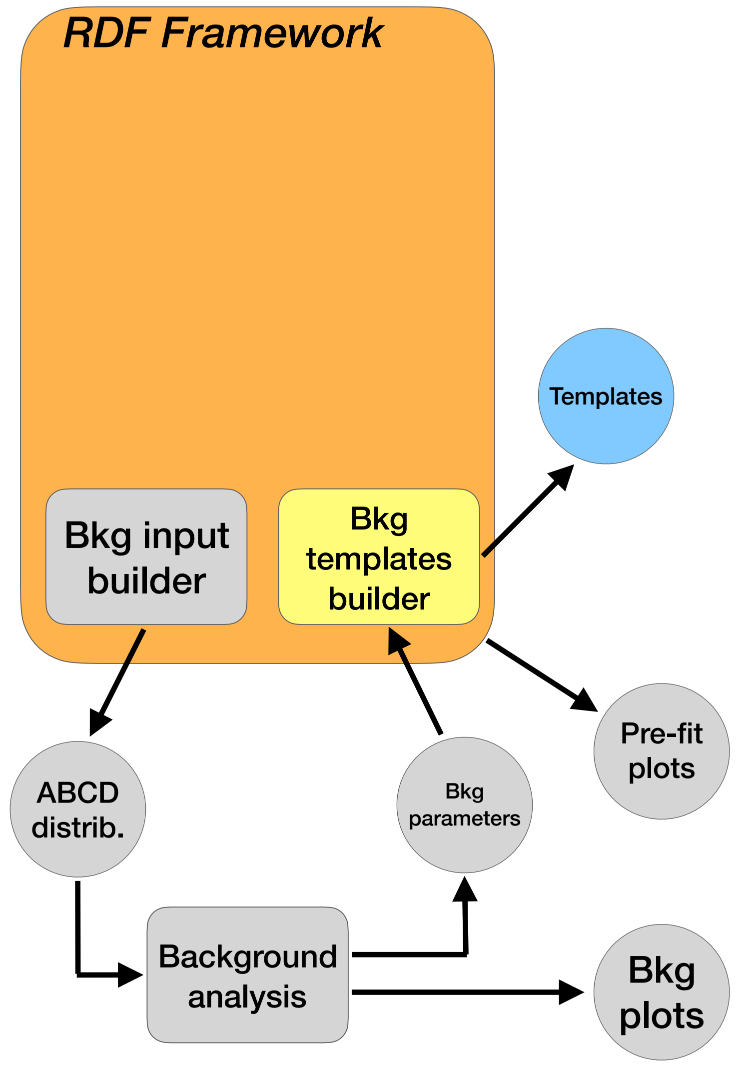






Backgrounds - Low Acceptance



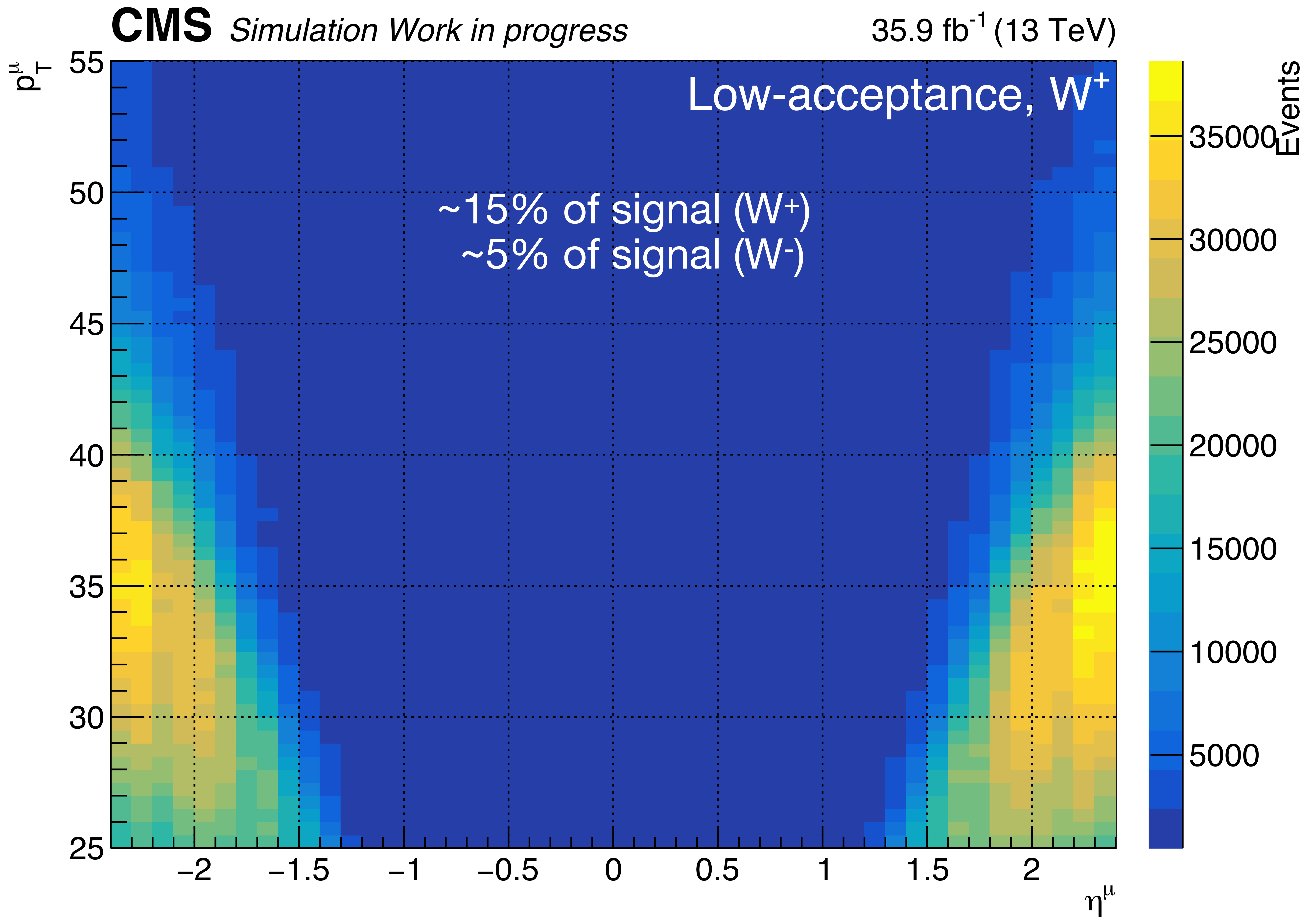


Source: $W \to \mu\nu$ events produced outside the $q_T^W \times |Y_W|$ range considered in the fit, which falls in the $p_T^\mu \times \eta^\mu$ acceptance

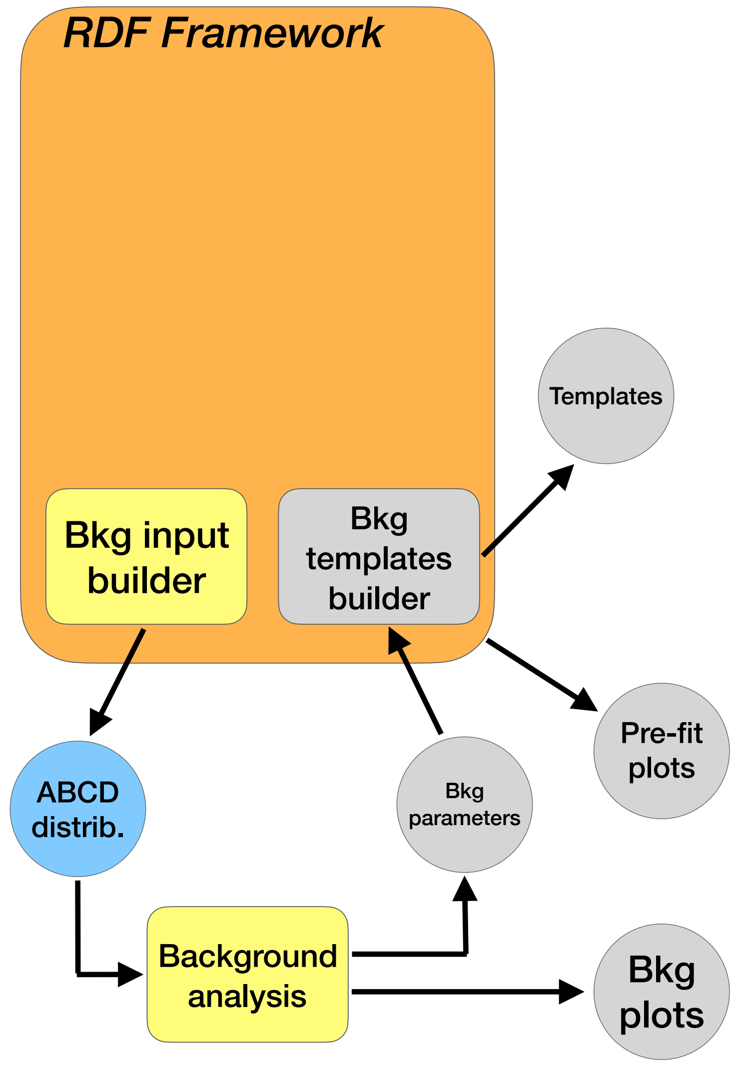
How: directly from MC samples, signal selection but requiring: $q_T^W > q_T^{\text{max}}$ or $Y_W > Y_W^{\text{max}}$

$$q_T^{\text{max}} = 60 \text{ GeV}$$

$$Y_W^{\text{max}} = 2.4$$



Backgrounds - QCD, ABCD method



Source: non-prompt muons from multijet production, isolated by chance

How: data driven estimation method:

- Relax m_T and RelIso cuts and define four regions
- From isolation efficiencies:

$$\textbf{fake rate: } f = \frac{N_D}{N_D + N_B}\bigg|_{\text{QCD}}$$

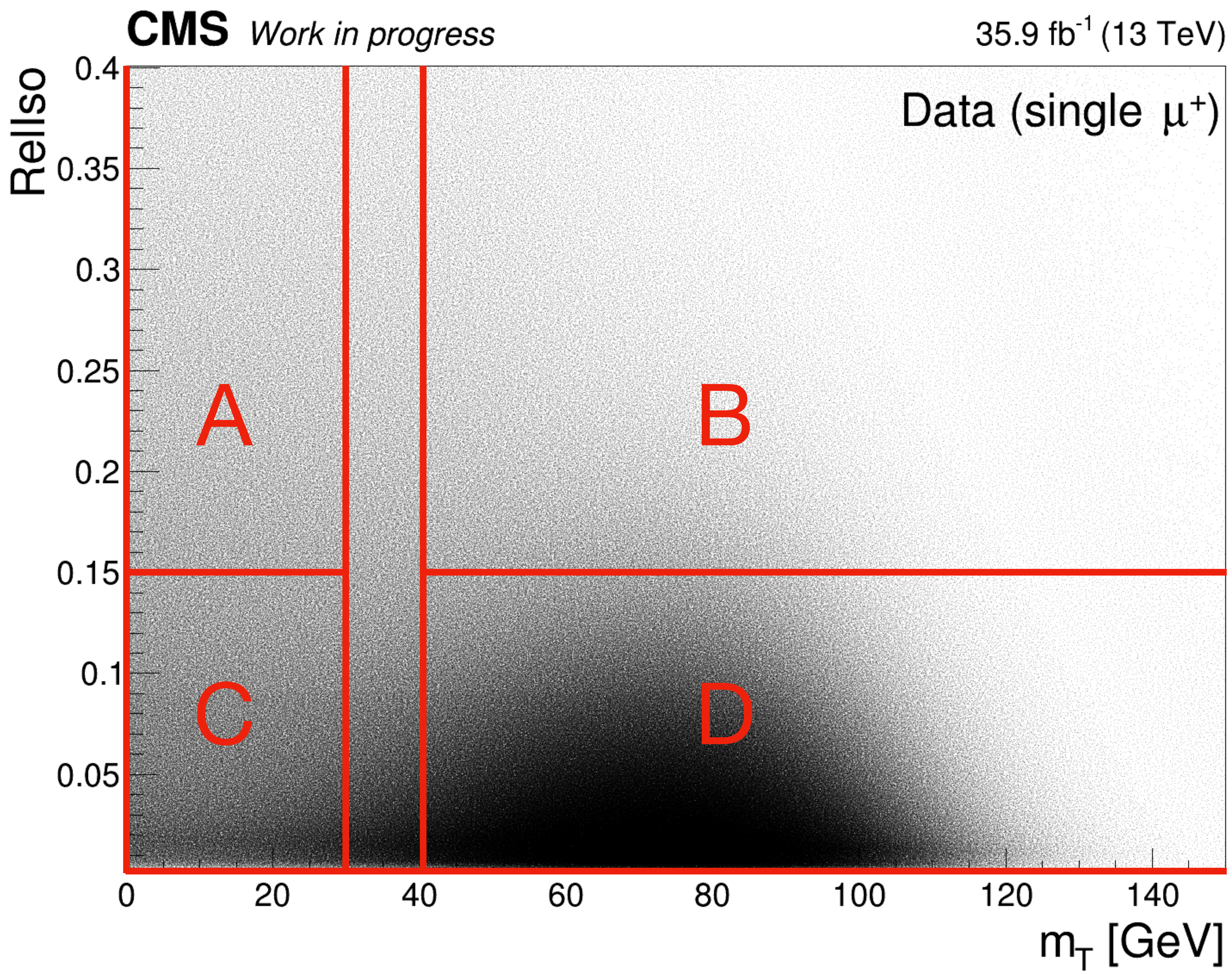
$$\textbf{prompt rate: } p = \frac{N_D}{N_D + N_B}\bigg|_{\text{EWK}}$$

- Extract the QCD yield in signal region (D):

$$N_D^{\text{QCD}} = \frac{f}{p - f}\left[pN_B^{\text{data}} - (1-p)N_D^{\text{data}}\right]$$

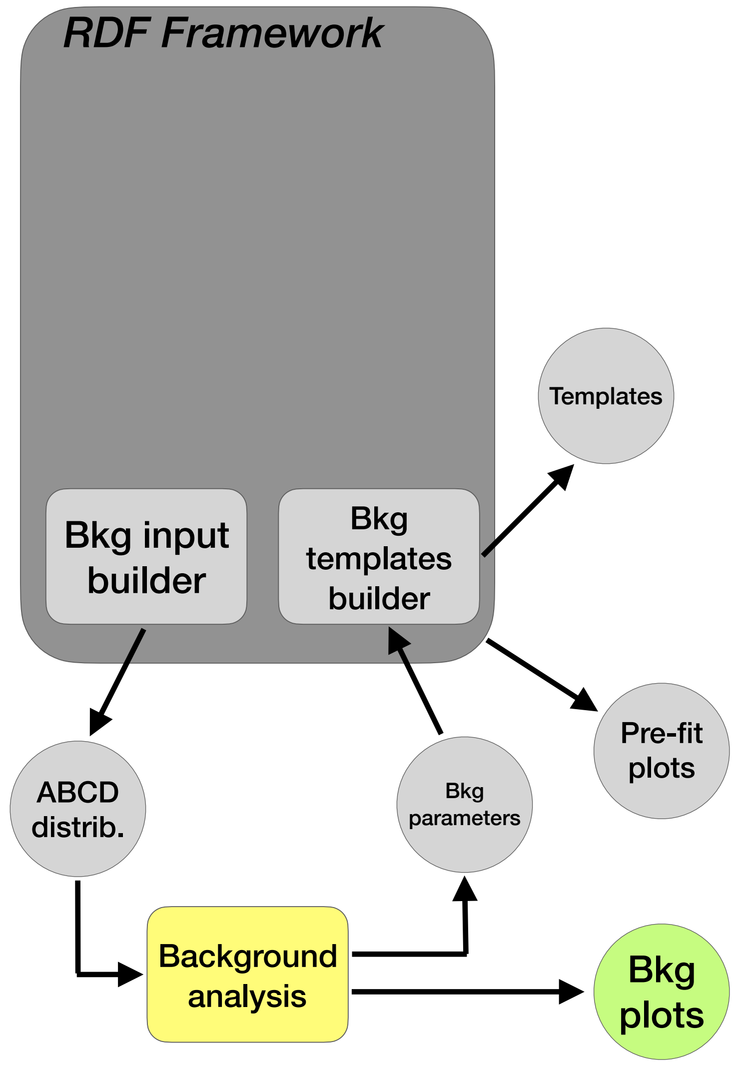
- Main hypothesis of the procedure (independence of f from m_T) :

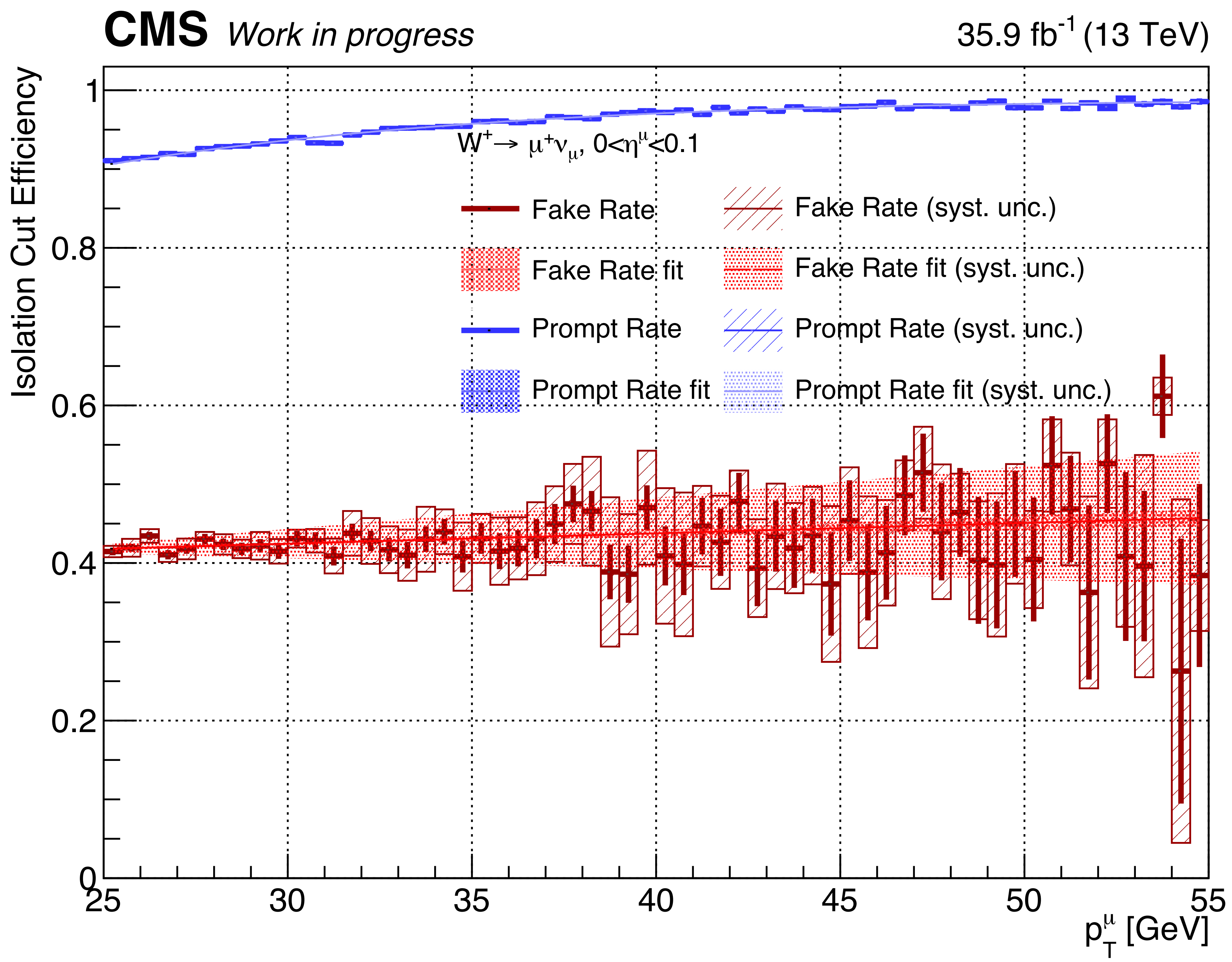
$$\frac{N_D}{N_D + N_B}\bigg|_{\text{QCD}} = \frac{N_C}{N_A + N_C}\bigg|_{\text{QCD}}$$



[tested (see backup)]

Backgrounds - QCD results and syst.





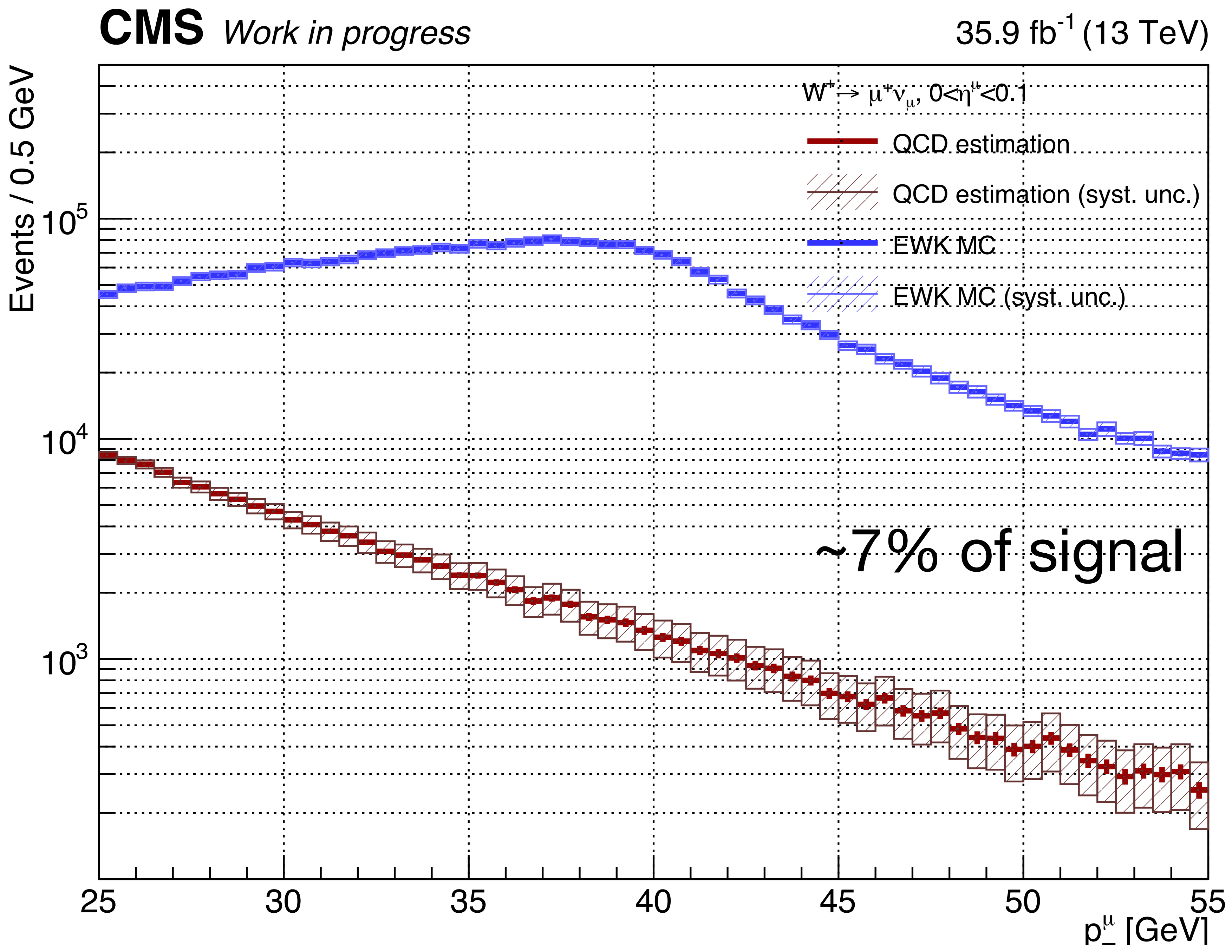
Systematic uncertainties

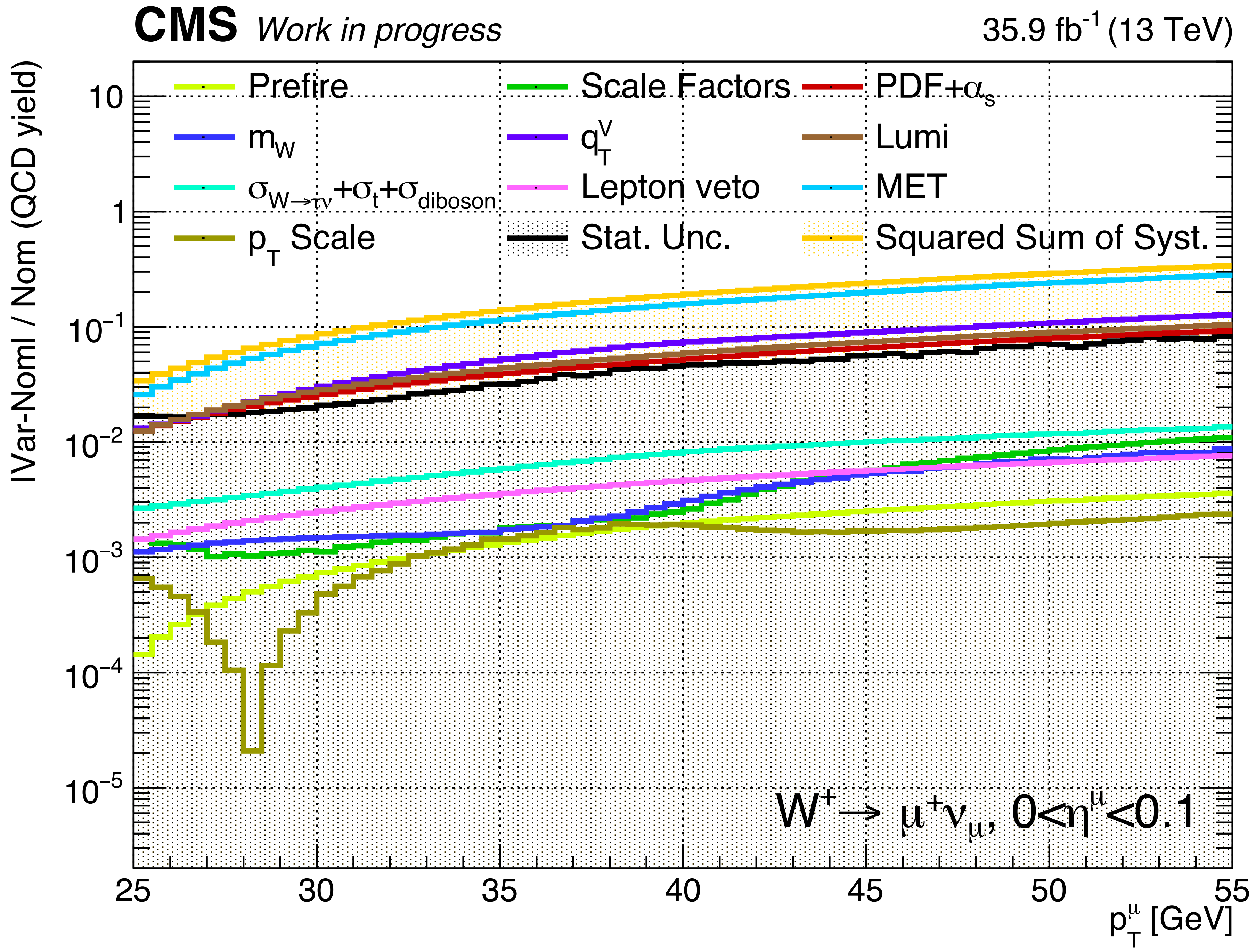
Variation of input variables propagated to QCD yield estimation

- Experimental: MET, p_T^μ scale, Scale Factors, Prefire
- Theoretical: PDF+α_S, q_T^W

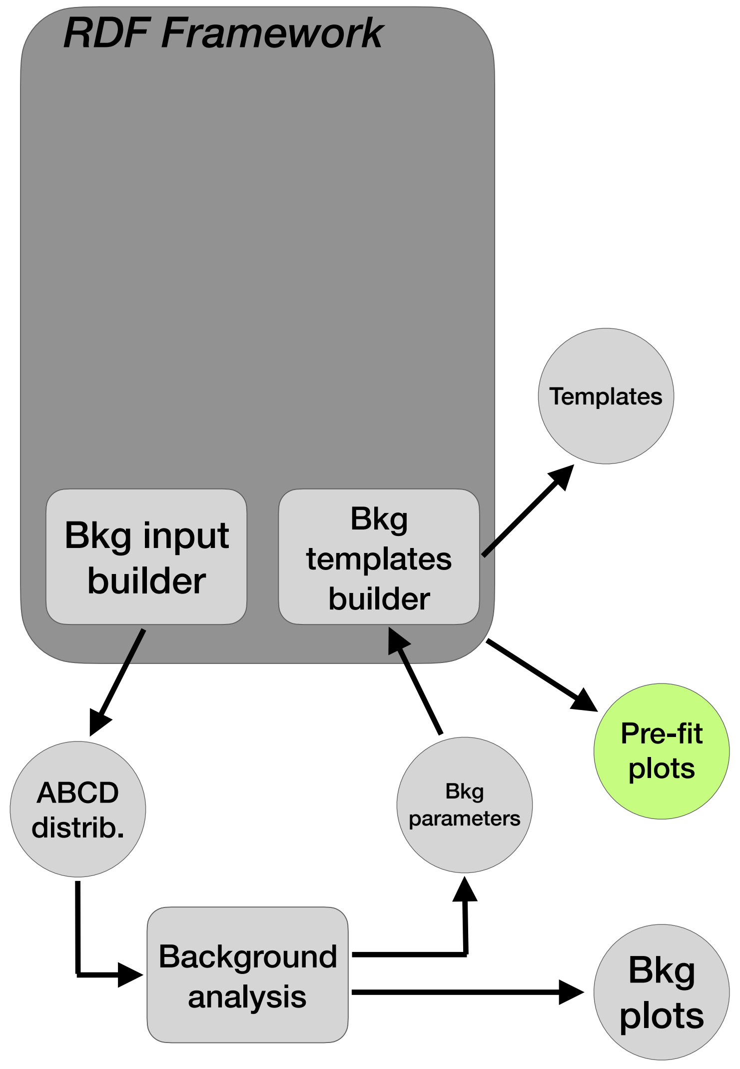
Uncertainty on QCD

- Stat.: up to 10%
- Syst: up to 20%

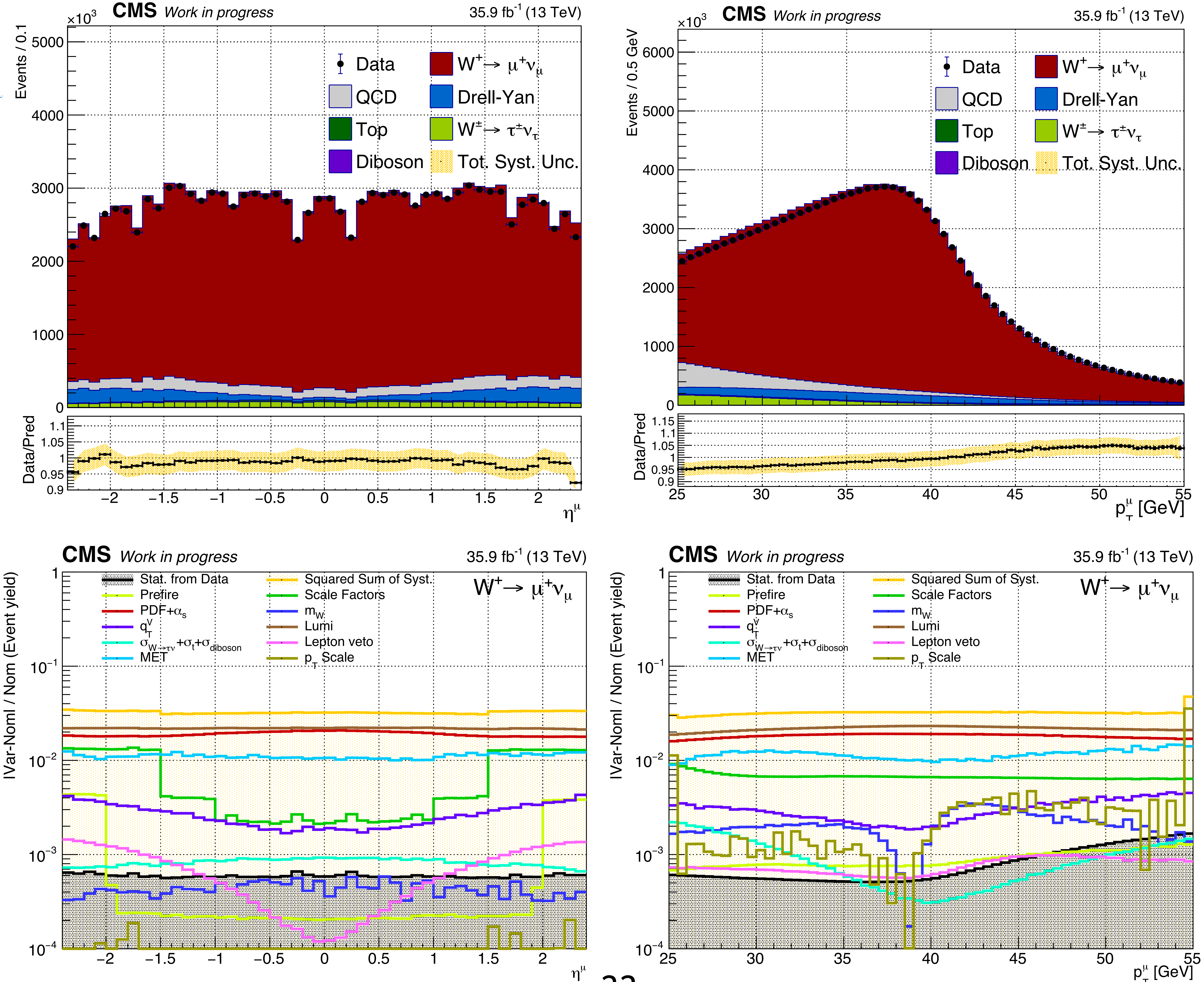




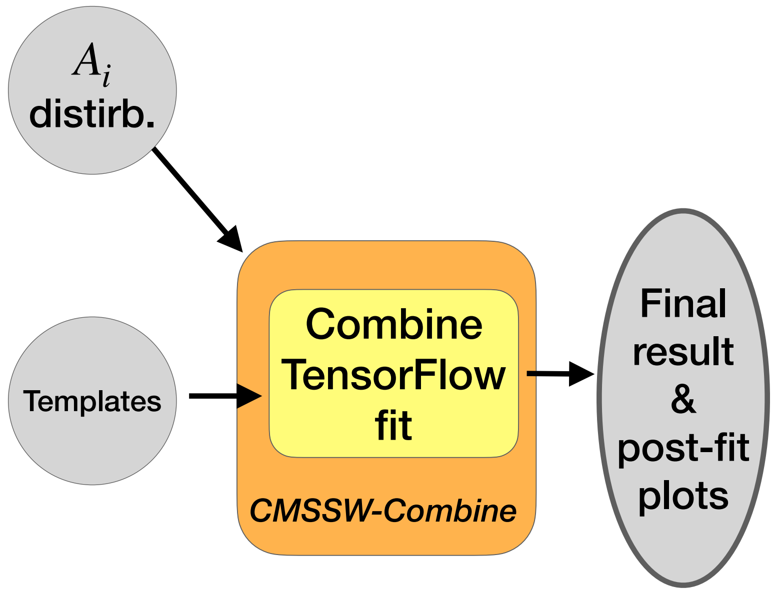
Pre-fit plots



- Discrepancy on data<5%
- Main syst: PDF, lumi, MET
- one known source of not-closure: missing SF in anti-iso region



Fit - likelihood



Extended binned Maximum-Likelihood fit:

$$L = -\ln\left(\mathscr{L}(\text{data}\,|\,\boldsymbol{\mu},\boldsymbol{\theta})\right) = \sum_i^{p_T^\mu,\eta^\mu \text{bins}} \left(n_i^{\text{obs}} \ln n_i^{\text{exp}}(\boldsymbol{\mu},\boldsymbol{\theta}) + n_i^{\text{exp}}(\boldsymbol{\mu},\boldsymbol{\theta})\right) + \frac{1}{2}\sum_k^{\text{nuisances}} (\theta_k - \theta_k^0)^2$$

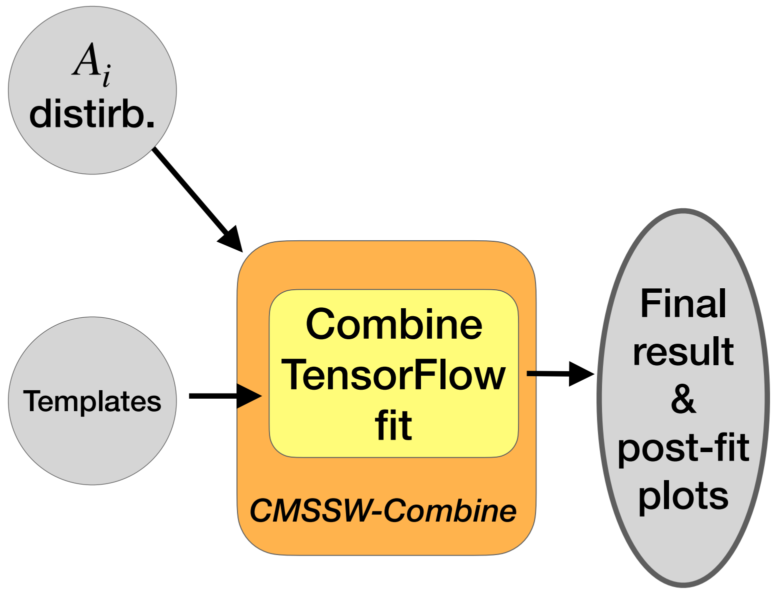
$$n_i^{\text{exp}}(\boldsymbol{\mu},\boldsymbol{\theta}) = \sum_p^{\text{processes}} \mu_p n_{i,p}^{\text{exp}} \prod_k^{\text{nuisances}} \kappa_{i,p,k}^{\theta_k}$$

- i = runs on bins of the template
  p= run over processes (i.e. templates)
  k = run over syst
- n_i^{obs} = observed number of events
- n_i^{exp} = expected number of events per bin per process
- μ_p = signal strength modifier per signal process (=1 for bkg proc.)
- $\theta_k =$ nuisance parameters, of size κ_{ipk} (with unit gaussian constraint)

- Parameters Of Interest = μ_p
- Covariance matrix: $V_{i,j}^{-1} = -\frac{\partial^2 L}{\partial x_i \partial x_j}\Big|_{x=\hat{x}}, \quad \boldsymbol{x} = \{\boldsymbol{\mu},\boldsymbol{\theta}\},$
- cross section unfolded as: $\hat{\mu}_p\sigma_p(\hat{\boldsymbol{\theta}})$, from the σ_p of the MC distribution
- This allow to extract the covariance matrix also for σ_p and other derived quantities (integrated distributions, angular coefficients…)

Fit - configuration

$^{*}A_i = \frac{\sigma_{helicity,i}}{\sigma^{U+L}}$

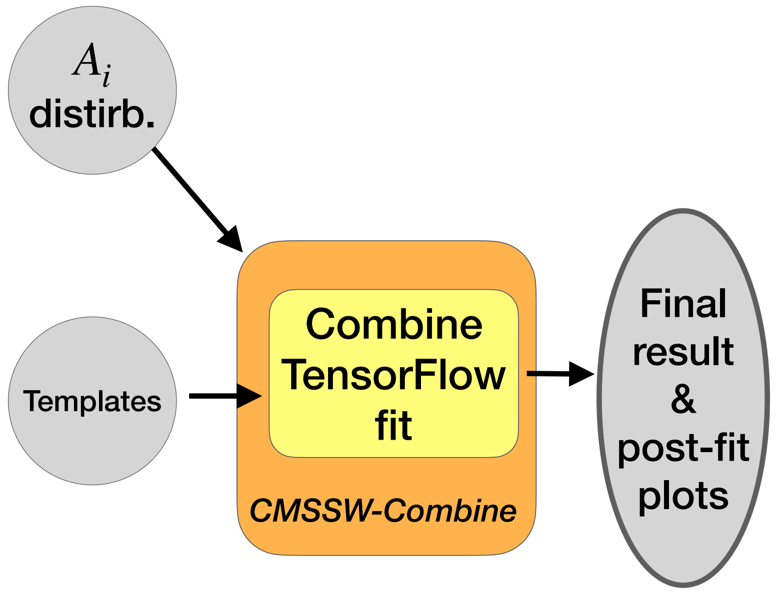


- **Template binning**:
  - $25\text{ GeV} < p_T^{\mu} < 55\text{ GeV},\ \Delta p_T = 0.5\text{ GeV}$
  - $0 < |\eta^{\mu}| < 2.4,\ \Delta|\eta| = 0.1$

  —> 2880 bins

- **Processes**: Signal (as 6 $\sigma_{helicity}$* in bin of $q_T^{w} \times |Y_W|$), bkg (QCD, Z, $W \to \tau\nu$, Top, Di boson, low acceptance)
  - q_T^{μ} bins (GeV): [0,2,4,6,8,10,12,16,20,26,36,60] —> 11 bins
  - $|Y_W|$ bins: [0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4] —> 6 bins
- **target**: $A_{0...4}$, σ^{U+L} in bin of $q_T^{W} \times |Y_W|$ (m_W)
- **POI**: signal strength multiplier for each signal process ($11 \times 6 \times 6 = 396$ POIs)

Fit - nuisance parameters



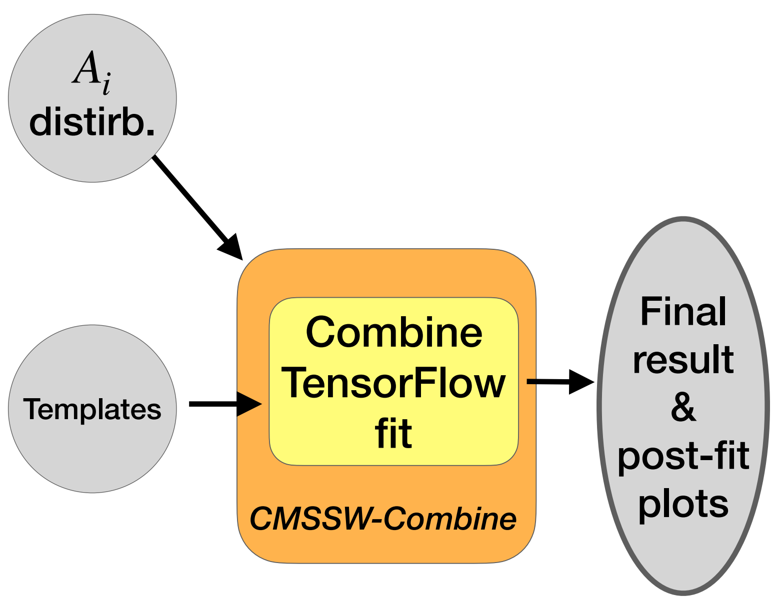
- $\ln \theta$ distributed as gauss($\ln \theta, \kappa$)
- $\Delta\theta/\theta = \kappa - 1$
- observable N estimated as $\hat{N}\kappa^{\theta}$ (with $\theta \sim$ unit Gaussian)
- nominal $\theta = 0, \theta = \pm 1 \Rightarrow \kappa$ or $1/k$ multiplying factor

- Shape = provided up/down templates
- Normalization = log normal prior $p(\theta) = \frac{1}{\sqrt{2\pi}\ln\kappa}\frac{1}{\theta}\exp\left[-\frac{(\ln\theta - \ln\theta_0)^2}{2(\ln\kappa)^2}\right]$

Nuisance	Signal	Z/γ^*	$W \to \tau\nu$	Top	Diboson	QCD	Low-acc.	$N_{\text{nui.}}$
Lepton veto	-	2%	-	-	-	-	-	1
Data Luminosity	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	1
$\sigma_{W\to\tau\nu}$	-	-	4%	-	-	-	-	1
σ_t	-	-	-	6%	-	-	-	1
σ_{diboson}	-	-	-	-	16%	-	-	1
QCD normalization	-	-	-	-	-	5%	-	1
JES, E_U	shape	shape	shape	shape	shape	shape	shape	2
p_T^μ scale	shape	shape	shape	shape	shape	shape	shape	1
SF_{stat}	shape	shape	shape	shape	shape	shape	shape	144
SF_{syst}	shape	shape	shape	shape	shape	shape	shape	1
L1 trigger prefire	shape	shape	shape	shape	shape	shape	shape	1
Luminosity on fake rate	-	-	-	-	-	shape	-	1
PDF	shape	shape	shape	-	-	shape	shape	60
α_s	shape	shape	shape	-	-	shape	shape	1
m_W	shape	-	-	-	-	shape	shape	1
q_T^Z (MC Scale)	-	shape	-	-	-	-	-	6
q_T^W (MC Scale binned in q_T^W)	-	-	shape	-	-	shape	shape	18

tot = 242

Fit - nuisance parameters



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q_T^W (MC Scale binned in q_T^W)	-	-	shape	-	-	shape	shape	18

simplified treatment

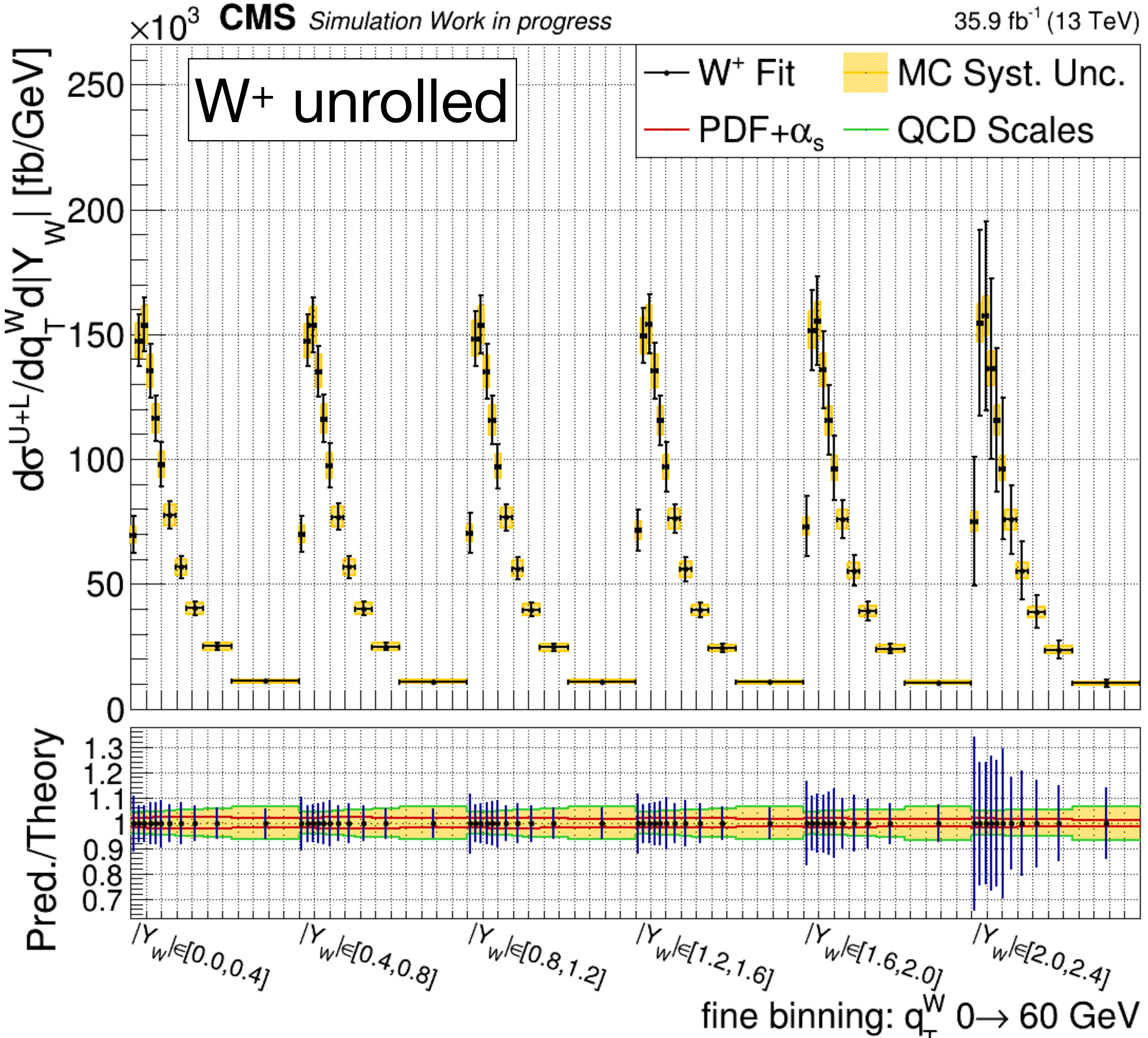
η-decorrelated

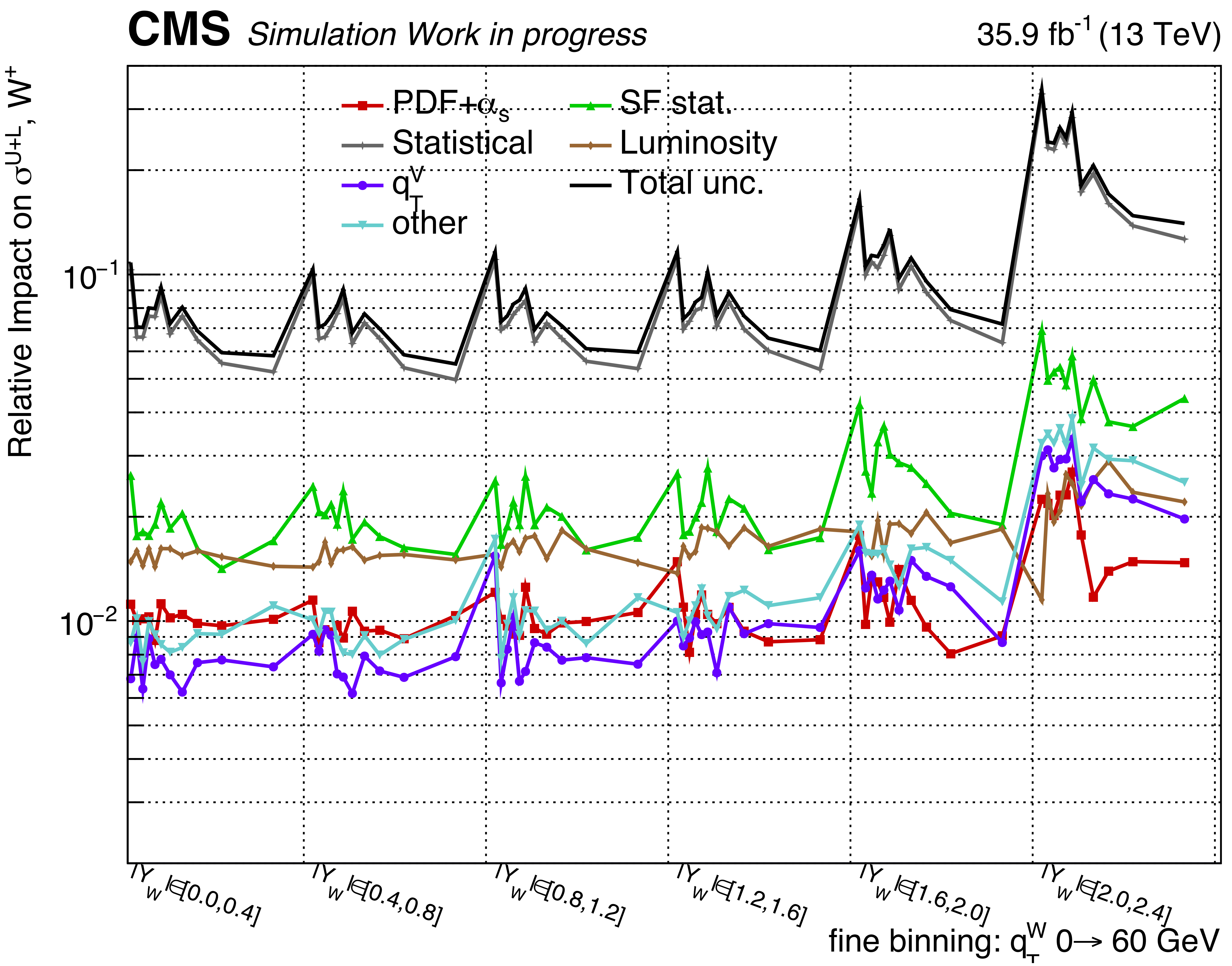
hessian eigenvalues

q_T^W-decorrelated

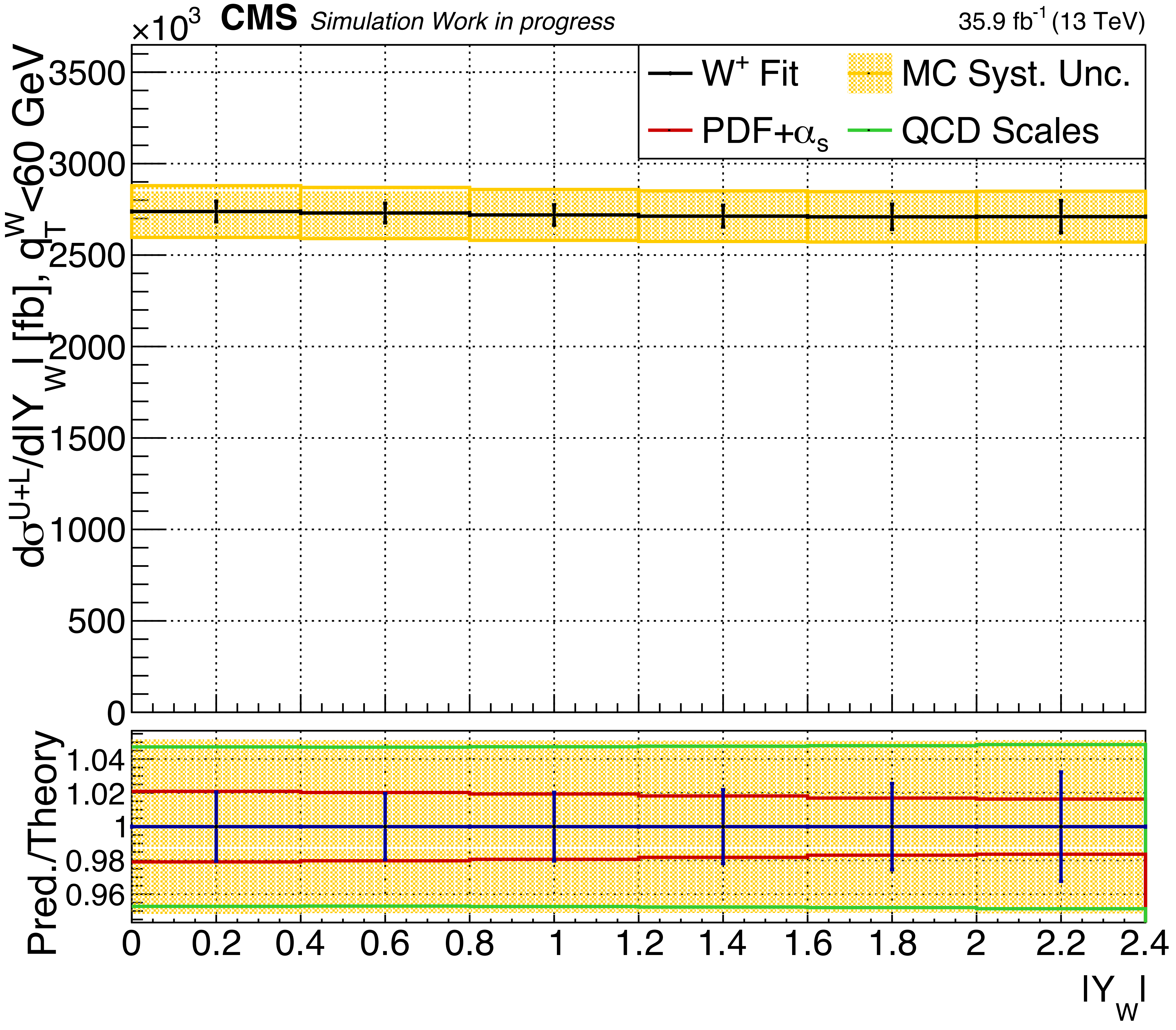
tot = 242

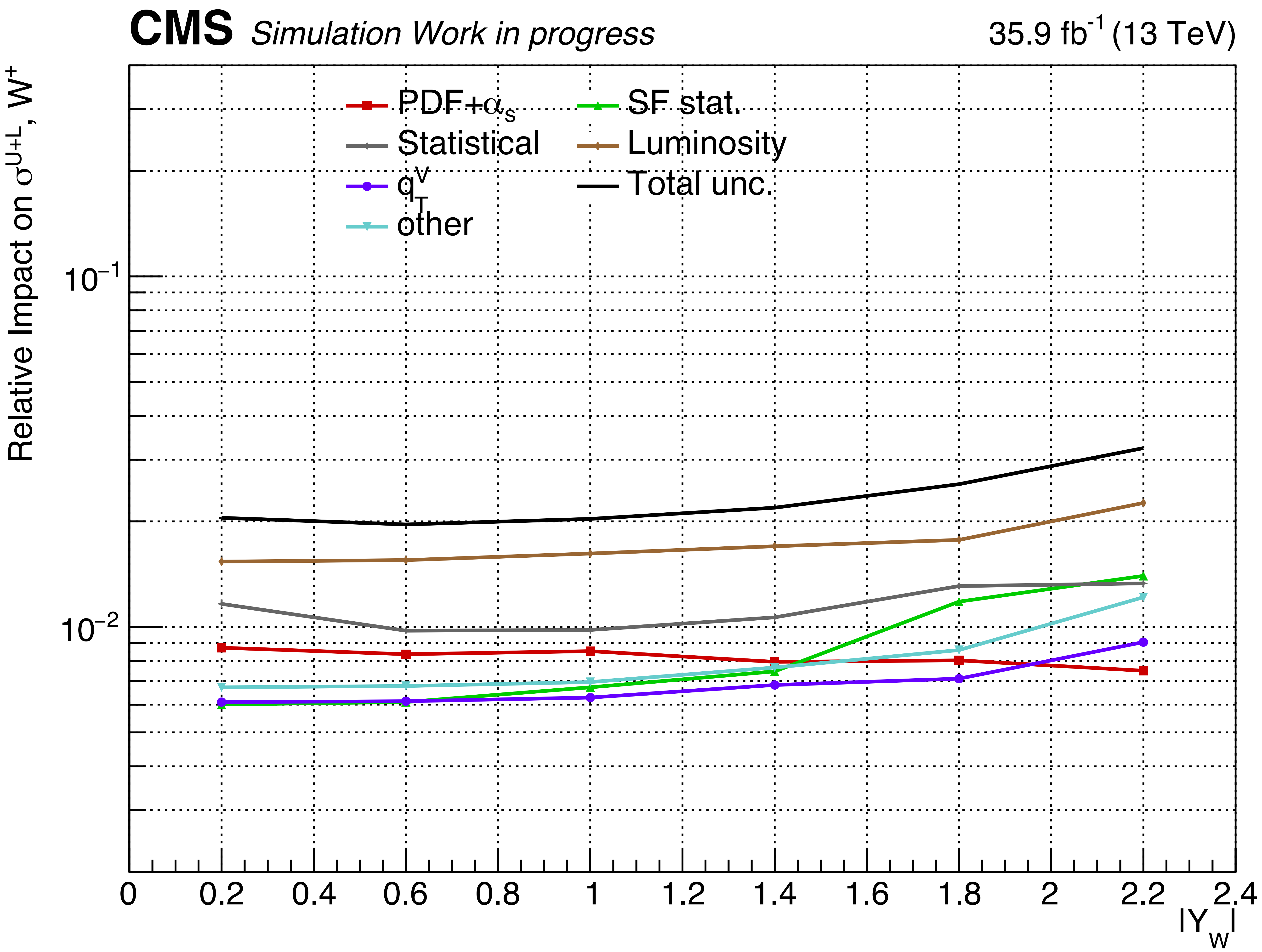
Fit - Asimov dataset results - $\frac{d\sigma^{U+L}}{d|Y_W|dq_T^W}$





Fit - Asimov dataset results - $\frac{d\sigma^{U+L}}{d|Y_W|}$ (q_T^W integrated)





Compatible with W-Helicity result [explicit comparison in the backup]

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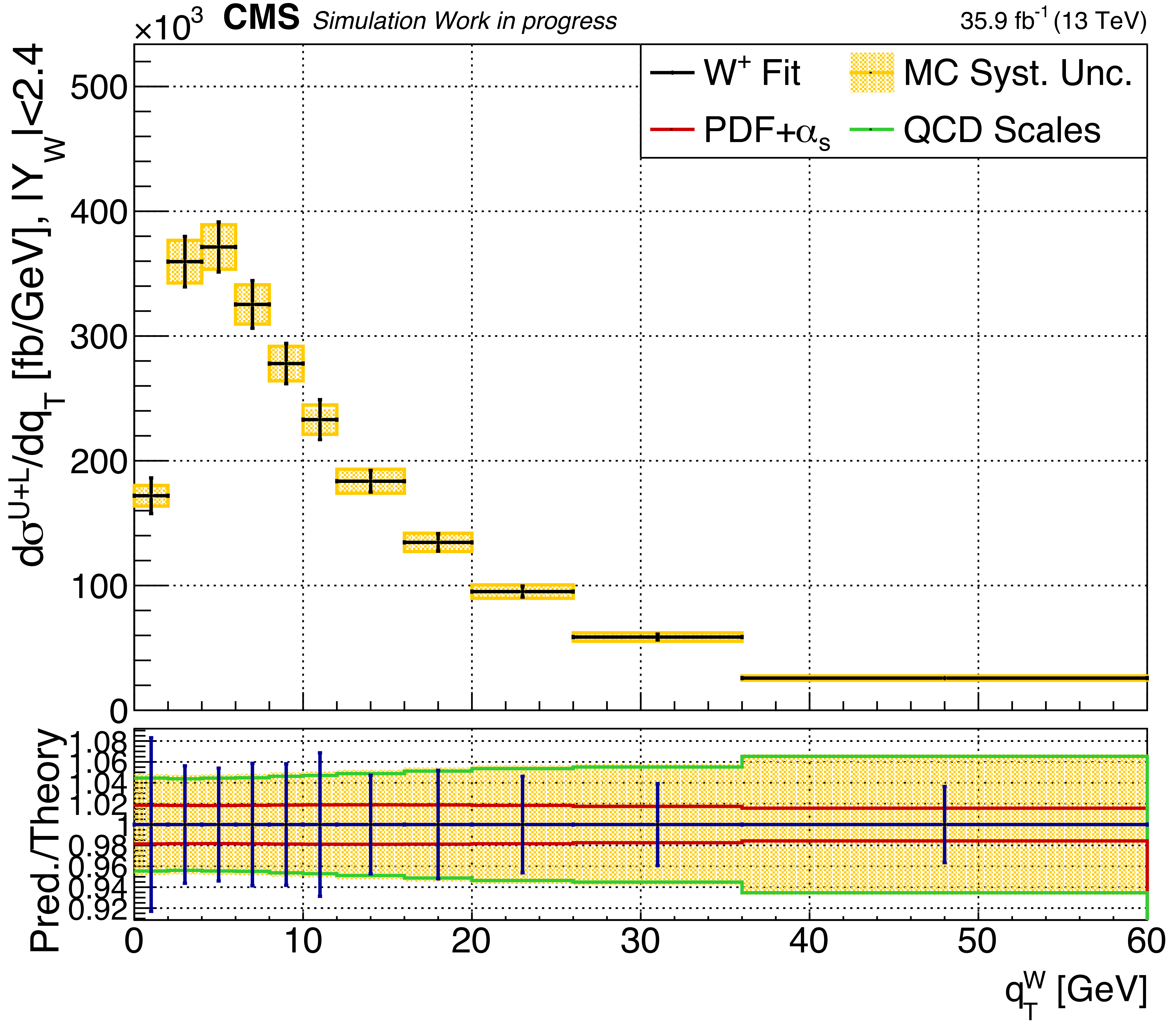
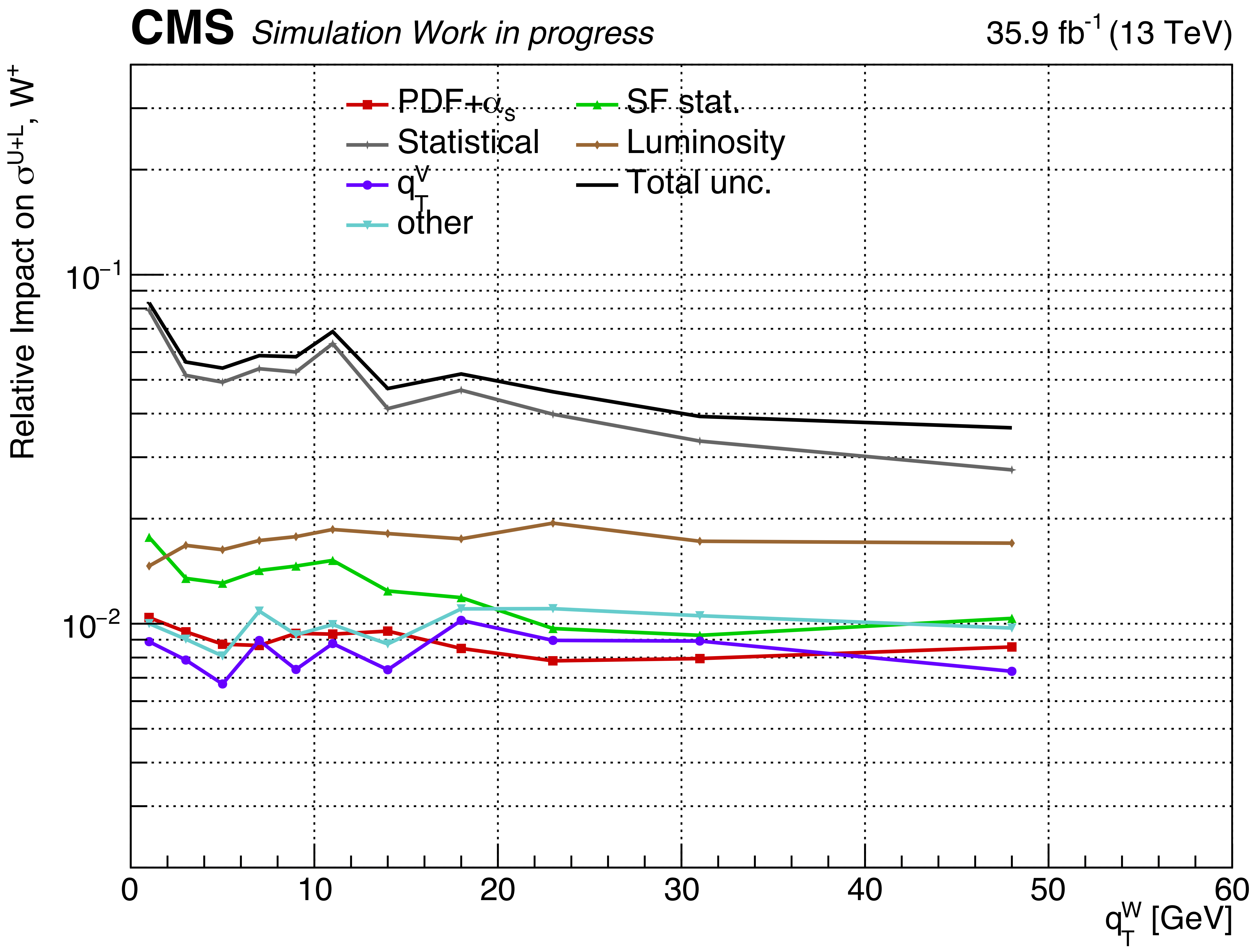
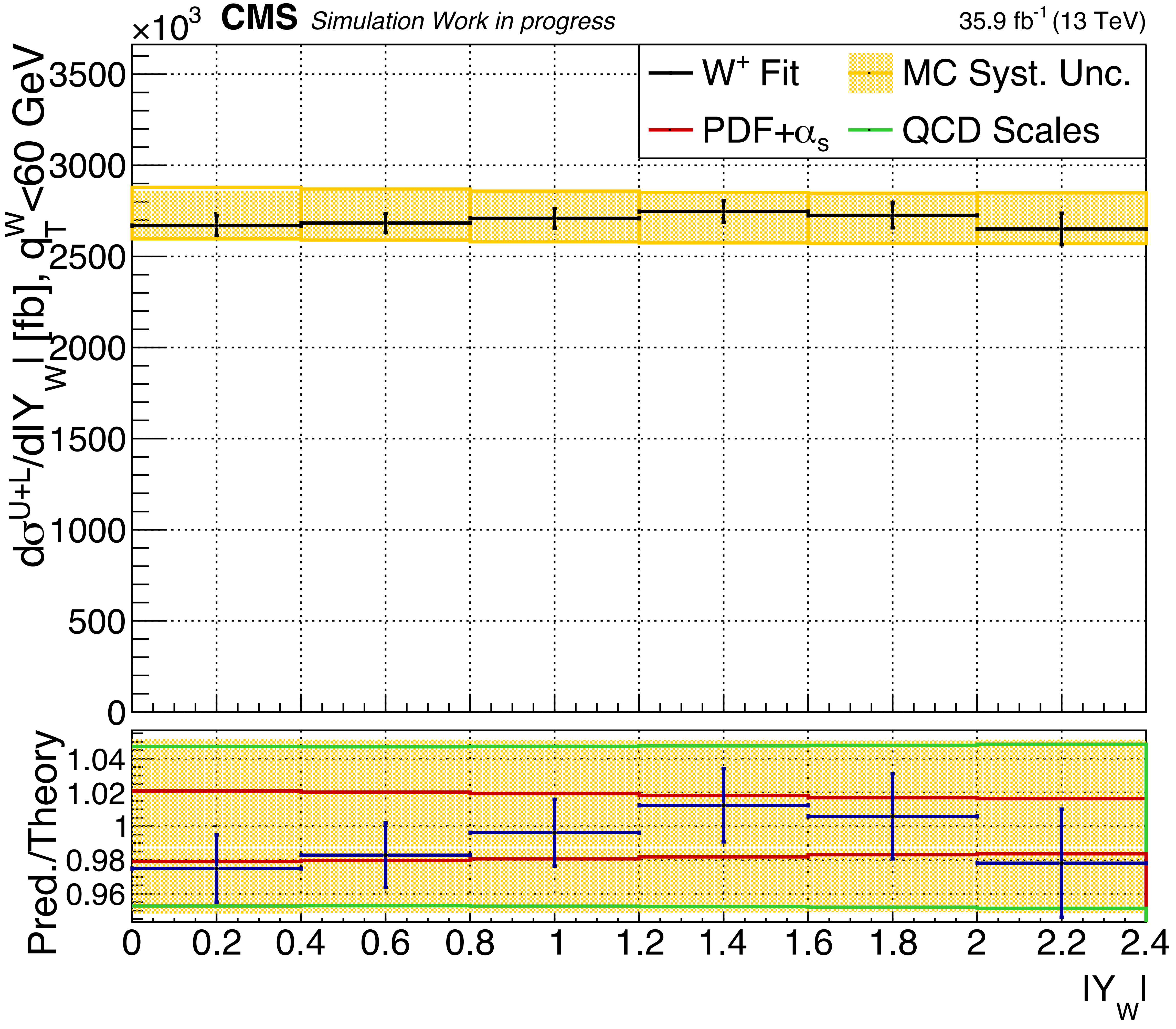
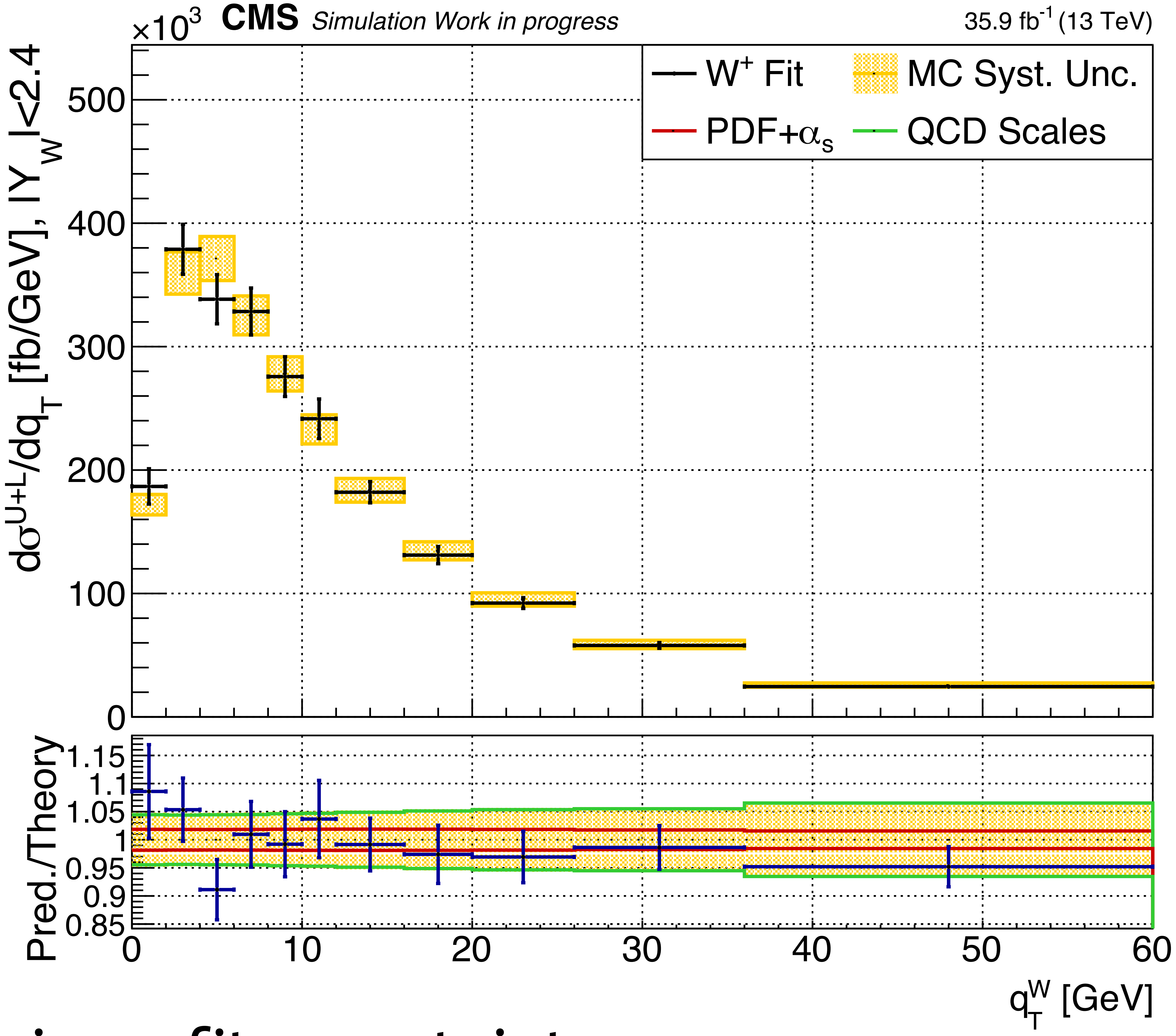




Fit - single toy results



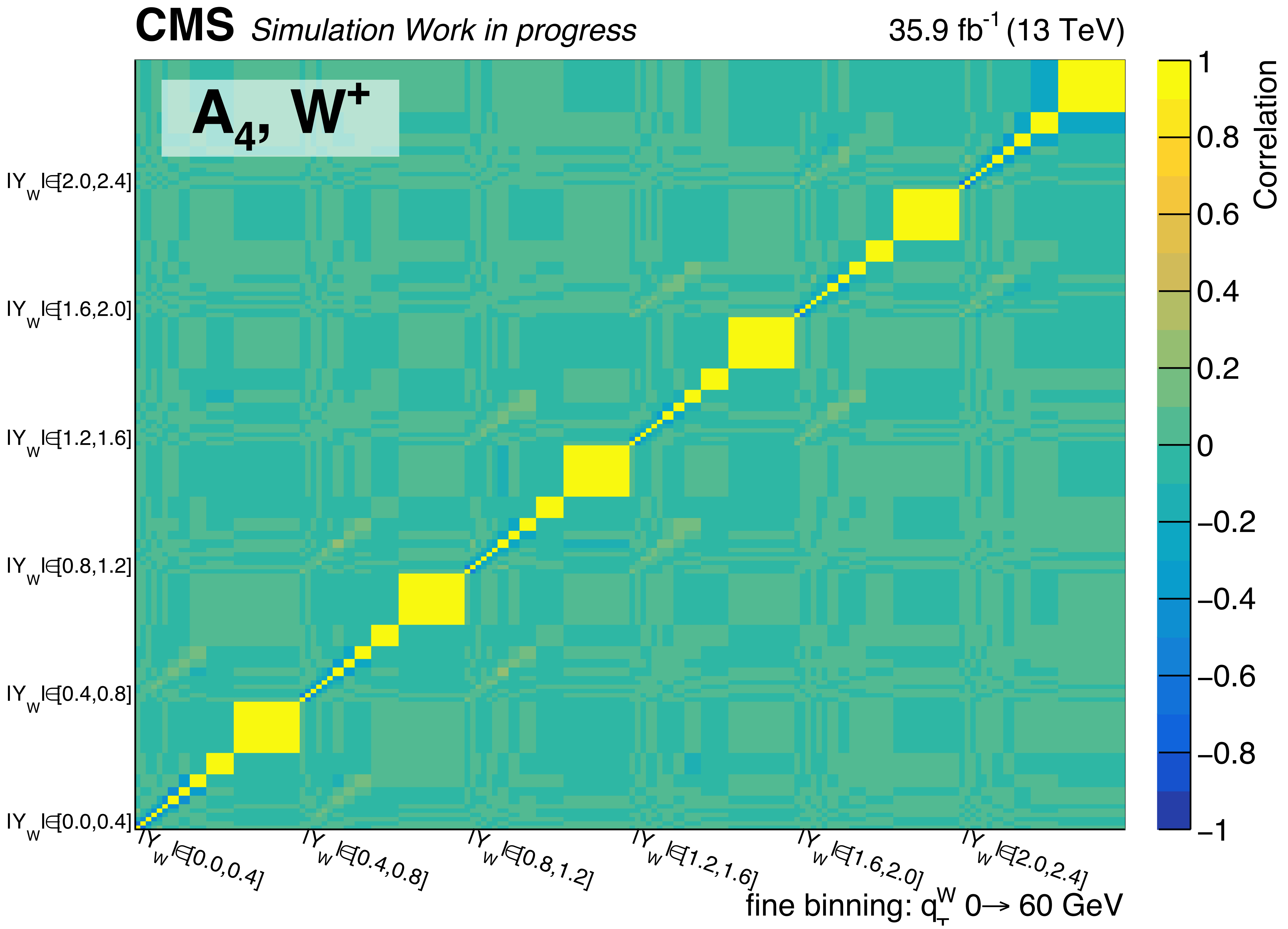


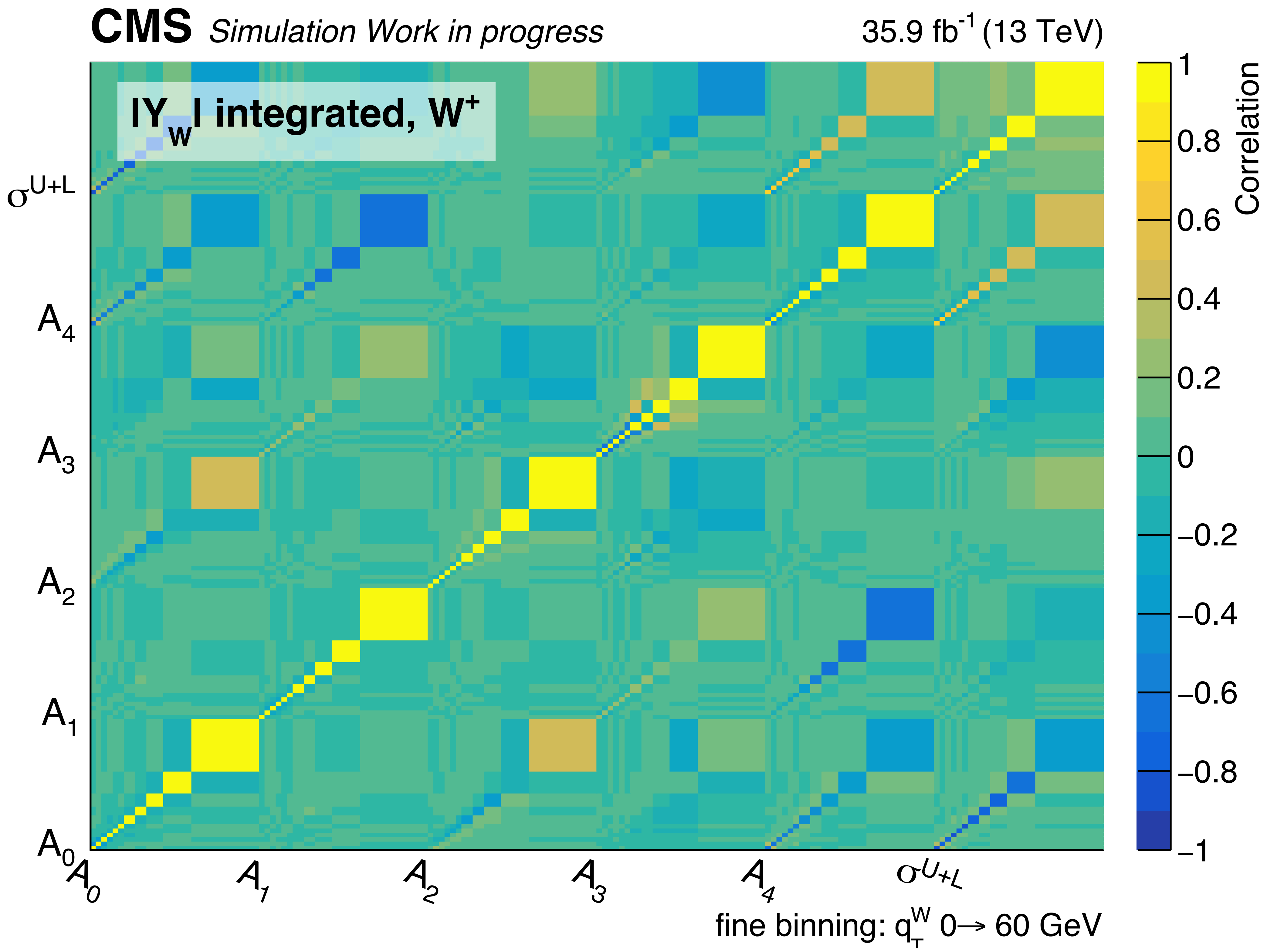
- Discrepancy within the Asimov fit uncertainty
- pull of 1K toys reasonable *[additional plots in the backup]*

$$\text{correlation}(i,j) = \frac{\text{covariance}(i,j)}{\sigma_i \sigma_j}$$

Fit - correlation matrices

- Clear correlation patterns, why? overlap of neighbor templates —> competition—> anti-correlation —> increase of uncertainties
- If only 2 overlapping templates—> strong anti-correlation between nearest-neighbor
- if multiples overlapping templates —> spread of correlations





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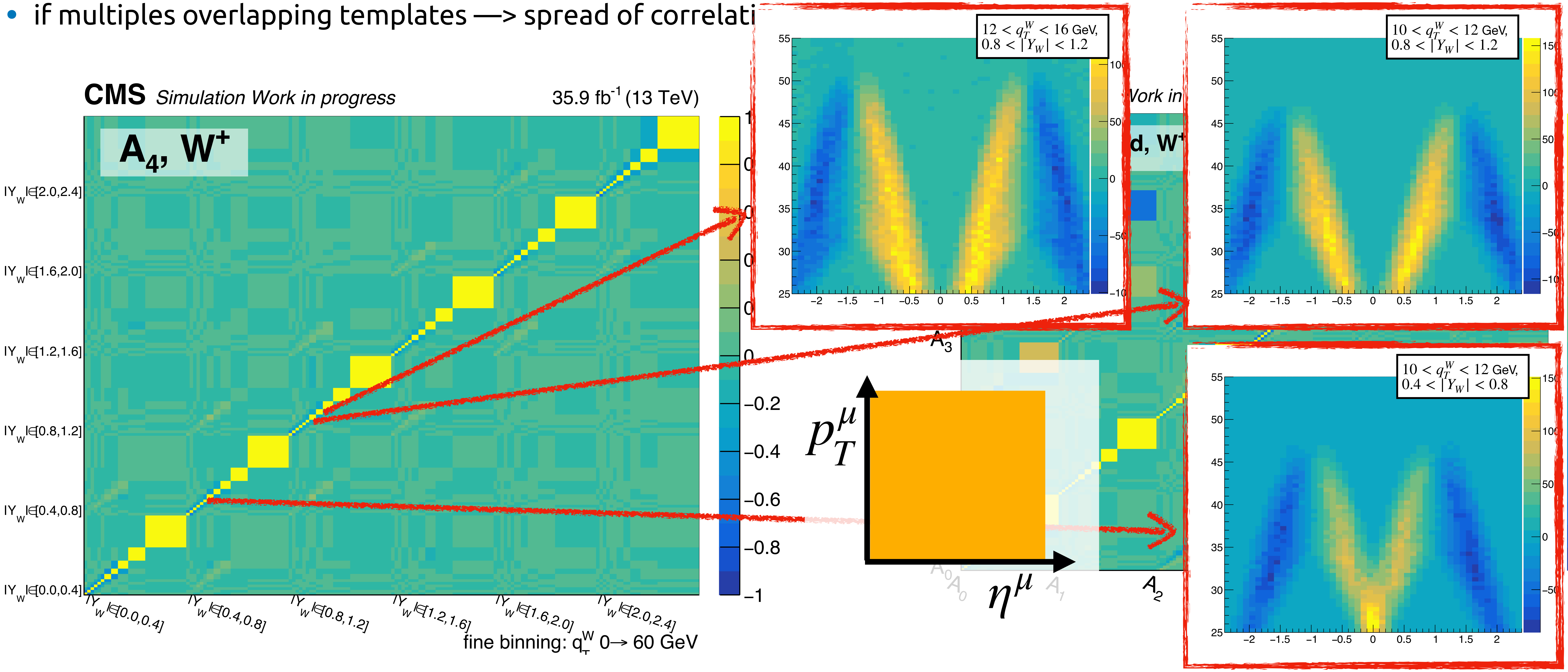

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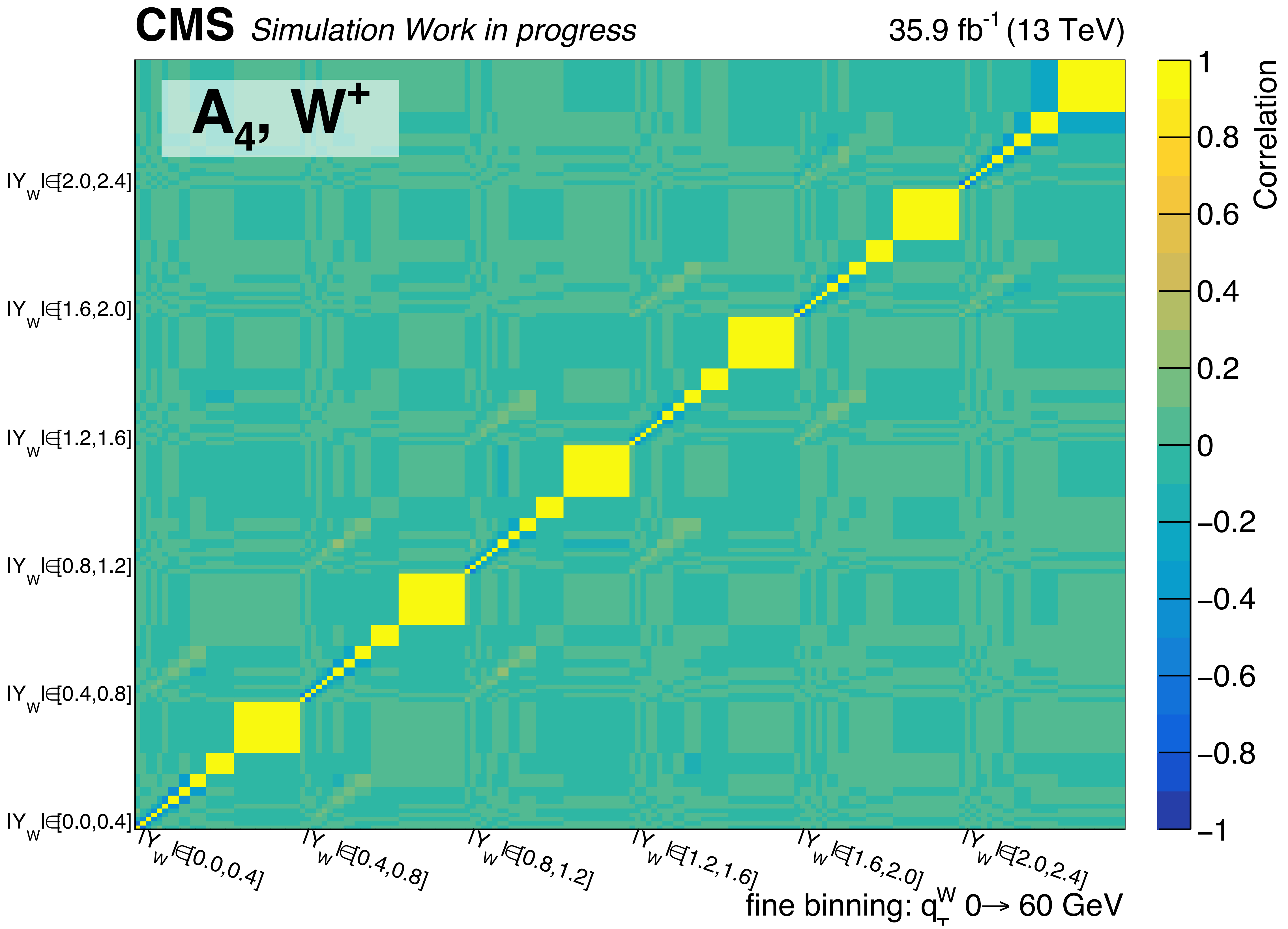
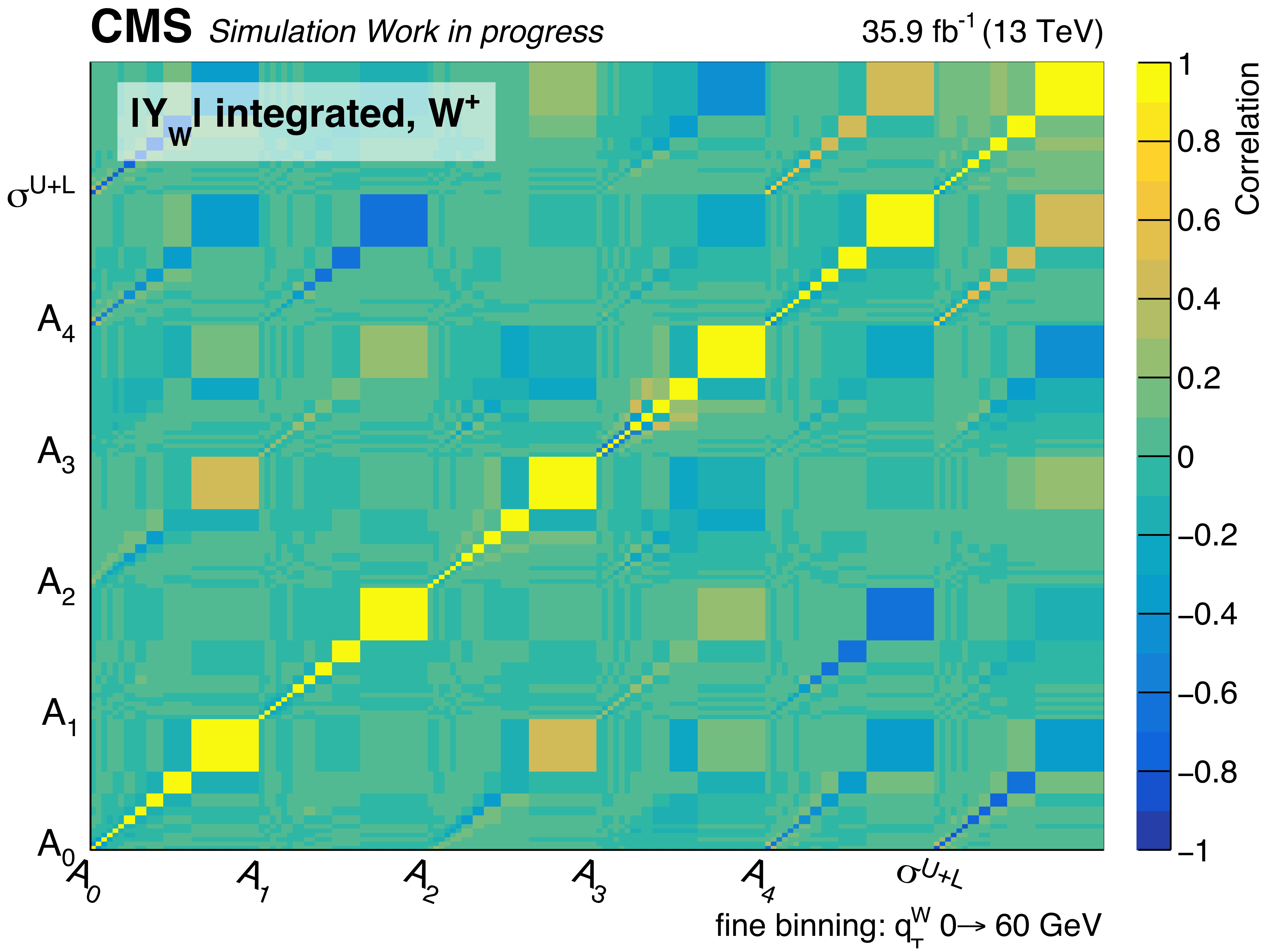
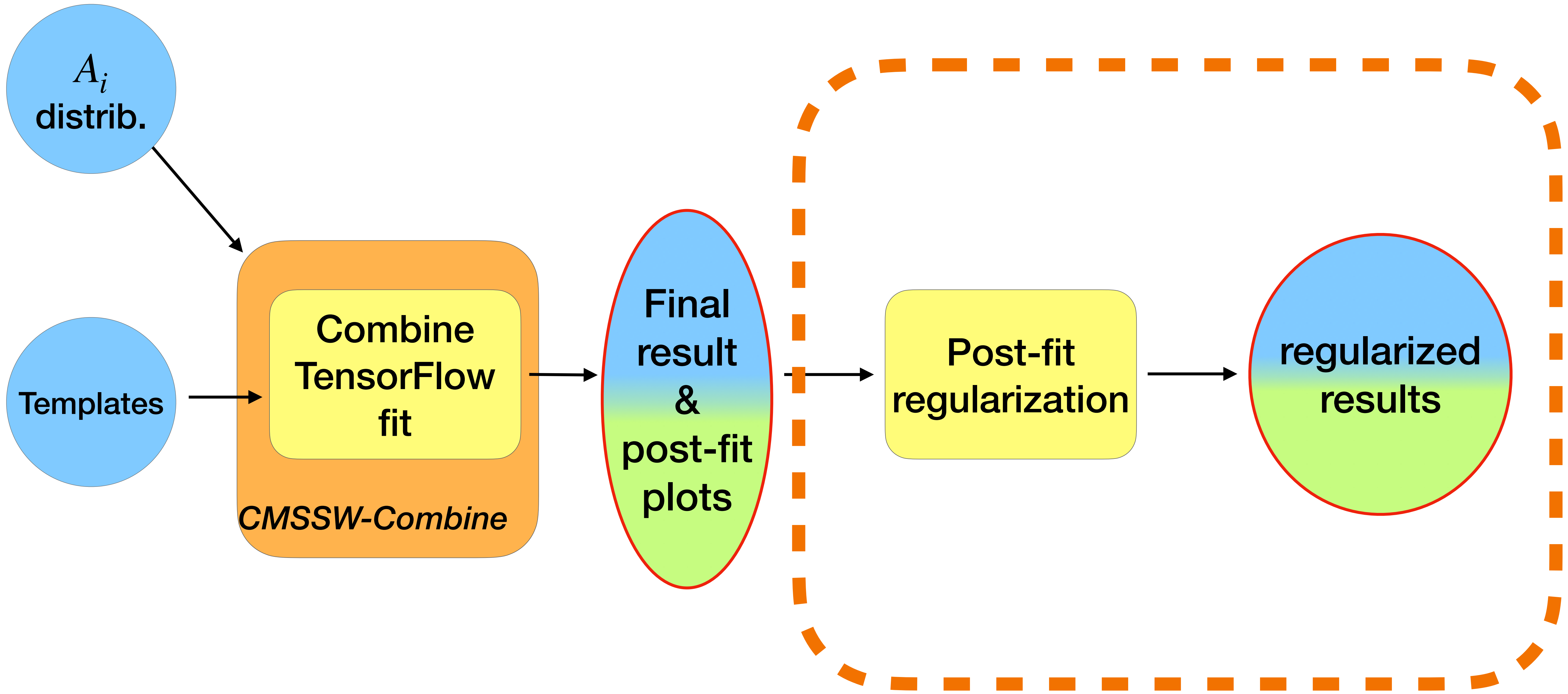




Fit - Regularization

- The angular coefficients has a smooth behavior in (Y_W, q_T^W) from previous measurements
- There are some physics-related constraints:
  - $A_i(q_T^W = 0) = 0,\ i = 0,1,2,3$, to recover LO V-A behaviour
  - $A_i(Y_W = 0) = 0,\ i = 1,4$, because P_i is odd wrt $\theta^* = \pi/2$
- Parametrize the angular coefficients with polynomials (Y_W, q_T^W) can also mitigate the anti-correlation pattern

Fit - Regularization implementation



- Simultaneous fit of the angular coefficient and σ^{U+L}
  - A_0, A_1, A_2, A_3 fitted with $\sim (q_T^W)^3 \times (Y_W)^2$
  - A_4 fitted with $\sim (q_T^W)^3 \times (Y_W)^3$
  - σ^{U+L} not directly regularized
- Full covariance matrix from template fit provided to the regularization fit

Fit - Regularization results, A_4

- small bias (<0.02 on A_i or <0.4% on σ^{U+L})
- reduction of uncertainties of factor 2-3

Fit - Regularization results, σ^{U+L}

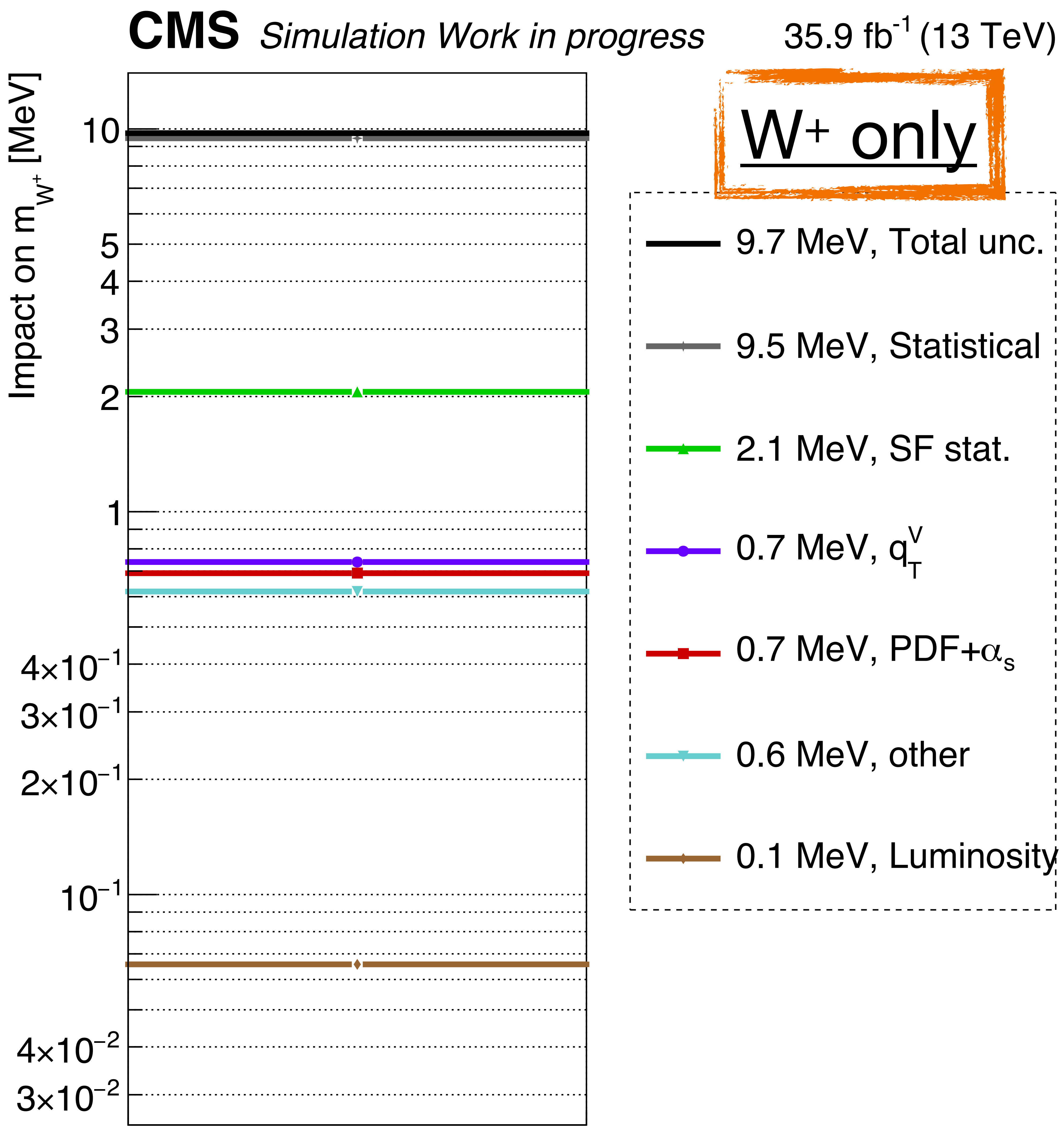
- small bias (<0.02 on A_i or <0.4% on σ^{U+L})
- reduction of uncertainties of factor 2-3

Fitting m_W (Asimov fit)

- m_W nuisance is implemented as ± 50 MeV shape variation, using a Breit-Wigner reweighting
- It can be considered as an additional "dimension" with 3 templates only
- removing the gaussian constraint to the nuisance —> measurement of the mass:

$$m_{W^+} = m_W^{\text{nom}} \pm 9.7 \text{ MeV} \pm \Delta m_{W^+},$$
$$m_{W^-} = m_W^{\text{nom}} \pm 9.9 \text{ MeV} \pm \Delta m_{W^-},$$

- negligible bias (0.02 MeV) testing with toys
- Δm_W are the missing uncertainties:
  - FSR
  - full p_T^μ scale



fitted separately 2 boson charges—> uncertainties will gain from combination!

NO regularization used in this fit

Conclusion

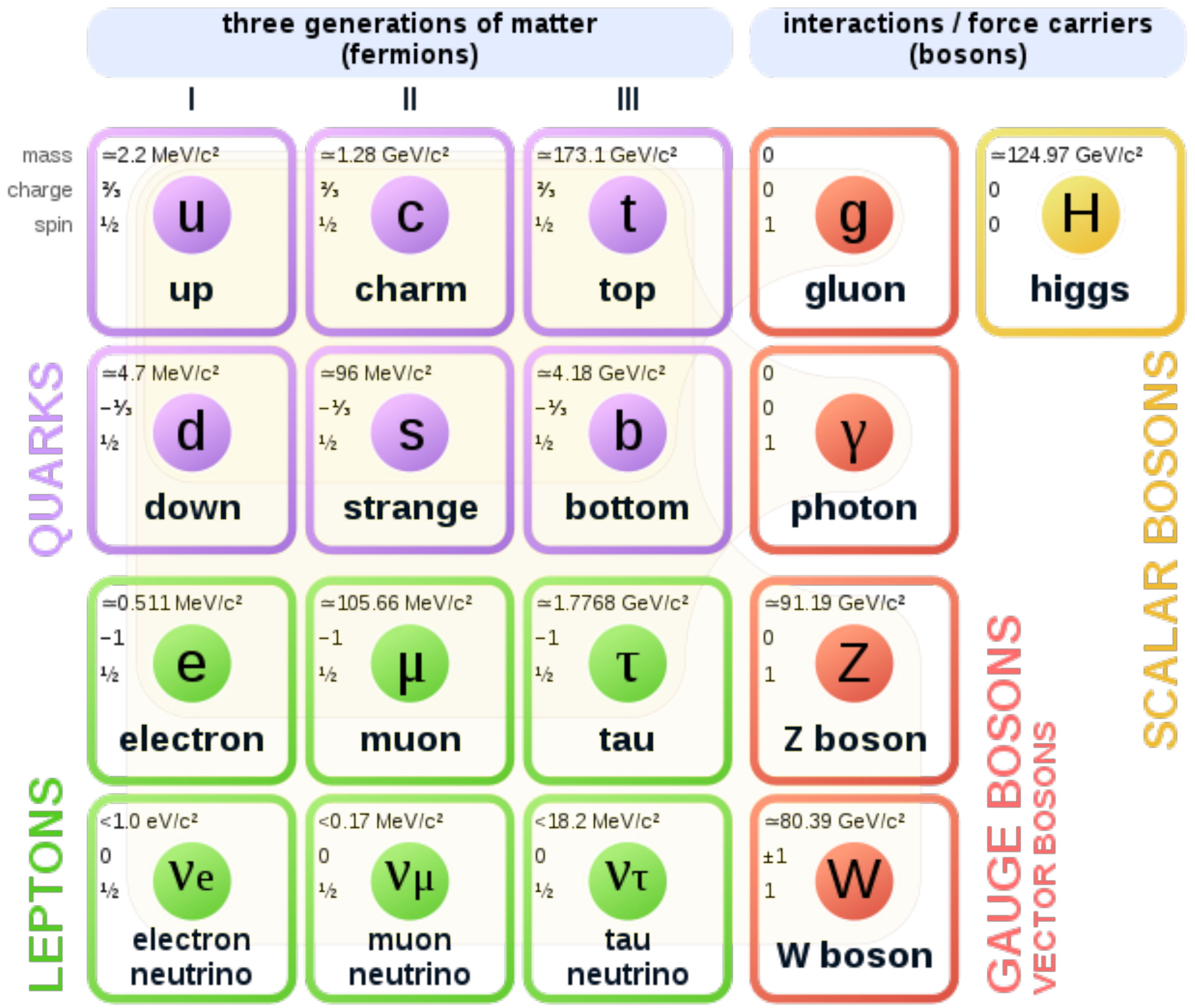
- The W production properties can be measured with extremely low systematics (1-5 % level)
- The statistical uncertainty can be tackled implementing a regularization of A_i
- a competitive (~10-15 MeV precision) **measurement of m_W with 2016 data sample** should be feasible with this approach

Beyond the PhD thesis

The W-mass group is working towards a traditional m_W measurement in parallel to the measurement described today on 2016 data and larger/more accurate MC

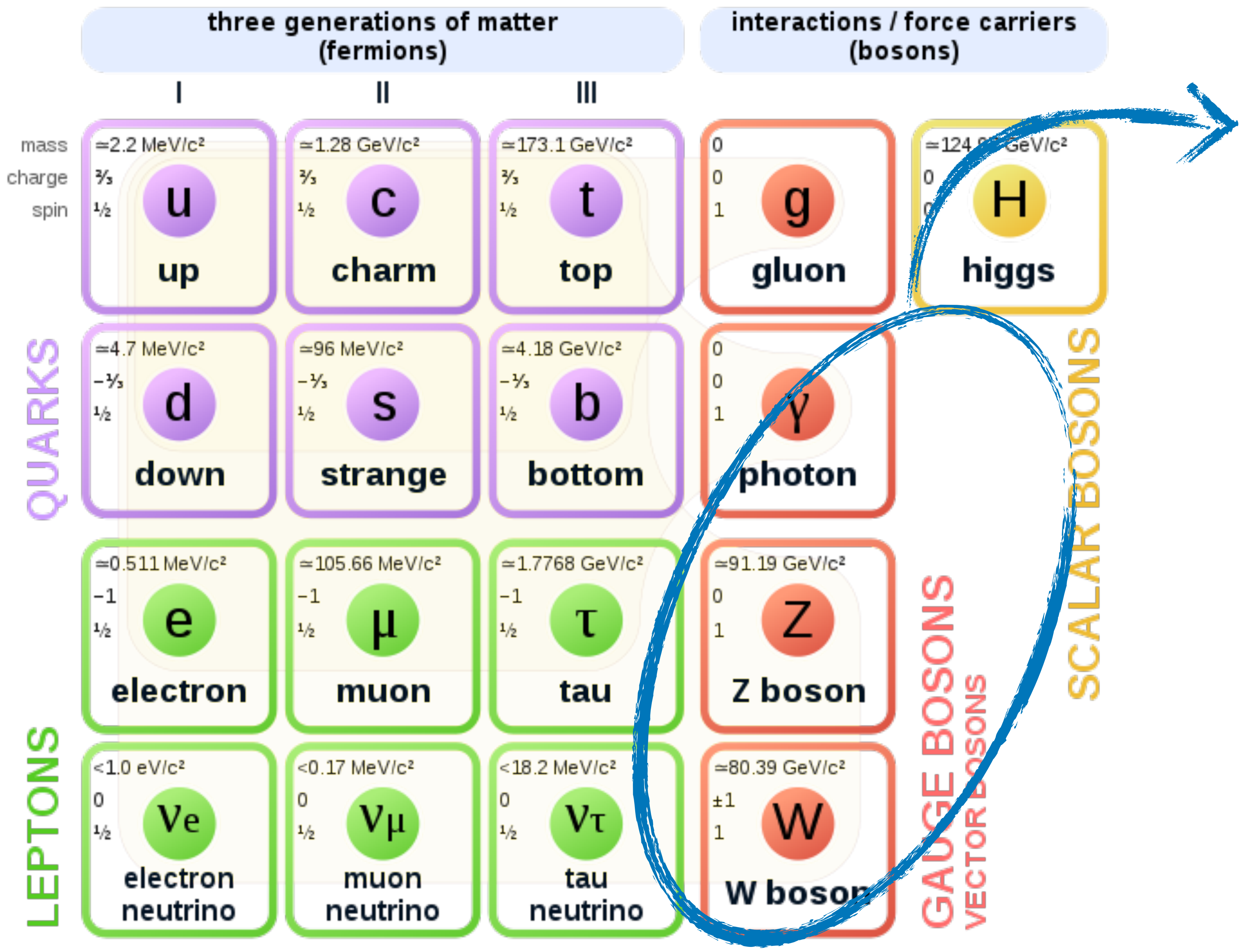
BACKUP SLIDES

The Standard Model (SM) of elementary particles



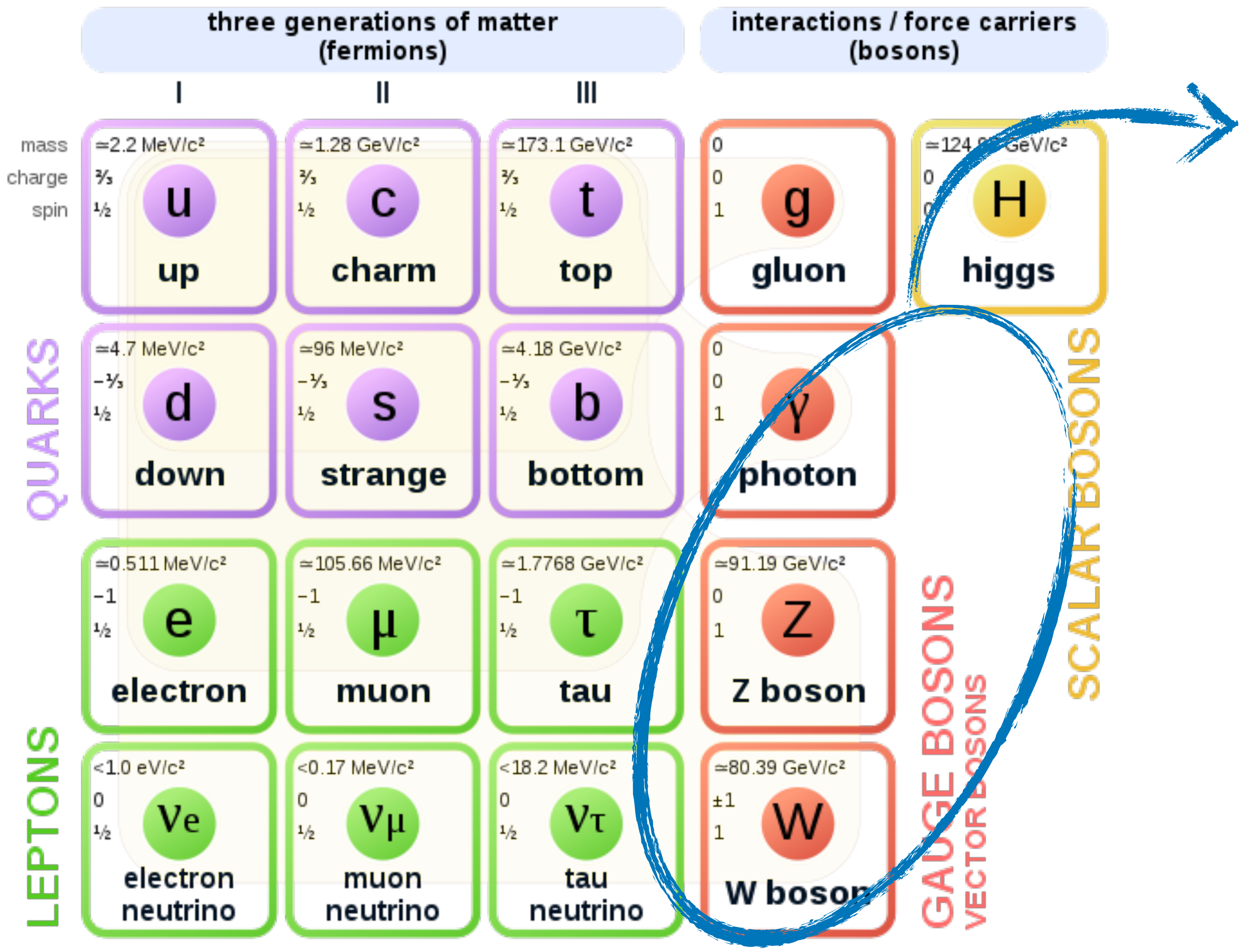
- No *evidence* of Beyond the Standard Model (BSM) phenomena at microscopic level
- but:
  - **larger-scale phenomena** (dark matter, baryonic asymmetry) not predicted by the SM
  - several **tensions** in SM measurements
  - **fine tuning** of different sectors of SM (Higgs, strong CP violation)

The electroweak sector



- **Precise theoretical prediction:** given 5 parameters $(\alpha, G_F, \alpha_S, m_H, m_Z)$ —> all the Electroweak precision observables (EWPO) predicted
- Clear experimental signature —>**precise measurements** of the EWPO

The electroweak sector



- **Precise theoretical prediction:** given 5 parameters $(\alpha, G_F, \alpha_S, m_H, m_Z)$ —> all the Electroweak precision observables (EWPO) predicted
- Clear experimental signature —>**precise measurements** of the EWPO

Electroweak global fit: simultaneous fit of the SM EW prediction to the full set of measurement

- predict all EWPO—>internal consistency of the model
- extend Standard Model (SM) likelihood with Beyond the Standard Model (BSM) assumptions and fit them
- **Indirect determination:** remove one (or more) EWPO measurement and predict it

SM lagrangian and parameters

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{EW}} + \mathcal{L}_{\text{H}} + \mathcal{L}_{\text{Yuk}}.$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\sum_{C=1}^{8} \mathcal{G}^{C}_{\mu\nu}\mathcal{G}^{\mu\nu,C} - \frac{1}{4}\mathcal{B}_{\mu\nu}\mathcal{B}^{\mu\nu} - \frac{1}{4}\sum_{i=1}^{3}\mathcal{W}^{i}_{\mu\nu}\mathcal{W}^{\mu\nu,i},$$

$$\mathcal{L}_{\text{QCD}} = \sum_{q=1}^{6}\sum_{a,b=1}^{3}\sum_{C=1}^{8} \bar{\psi}_{q,a} i\left(\frac{1}{2} i\gamma^{\mu} g_s \lambda^{C}_{ab} G^{C}_{\mu}\right)\psi_{q,b}.$$

$$\mathcal{L}_{\text{EW}} = \sum_{g=1}^{3}\sum_{f=\{Q_L,L_L,u_R,u_L,e_R\}} i\bar{\psi}_{f,g}\gamma^{\mu}D_{\mu}\psi_{f,g},$$

$$\mathcal{L}_{\text{H}} = (D_{\mu}\phi)^{\dagger}(D^{\mu}\phi) - V(\phi), \quad \text{with} \quad V(\phi) = \mu^2\phi^{\dagger}\phi + \lambda(\phi^{\dagger}\phi)^2,$$

$$\mathcal{L}_{\text{Yuk}} = -y^{d}_{ij}\bar{Q}_{L_i}\phi d_{R_j} - y^{u}_{ij}\bar{Q}_{L_i}\tilde{\phi}u_{R_j} - y^{e}_{ij}\bar{L}_{L_i}\phi e_{R_j} + h.c.,$$

$$D_{\mu} = \partial_{\mu} + \frac{1}{2}ig'YB_{\mu} + \frac{1}{2}ig\sum_{i=1}^{3}\tau^{i}W^{i}_{\mu},$$

$$\begin{aligned}
\mathcal{G}^{C}_{\mu\nu} &= \partial_{\mu}G^{C}_{\nu} - \partial_{\nu}G^{C}_{\mu} - g_s f_{CAB}G^{A}_{\mu}G^{B}_{\nu}\\
\mathcal{B}_{\mu\nu} &= \partial_{\mu}B_{\nu} - \partial_{\nu}B_{\mu}\\
\mathcal{W}^{i}_{\mu\nu} &= \partial_{\mu}W^{i}_{\nu} - \partial_{\nu}W^{i}_{\mu} - g\varepsilon_{ijk}W^{j}_{\mu}W^{k}_{\nu},
\end{aligned}$$

$$\begin{aligned}
A_{\mu} &\equiv B_{\mu}\cos\theta_W + W^{3}_{\mu}\sin\theta_W,\\
W^{\pm}_{\mu} &\equiv \frac{1}{\sqrt{2}}(W^{1}_{\mu} \pm iW^{2}_{\mu}),\\
Z^{\mu} &\equiv -B_{\mu}\sin\theta_W + W^{3}_{\mu}\cos\theta_W,\\
\phi &= \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v + H(x)\end{pmatrix},
\end{aligned}$$

$$m_Z = \frac{v}{2}\sqrt{g^2 + g'^2} = \frac{ev}{2\sin\theta_W\cos\theta_W}, \qquad m_{W^{\pm}} = \frac{v}{2}g = \frac{ev}{2\sin\theta_W} = m_Z\cos\theta_W,$$

$$m_{\gamma} = 0, \qquad m_H = \sqrt{2\lambda}v = 2|\mu|.$$

Free parameters:

- 9 Yukawa coupling (6 quarks+3 leptons)
- 4 CKM matrix parameters (3 mixing angles+complex phase)
- 5 electroweak parameters, eg: $(g, g', g_s, \mu, \lambda)$ or $(\alpha, G_F, \alpha_S, m_H, m_Z)$

$$\alpha \equiv \frac{g^2 g'^2}{4\pi(g^2 + g'^2)} = \frac{1}{4\pi}g^2\sin^2\theta_W$$

$$G_F \equiv \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2}$$

$$\alpha_s \equiv \frac{g_s^2}{4\pi}$$

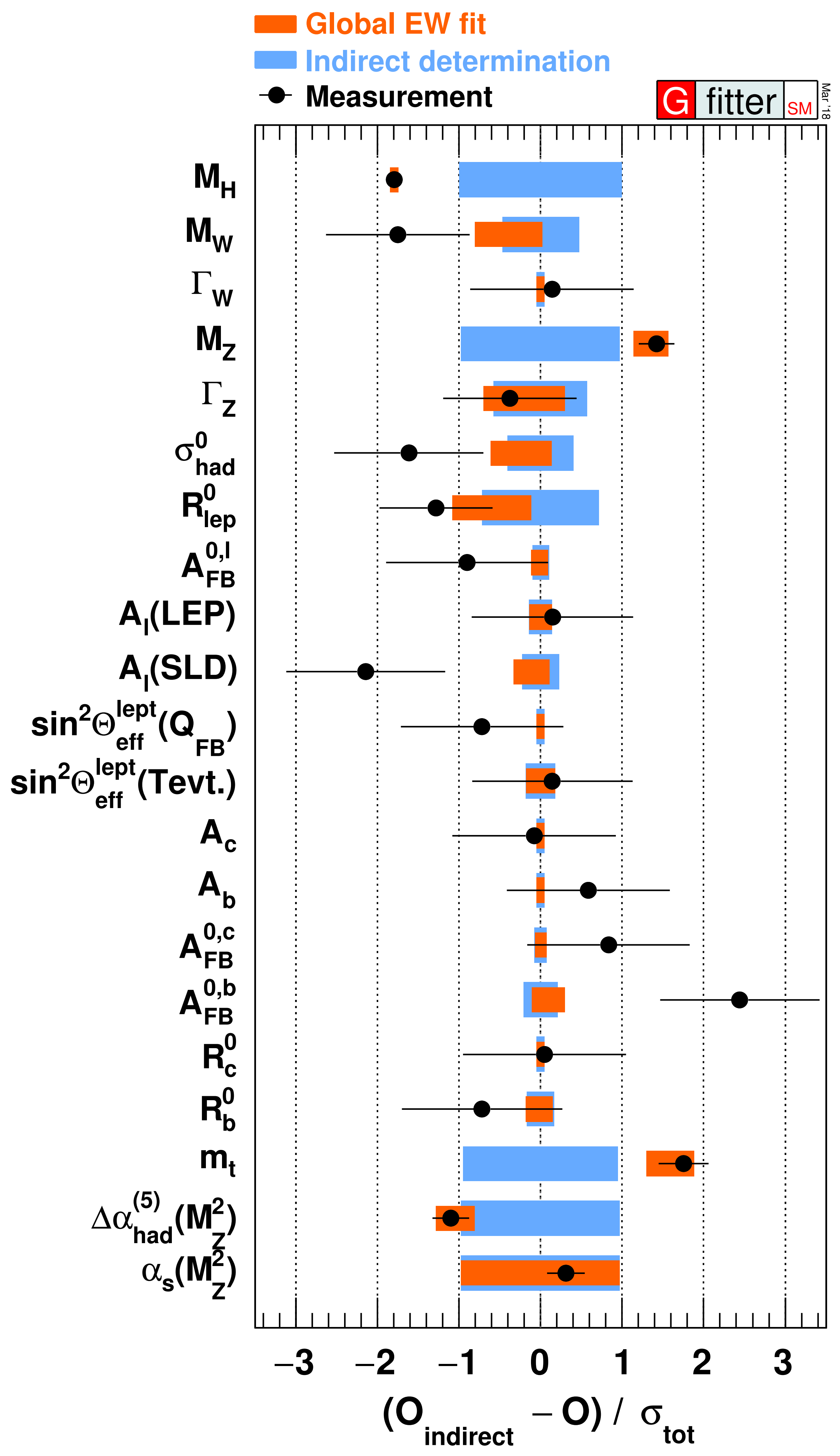
The W boson mass

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

- at tree level depends on m_Z, G_F, α only
- Δr describe the radiative corrections and includes a m_t, m_H dependence, producing a shift of ~500 MeV on m_W
- New Physics can modify m_W through Δr

[More details in the backup]

EW fit: all the EWPO



Parameter	Input value	Global fit result	Indirect determination result
m_H [GeV]	125.1 ± 0.2	125.1 ± 0.2	90^{+21}_{-18}
m_Z [GeV]	91.1875 ± 0.0021	91.1882 ± 0.0020	91.2013 ± 0.0095
m_c [GeV]	$1.27^{+0.07}_{-0.11}$	$1.27^{+0.07}_{-0.11}$	-
m_b [GeV]	$4.20^{+17}_{-0.07}$	$4.20^{+17}_{-0.07}$	-
m_t [GeV]	172.47 ± 0.68	172.83 ± 0.65	176.4 ± 2.1
$\Delta\alpha(m_Z^2)^{(5)}_{\rm had}$	$(2760 \pm 9) \cdot 10^{-5}$	$(2758 \pm 9) \cdot 10^{-5}$	$(2713 \pm 39) \cdot 10^{-5}$
α_s	-	0.1194 ± 0.0029	0.1194 ± 0.0029

- G_F fixed (very precise at low energy)
- $\alpha(m_Z)$ measurement not included (no improvement)
- $\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha(s)}$, where $\Delta\alpha(s) \simeq \Delta\alpha_\ell(s) + \Delta\alpha(s)^{(5)}_{\rm had}(s) + \Delta\alpha_t(s)$
- 10 theoretical nuisances
- profile likelihood ratio scans

Profile likelihood error estimation reminder

- given the test statistic: $q(\boldsymbol{\mu}) = -2\ln\left(\dfrac{\mathscr{L}(\boldsymbol{\mu}\,|\,\hat{\hat{\boldsymbol{\theta}}})}{\mathscr{L}(\hat{\boldsymbol{\mu}}\,|\,\hat{\boldsymbol{\theta}})}\right)$
  - $\hat{\theta}$ = MLE, double $\hat{\hat{\theta}}$=MLE at fixed μ
  - denominator= absolute max
  - numerator=profiled likelihood i.e. a function of μ only
- $q(\boldsymbol{\mu}) \sim \chi^2_{N_\theta}$ (Wilk's theorem) —> uncertainty from $\Delta\chi^2 = 1$
- if Gaussian approximation: $-2L = \chi^2$ —> $V^{-1}_{i,j} = -\dfrac{\partial^2 L}{\partial x_i \partial x_j}\Big|_{\vec{x}=\hat{\vec{x}}}\,, \quad \vec{x} = \{\boldsymbol{\mu}, \boldsymbol{\theta}\},$

More on m_W theory

- $$m_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}}$$
- $$\Delta r = \Delta\alpha - \Delta\rho\frac{1}{\tan^2\theta_W} + \Delta r_{\text{rem}}, \quad \text{where } \Delta\rho = \frac{3G_F m_t^2}{8\sqrt{2}\pi^2}$$
- $\Delta\alpha$ from α running: $\alpha(s) = \dfrac{\alpha(0)}{1-\Delta\alpha(s)}$, where $\Delta\alpha(s) \simeq \Delta\alpha_\ell(s) + \Delta\alpha(s)^{(5)}_{\text{had}}(s) + \Delta\alpha_t(s)$
- $\Delta\rho$ dominant term due to top quark loops
- Δr_{rem} contains remaining corrections (m_H-log terms, higher order corrections $O(\alpha\alpha_s)$, $O(\alpha\alpha_s^2)$…

More on m_W electroweak fit prediction

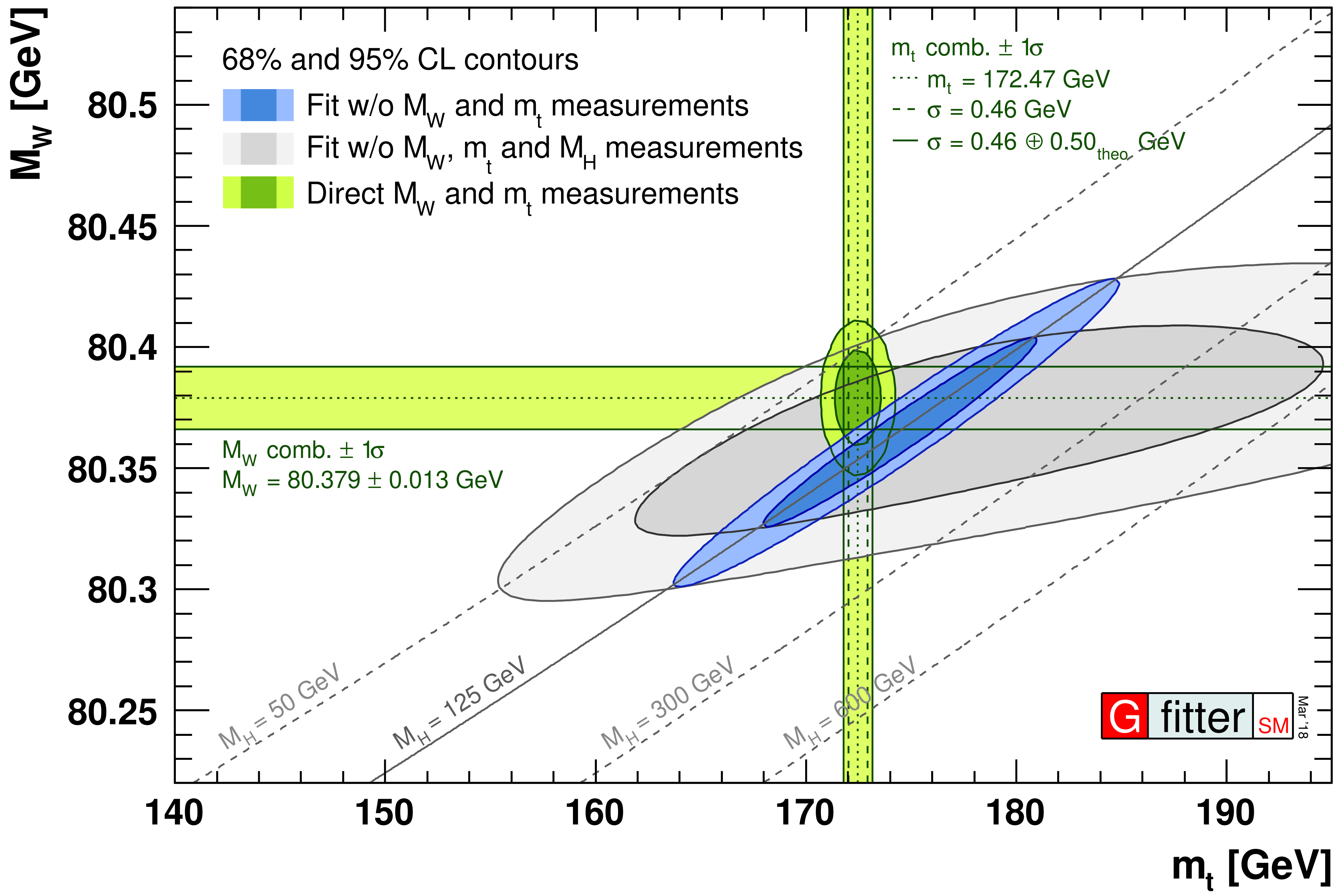
breakdown of uncertainties on m_W:

source	total	m_t	m_t^{theo}	m_Z	α_S	$\Delta\alpha(m_Z^2)^{(5)}_{\text{had}}$	m_H	m_W^{theo}
value [MeV]	7	2.7	3	2.6	2.6	2.4	1	4.

- m_W^{theo} is ruled by higher order corrections at 3 loops

m_W is correlated with other EWPO

- m_t uncertainty is ruled by m_W knowledge
- simultaneous indirect determination:

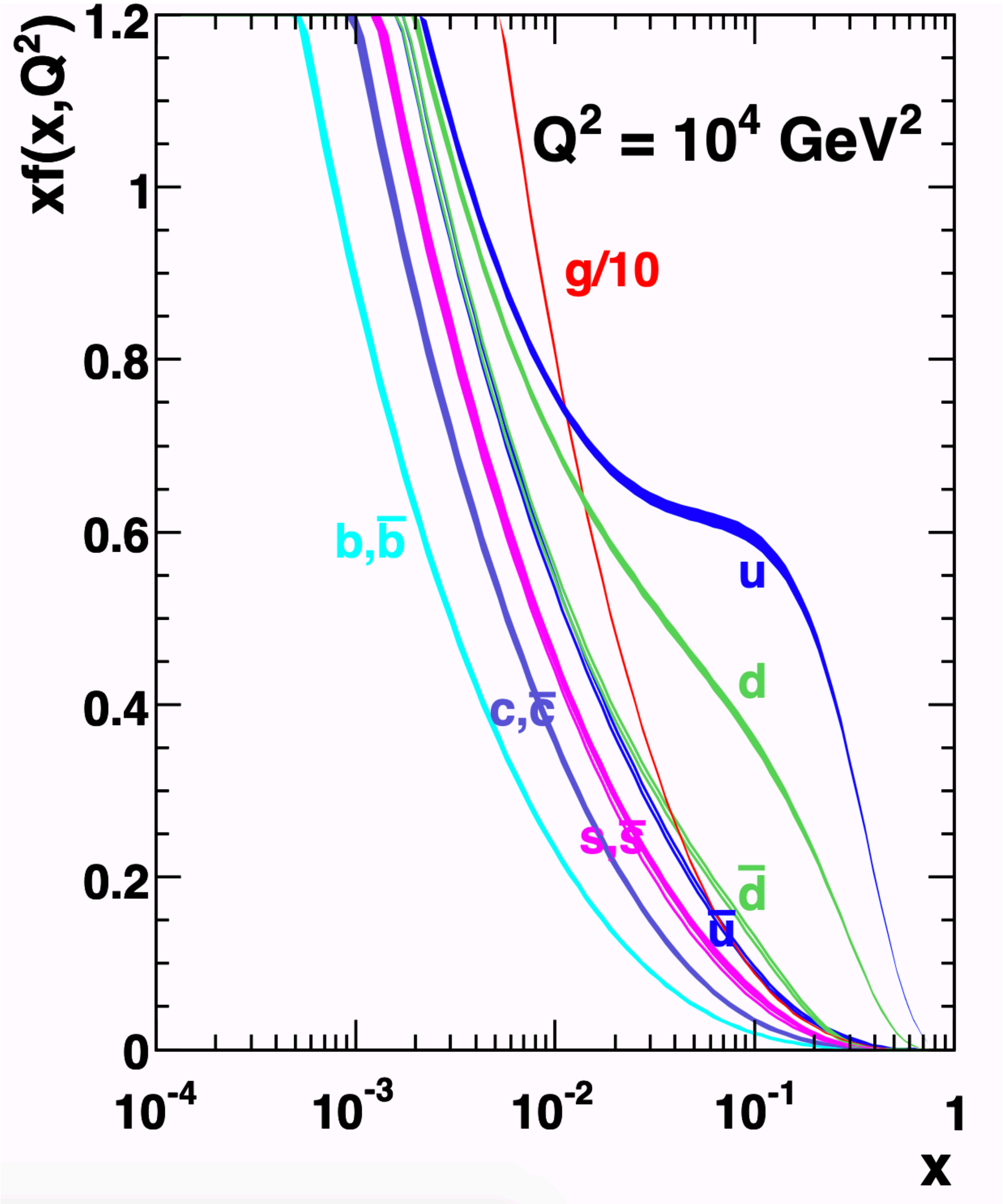


In the framework of the previous measurements

W mass measurement	Tevatron	ATLAS	CMS (traditional)	CMS (this/future works)
Prod. syst. approach	External theoretical assumptions	• External theoretical assumptions • calibration on Z properties • Validation on q_T^W, Y^W	• Constraint of Y^W measurement • Constraint of q_T^W measurement (?) • assumption and validation on A_i	Simultaneous measurement of Y^W, q_T^W, A_i and m_W
Luminosity	2+4 fb^{-1} (1+1.5 M Wevents)	4.6 fb^{-1} (14 M Wevents)	36 fb^{-1} (200 M Wevents)	36 fb^{-1} (2016) or 160 fb^{-1} (UL) (200 M or 900 M Wevents)
Pile-Up	1-4	9	27	27 (34)

The Large Hadron Collider (LHC)

- circular proton-proton collider
- $\sqrt(s) = 13\ \text{TeV}, \mathscr{L} \sim 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
- interaction ruled by Parton Distribution Function (PDF) $\sigma_{pp} = \int \sum_{i,j} f_i f_j \hat{\sigma}_{i,j} dx_1 dx_2$
- 20-40 Pile-Up (PU) interaction each event



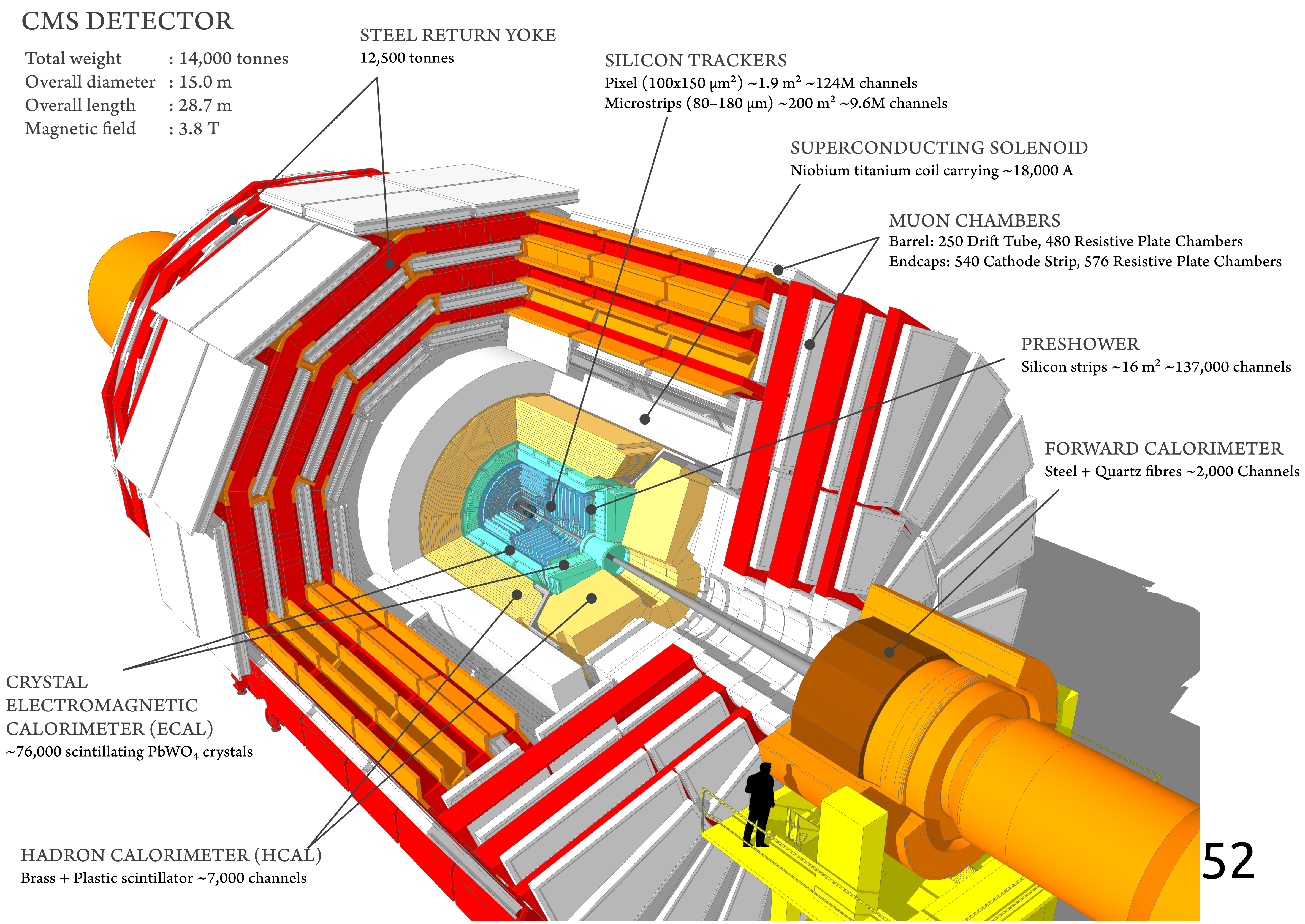
Compact Muon Solenoid (CMS)

general-purpose detector:

- organized in concentric sub-detecors
- hermetic
- Trigger system to handle 40 MHz input

key point of muon reconstruction:

- silicon tracker (pixel+strip) + muon chambers (DT+CSC+RPC)
- p_T resolution 1-8%
- p_T scale calibration at $10^{-3} - 10^{-4}$
- $> 99\,\%$ tracking efficiency and ~0.1% fake rate



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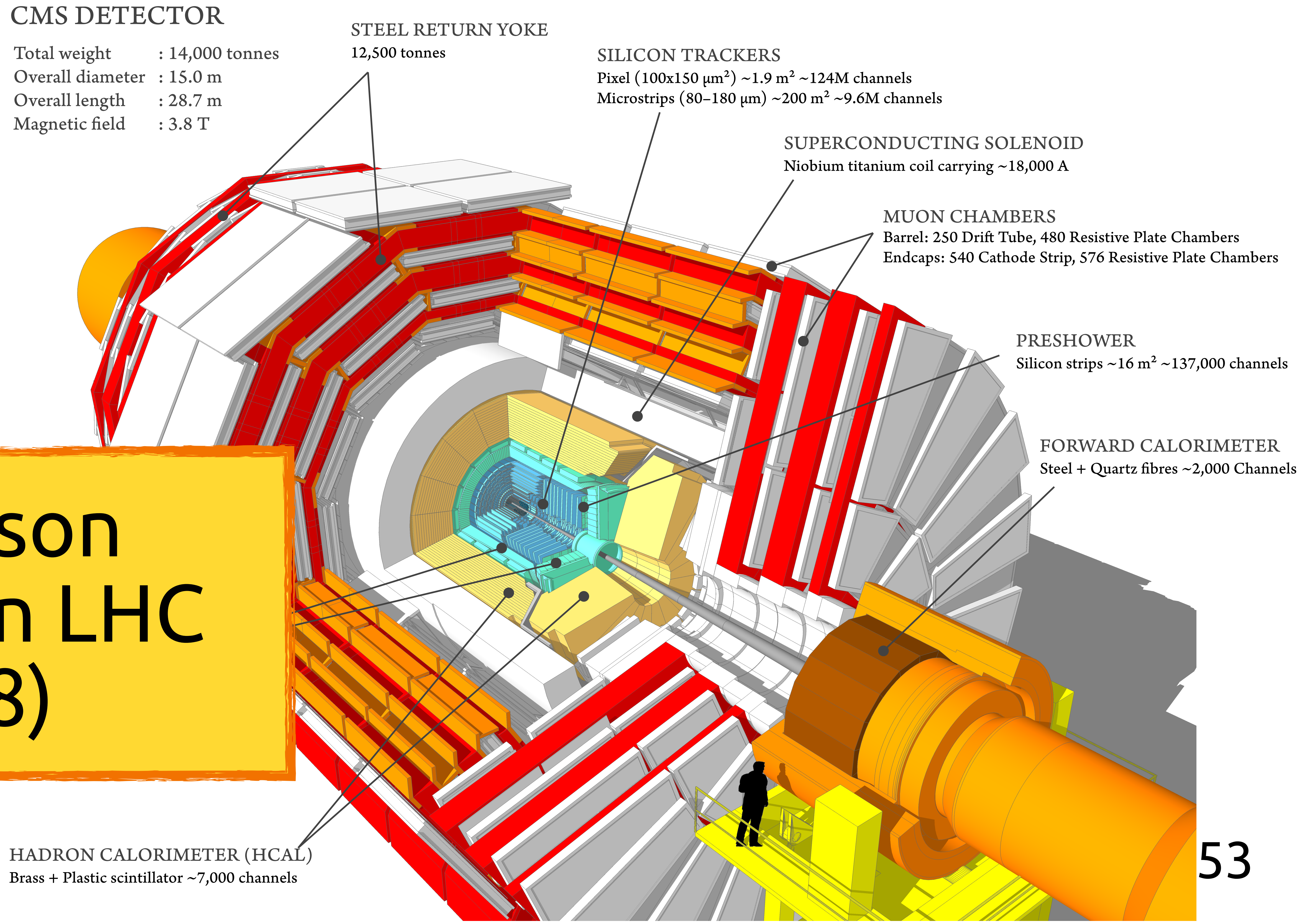
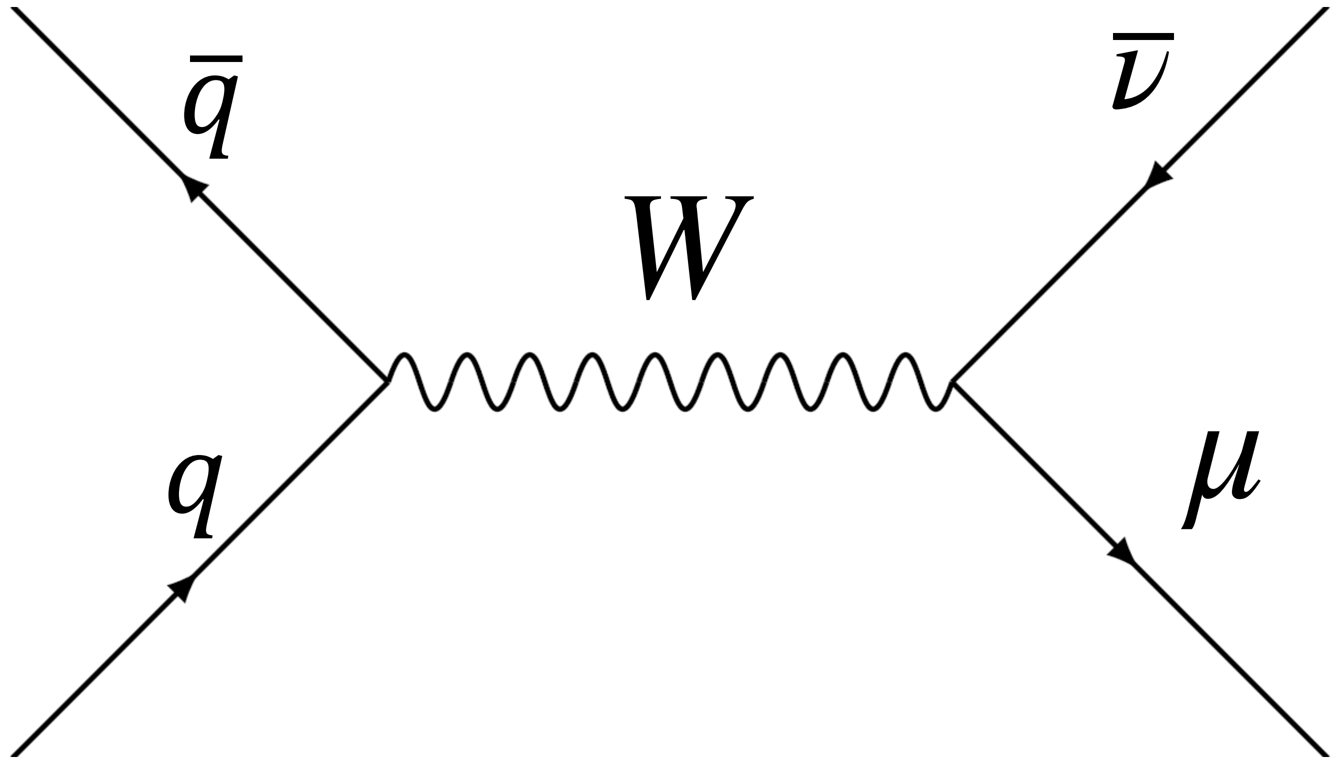
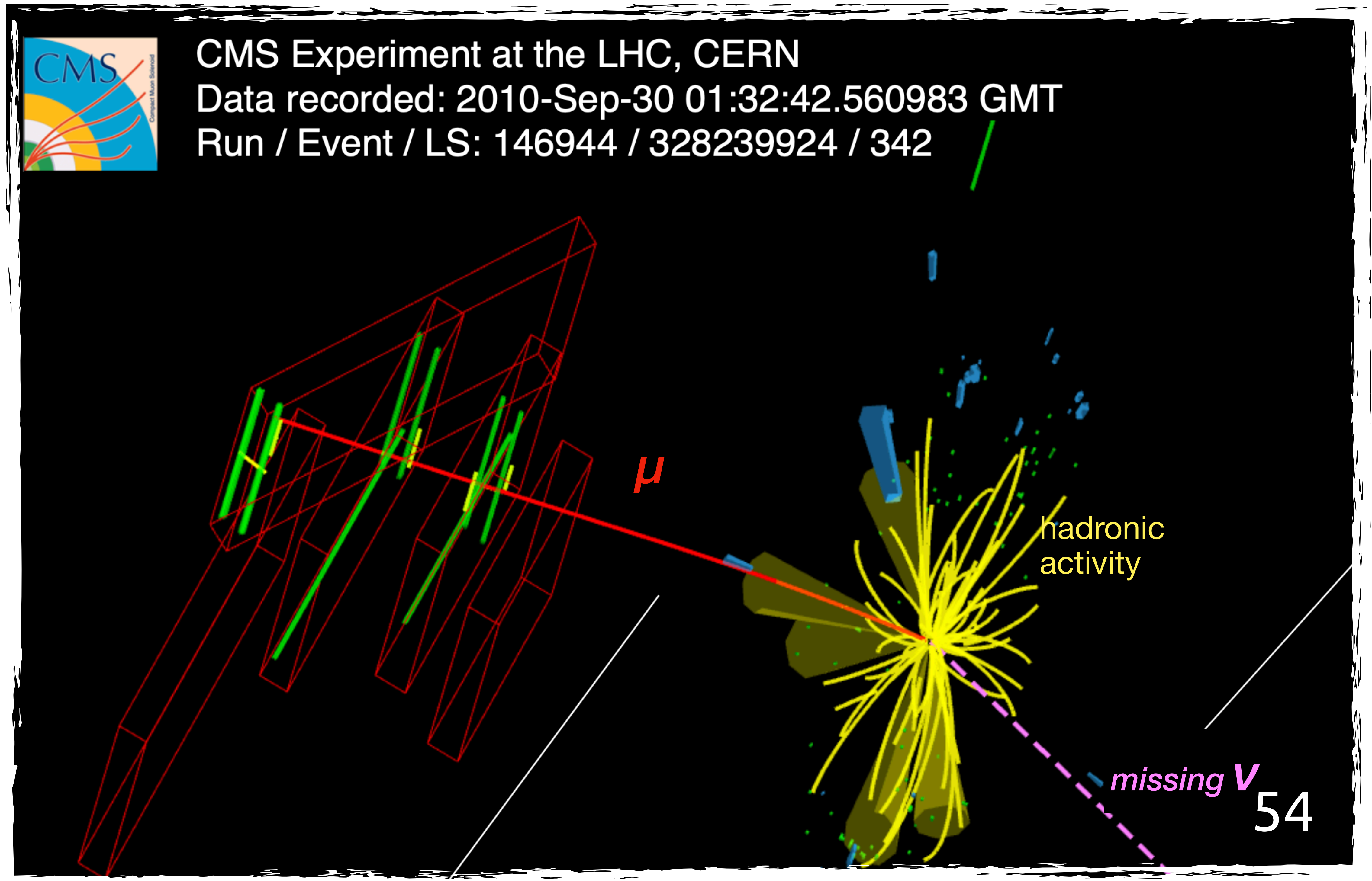


Order of 10^9 W boson candidate collected in LHC Run 2 (2016-2018)

m_W measurement at hadron colliders

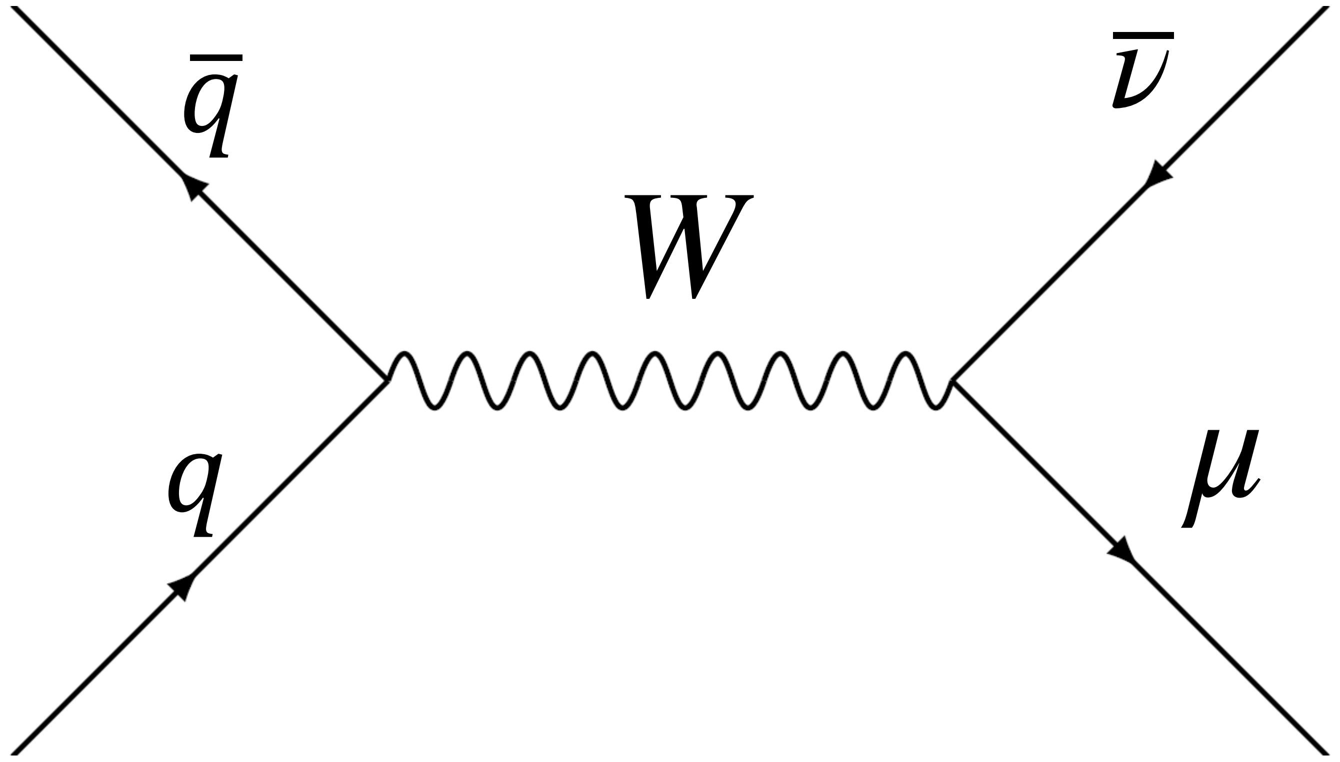
- channel: $W^{\pm} \to \mu^{\pm}\nu$
  - Only one reconstructed particle in the final state
  - Missing the neutrino —> not closure of the event





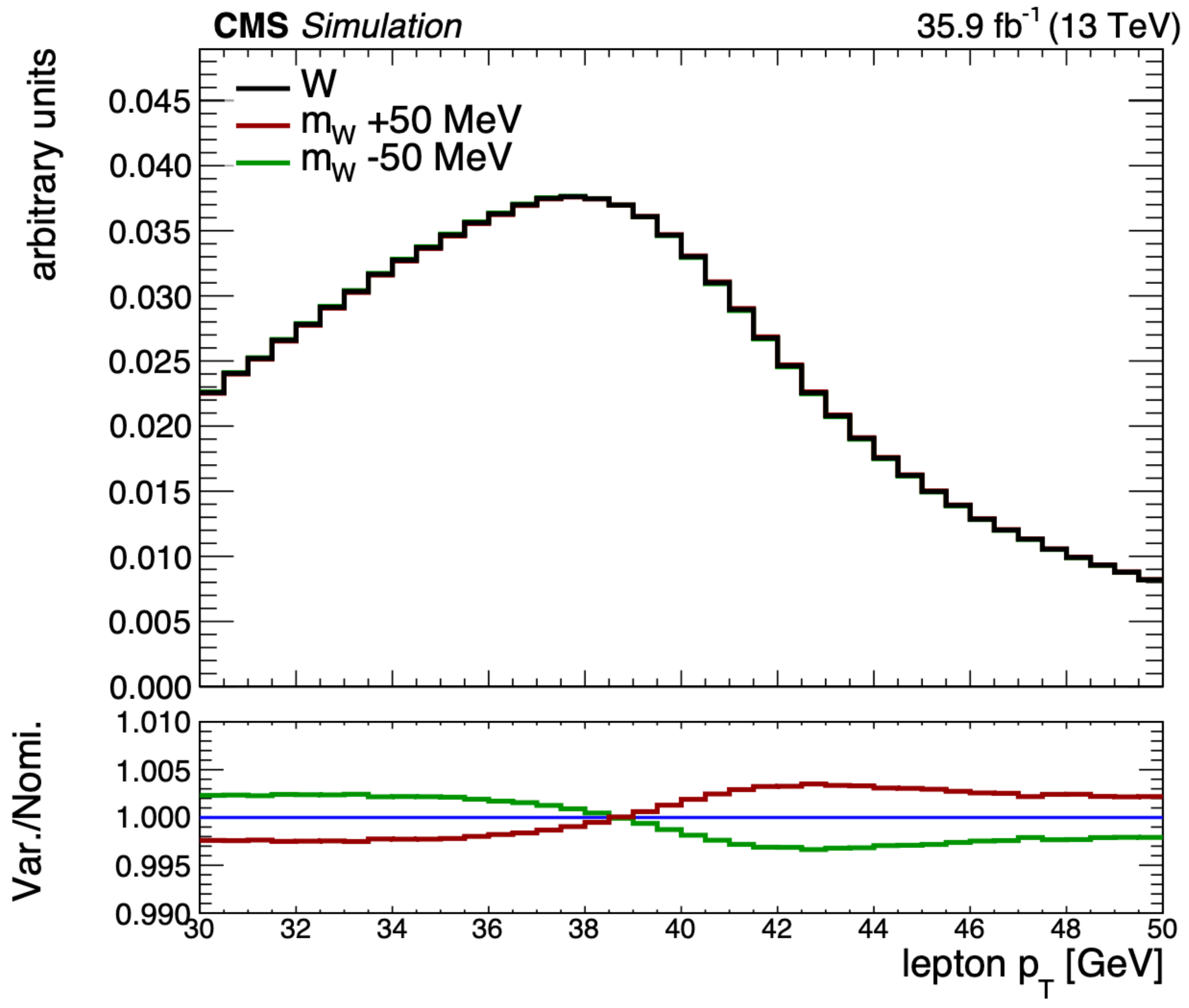
m_W measurement at hadron colliders

- channel: $W^{\pm} \rightarrow \mu^{\pm}\nu$
  - Only one reconstructed particle in the final state
  - Missing the neutrino —> not closure of the event
- Use of transverse plane variables sensitive to the mass
- Template fit to m_W using p_T^{μ} distribution



[From M. Cipriani PhD. thesis]

- Produce set of p_T^{μ} distribution with different m_W encoded
- extract m_W from data minimizing the χ^2 with the distribution observed on data



m_W measurement at hadron colliders

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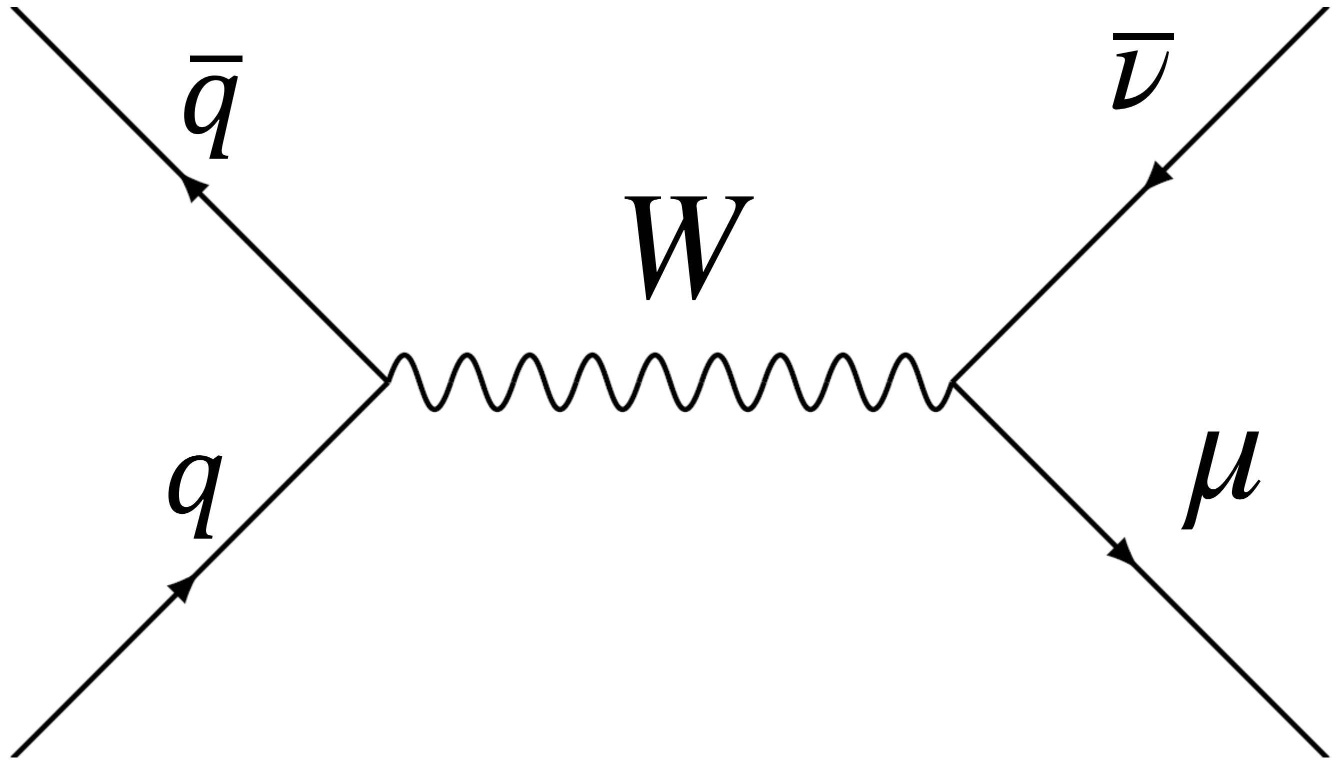
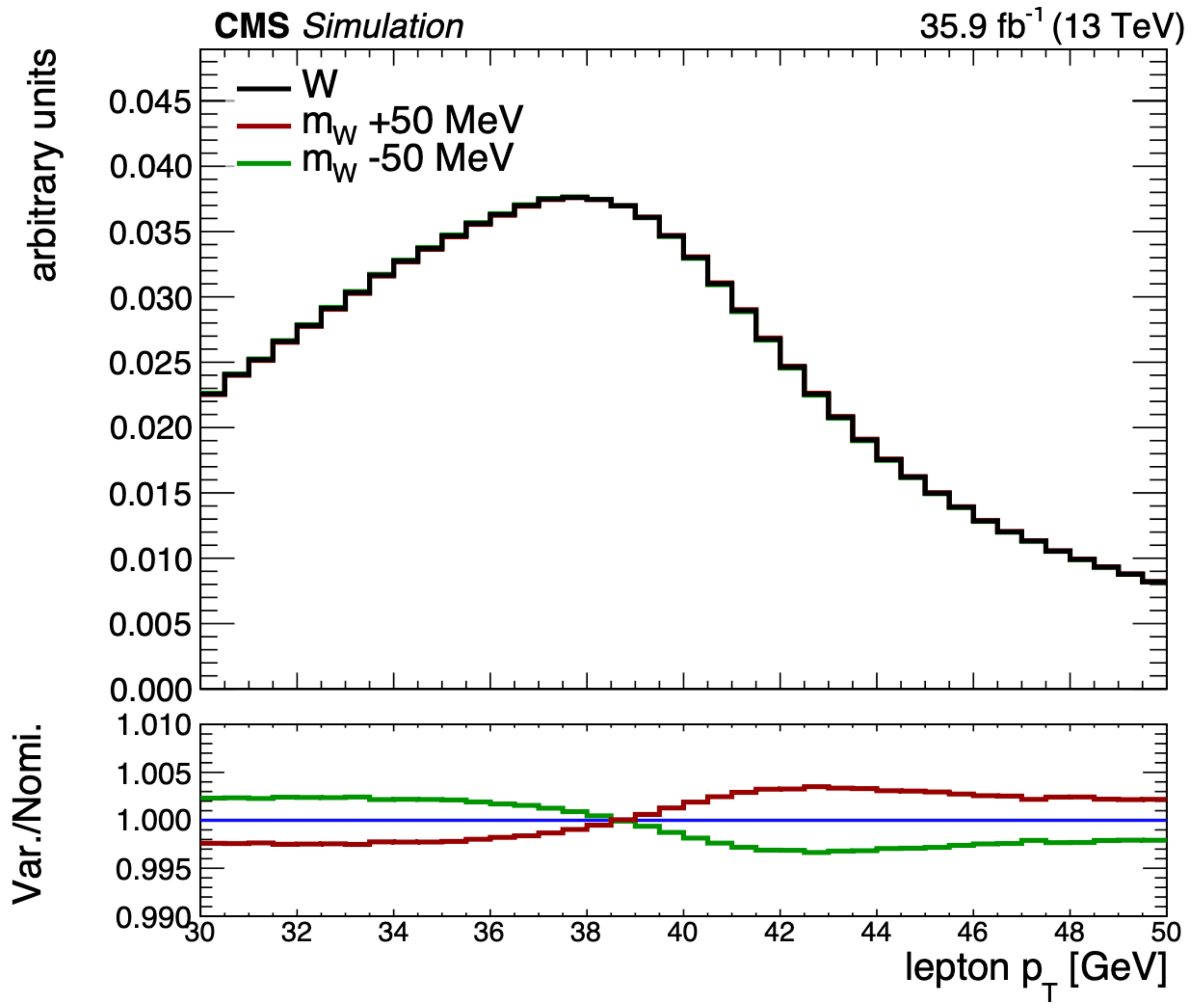


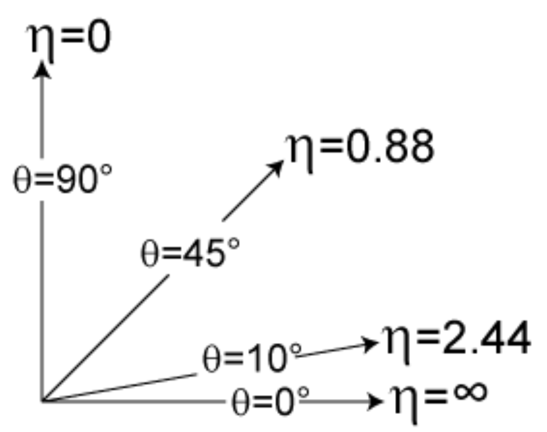
Introduced a dependency from W boson production mechanism on m_W

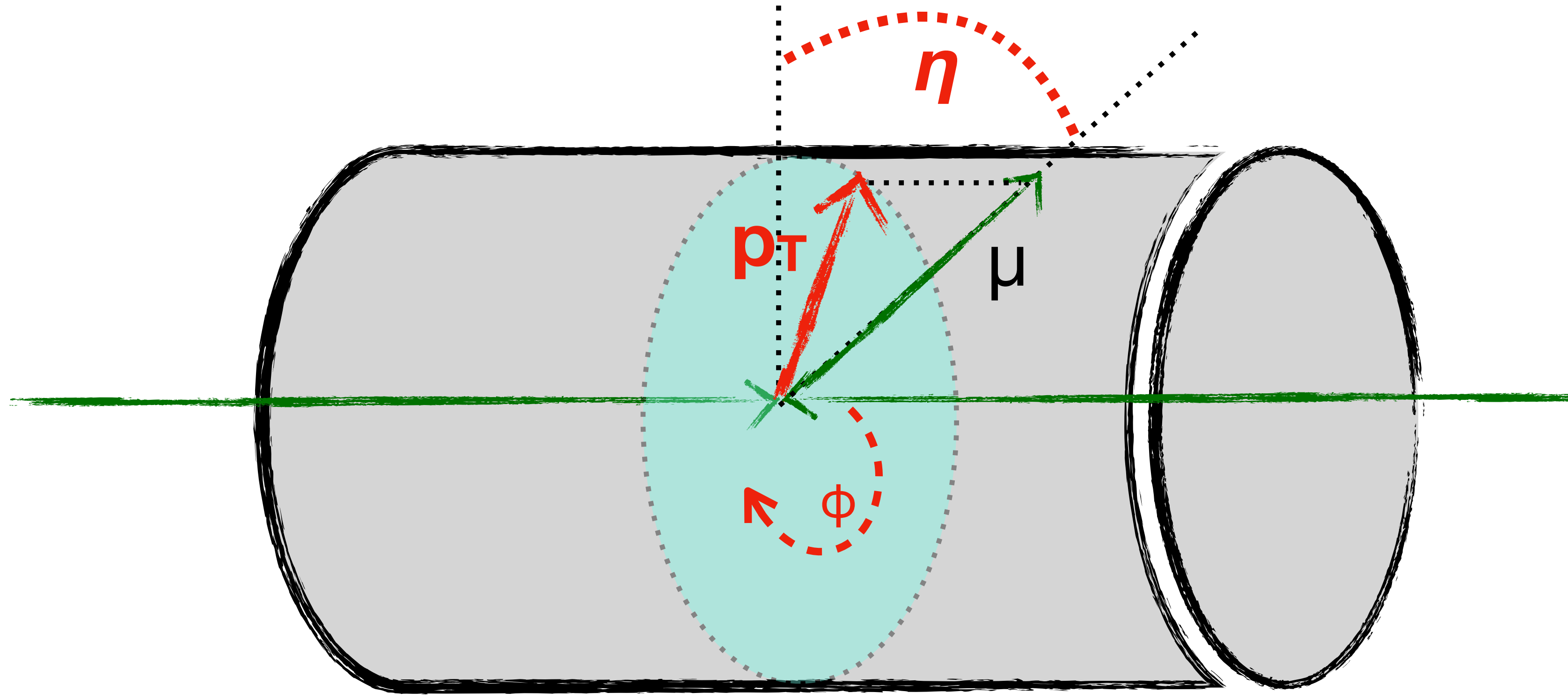
- Produce set of p_T^{μ} distribution with different m_W encoded
- extract m_W from data minimizing the χ^2 with the distribution observed on data

[From M. Cipriani PhD. thesis]

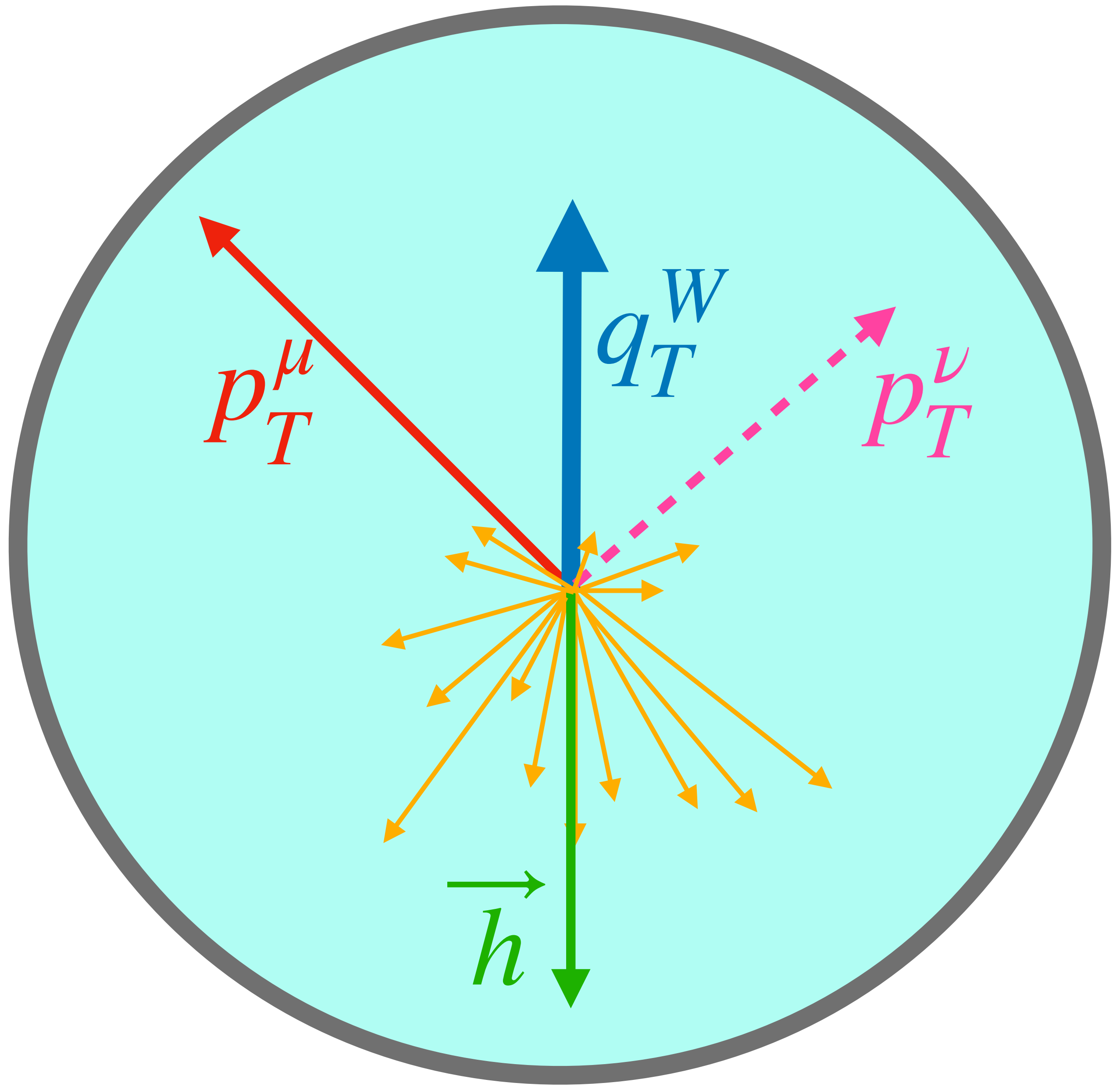


CMS coordinate system and variables



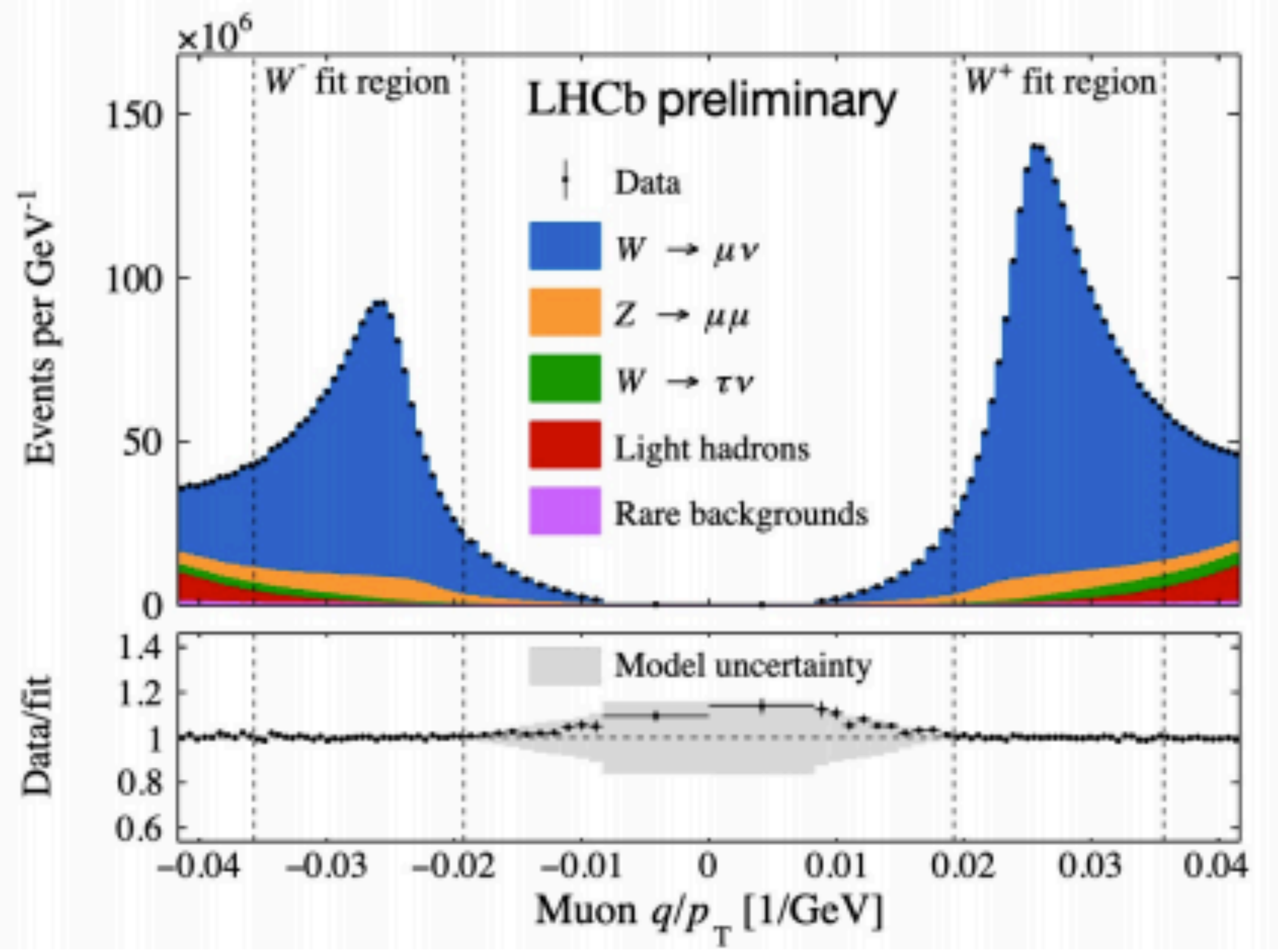


- x points to center of LHC, y upward, z along beam line
- $r = \sqrt{x^2 + y^2}$, $\tan(\theta) = r/z$, $\tan(\phi) = y/z$
- **rapidity**: $Y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$
- **pseudorapidity**: $\eta = -\ln(\tan\frac{\theta}{2})$ for $|p| \gg m \Rightarrow Y \simeq \eta$
- $|p| = p_T \cosh(\eta)$ —> **transverse momentum**: $p_T = (p_x, p_y, 0)$
- W boson four-momentum: $\left(\sqrt{(q_T^W)^2 + Q^2} \cosh Y_W,\ q_T^W \cos\phi,\ q_T^W \sin\phi,\ \sqrt{(q_T^W)^2 + Q^2} \sinh Y_W\right)$
- **transverse mass**:
  $m_T = \sqrt{2 p_T^\ell p_T^\nu \left(1 - \cos(\Delta\phi_{\ell,\nu})\right)} = \sqrt{2\left(p_T^\ell |\vec{p}_T^{\,\ell} + \vec{h}| + (p_T^\ell)^2 + \vec{p}_T^{\,\ell} \cdot \vec{h}\right)}$, where: $\vec{q}_T^{\,W} = \vec{p}_T^{\,\ell} + \vec{p}_T^{\,\nu} \equiv -\vec{h}$
- **isolation**: $\mathrm{Iso}_{\mathrm{PF}} \equiv \sum_{x^\pm \mathrm{PV}} p_T + \max\left(0, \sum_\gamma p_T + \sum_{h^0} p_T - \frac{1}{2} \sum_{x^\pm \mathrm{PU}} p_T\right)$, counting in a cone of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$



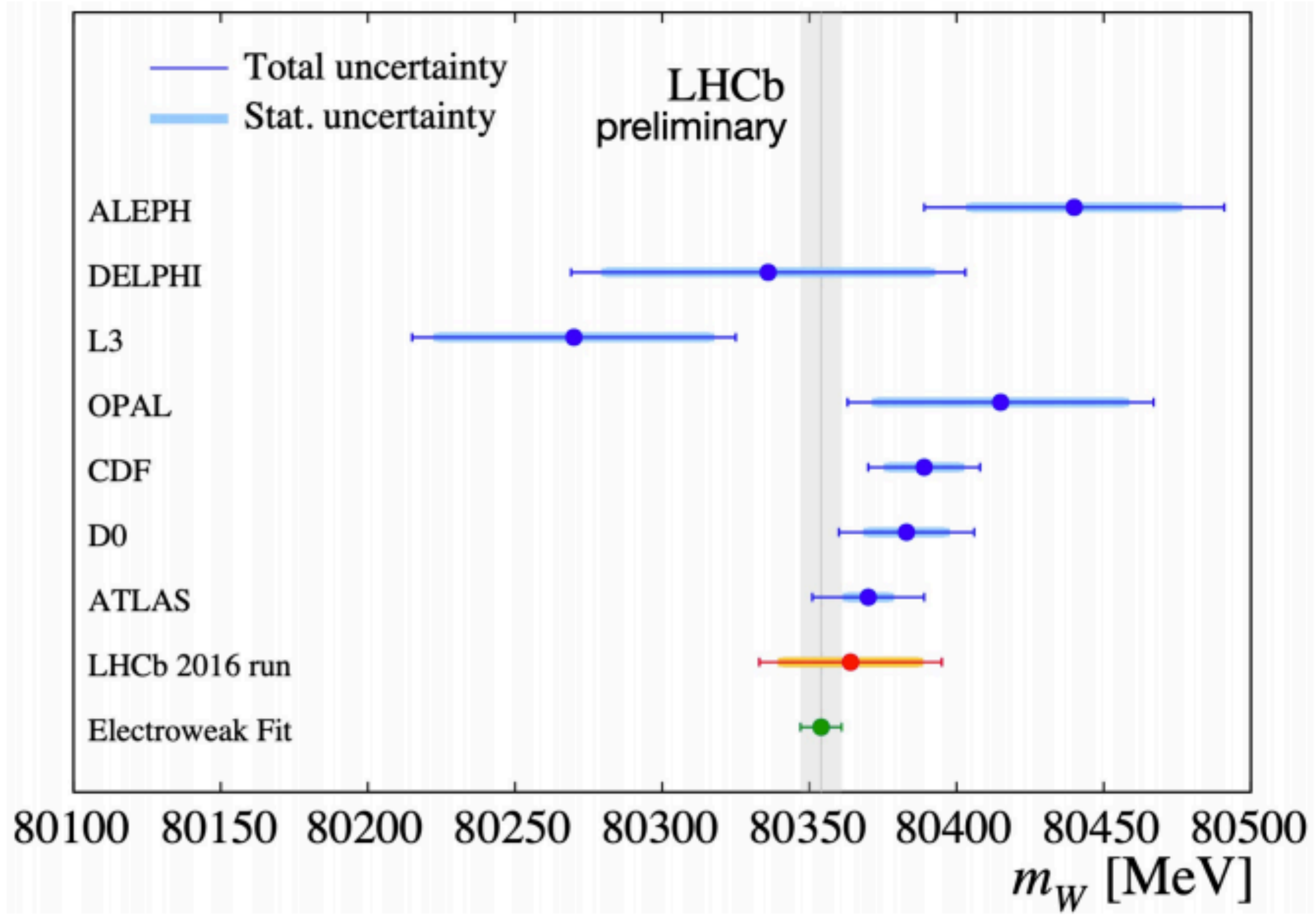
recent LHCb measurement

- NB: not published yet!



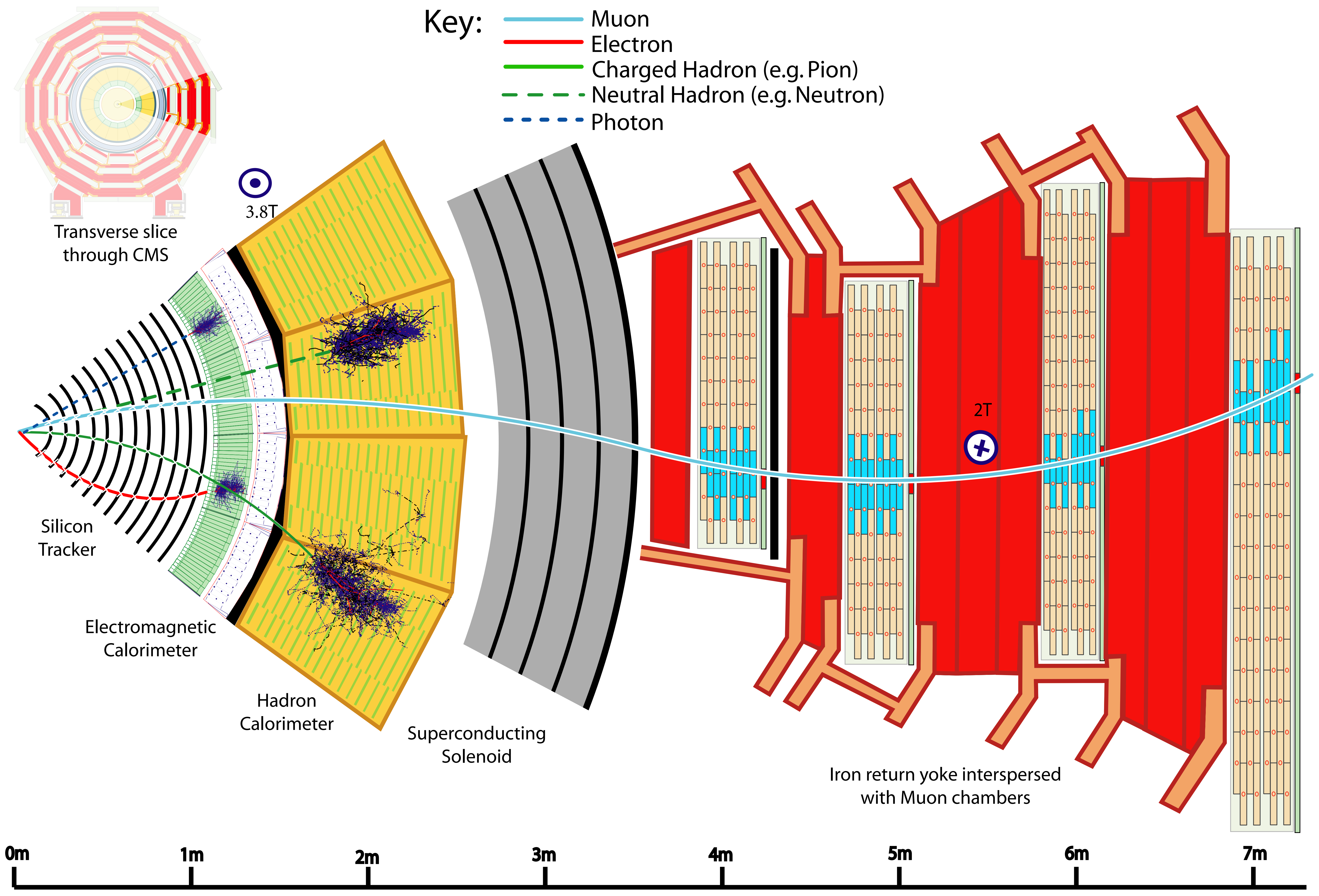
Source	Size [MeV]	
Parton distribution functions	**9.0**	Average of NNPDF31, CT18, MSHT20
Theory (excl. PDFs) total	**17.4**	
Transverse momentum model	12.0	Envelope of 5 different models*
Angular coefficients	9.0	Uncorrelated scale variation
QED FSR model	7.2	Envelope of Photos, Pythia8, Herwig7
Additional electroweak corrections	5.0	Tested with POWHEG ew
Experimental total	**10.6**	
Momentum scale and resolution modelling	7.5	Determined from statistical variations, modelling details, and dependence on external inputs
Muon ID, trigger and tracking efficiency	6.0	
Isolation efficiency	3.9	
QCD background	2.3	
Statistical	**22.7**	
Total	**31.7**	

*This 12 MeV envelope is consistent with the 10 MeV spread observed in the data challenges.

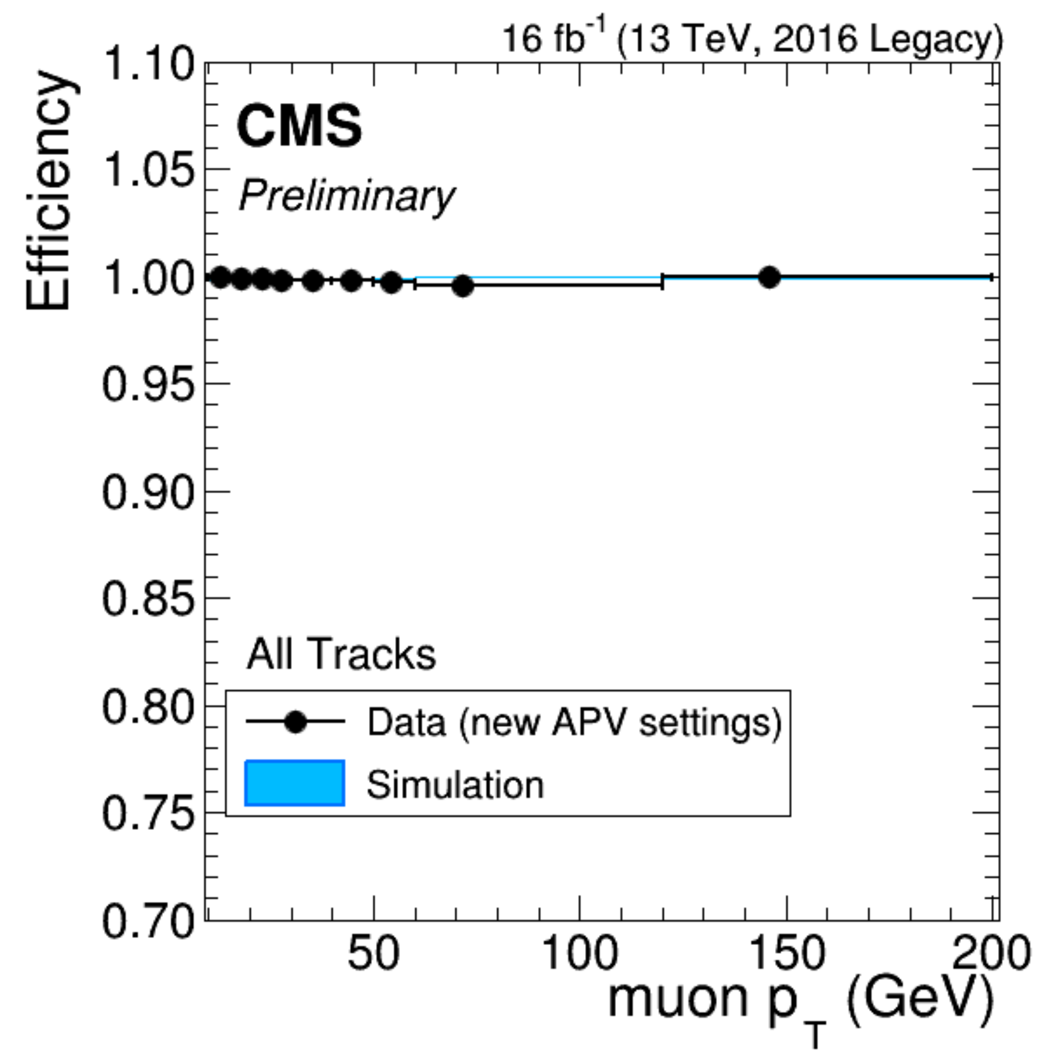


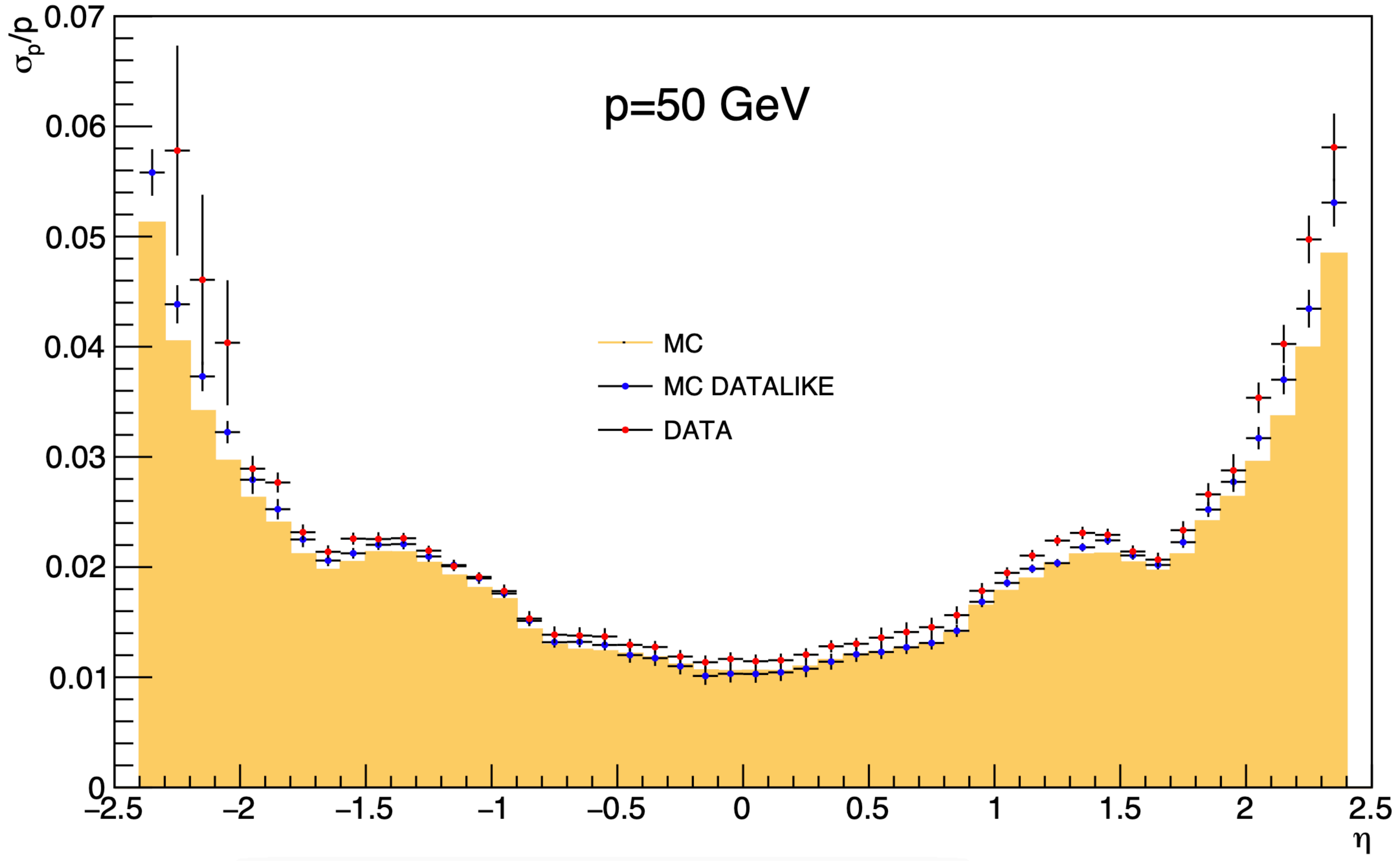
$$m_W = 80364 \pm 23_{\text{stat}} \pm 11_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

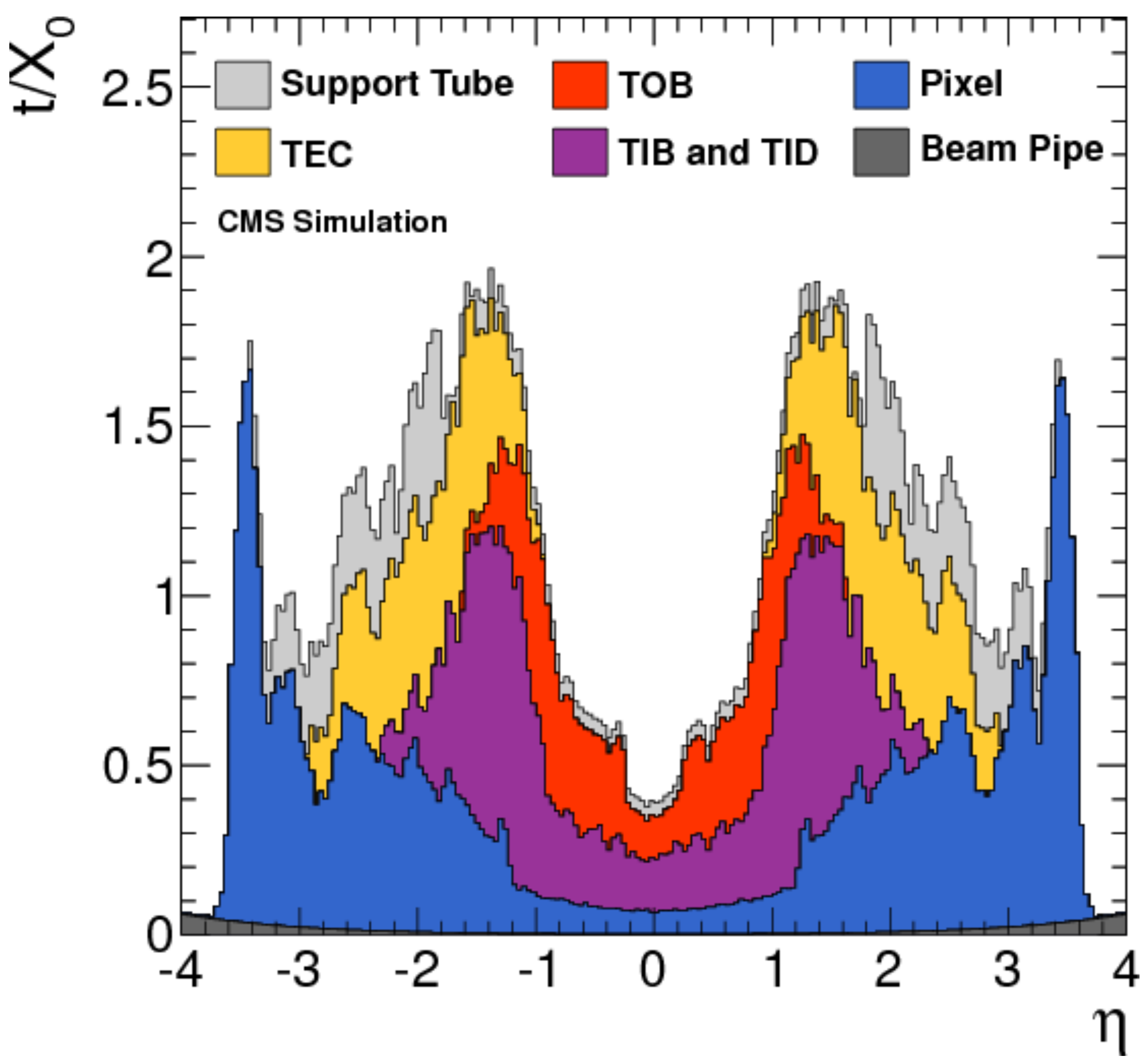
CMS - Particle Flow

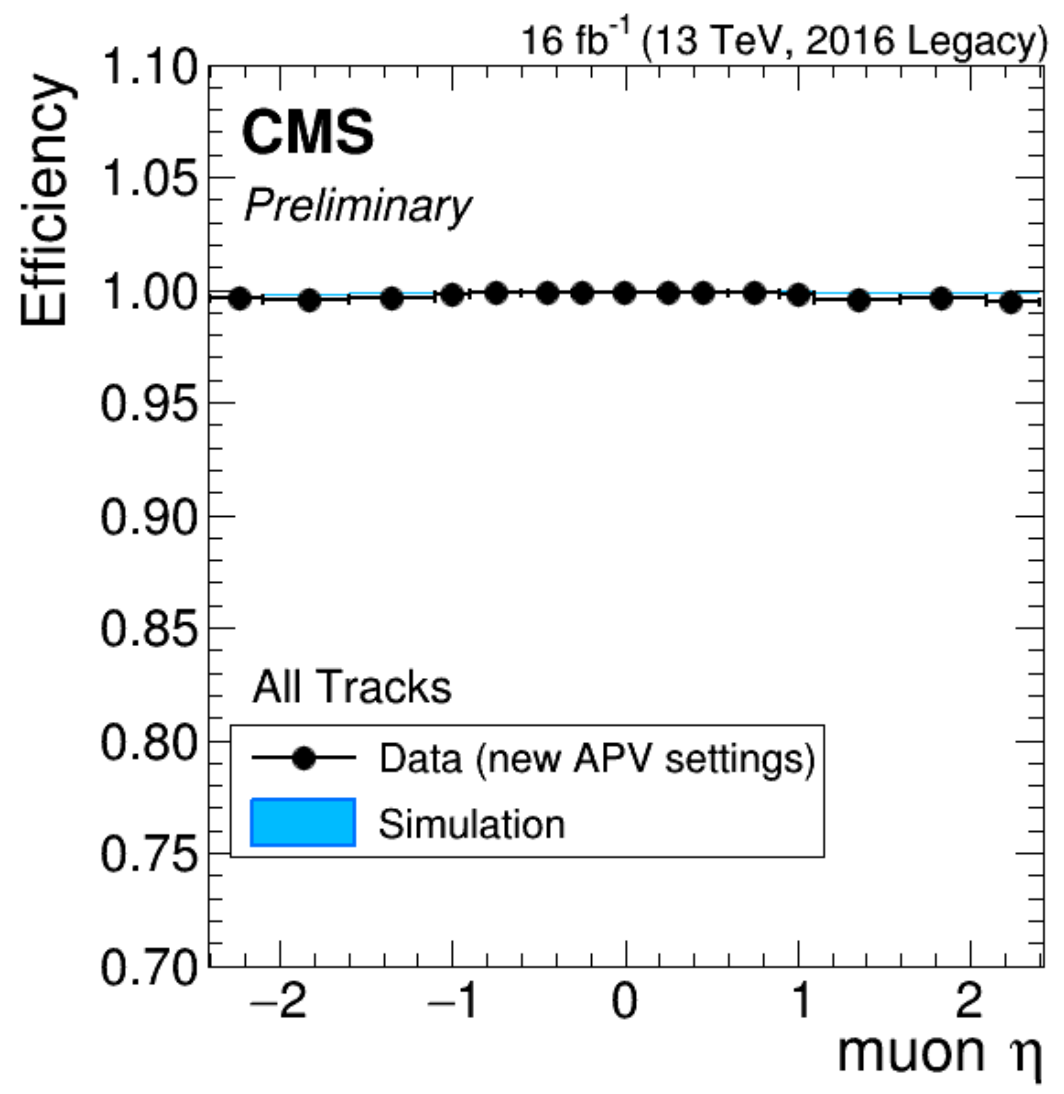


Muon Reconstruction performance





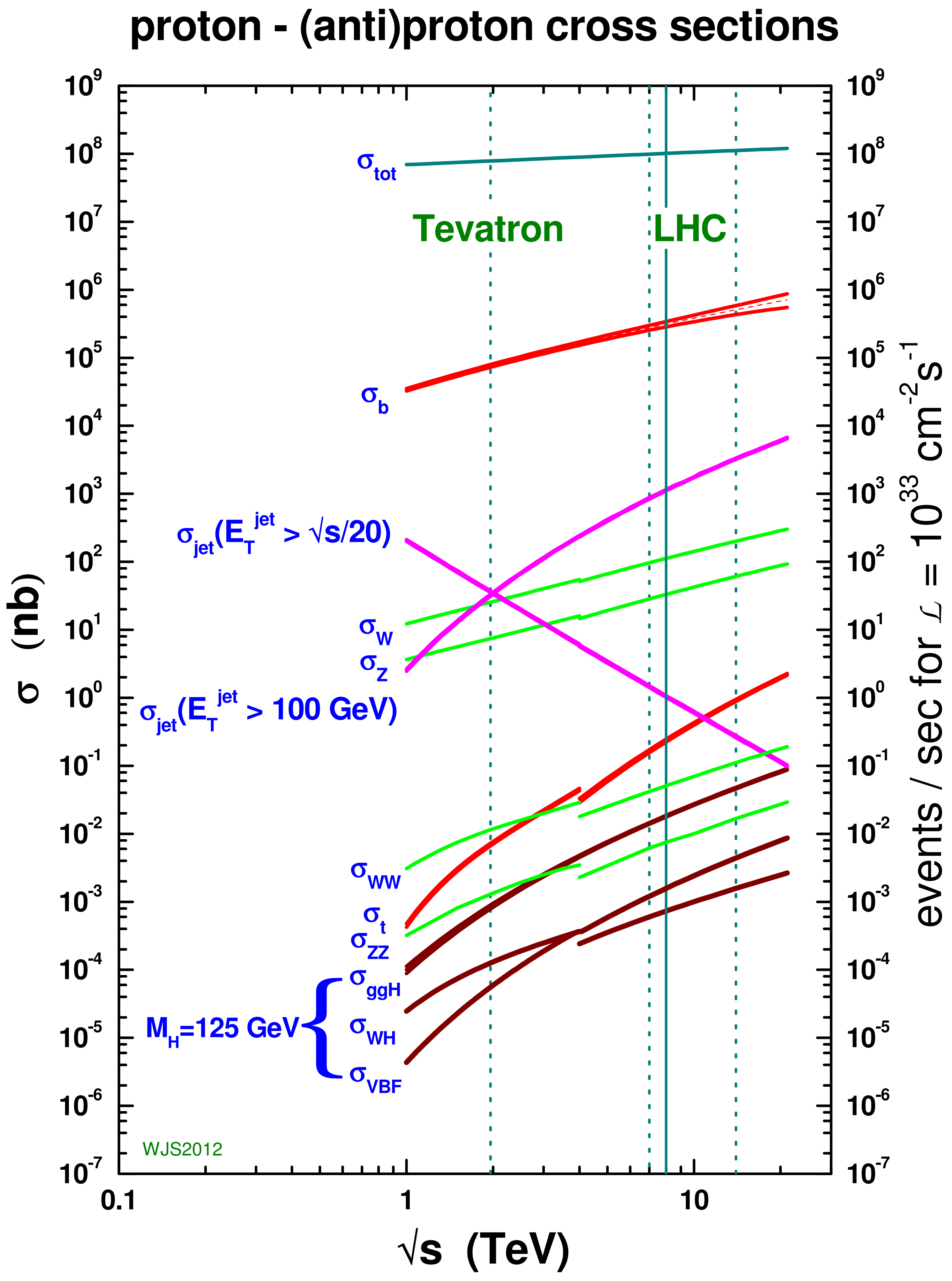


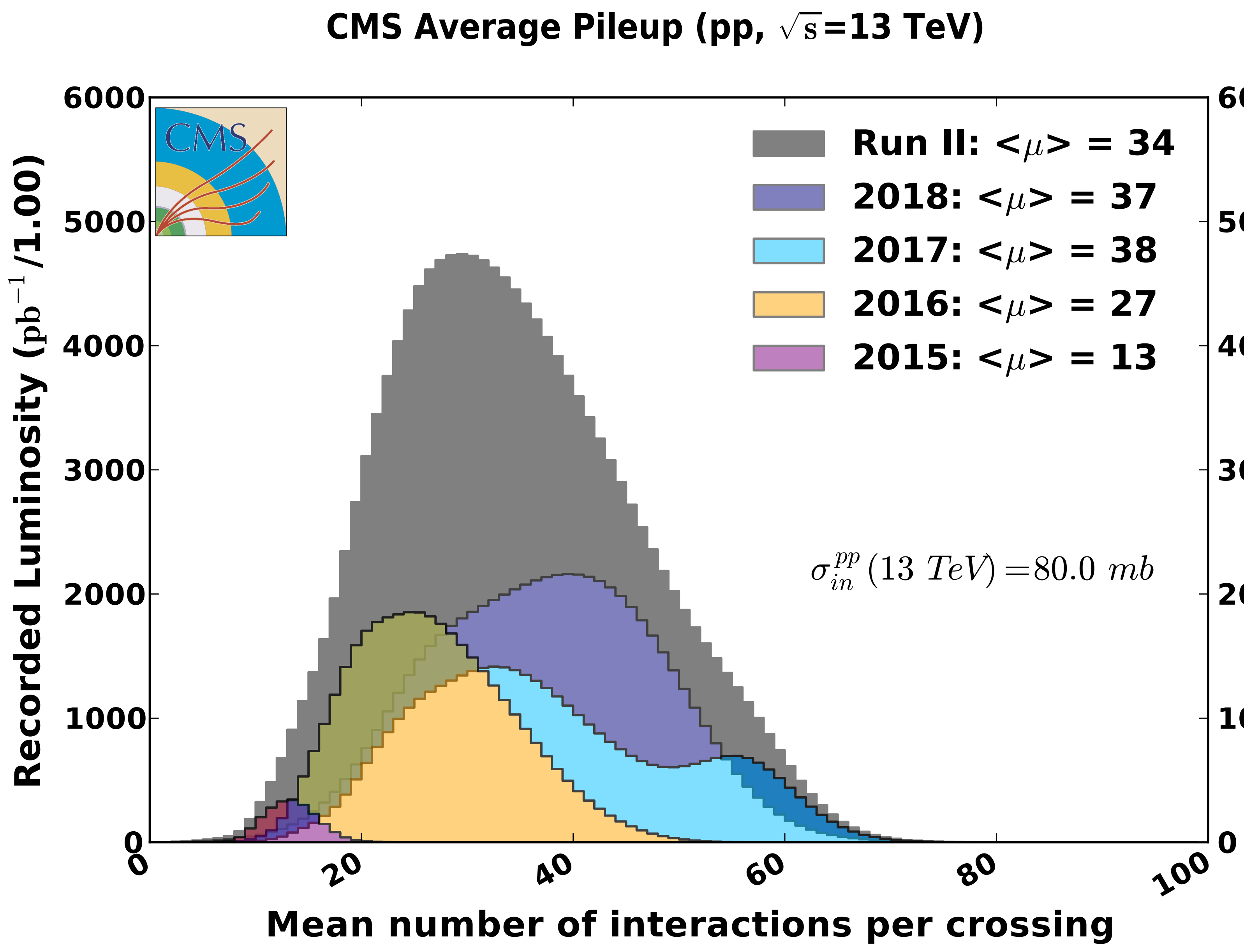


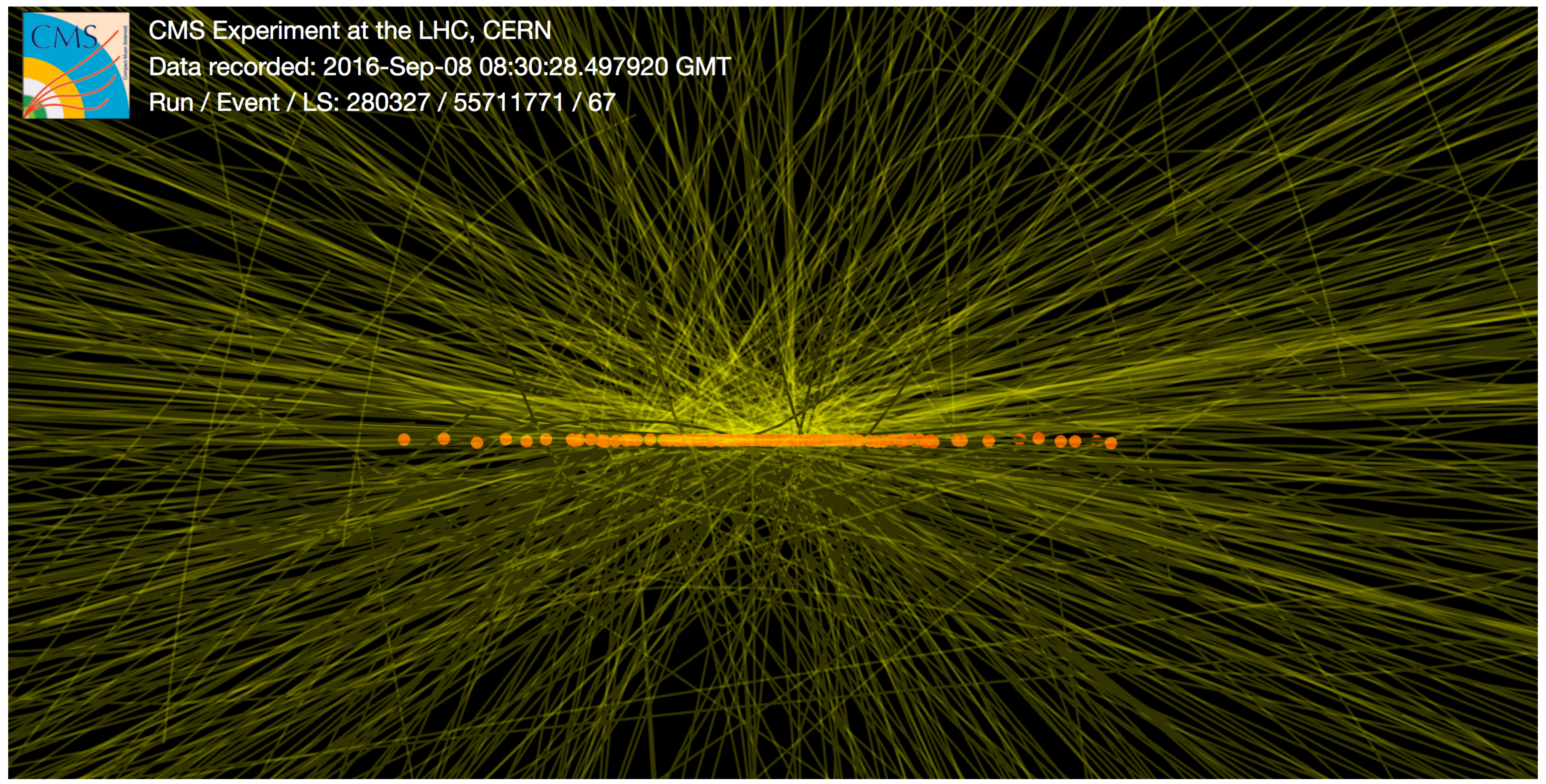
CMS numbers

System	Subsystem	Technology	Configuration	$N_{channels}$	$\|\eta\|$ acceptance
Pixel	BPIX	n^+-in-n silicon pixel	pixel size: $100 \times 150\ \mu m^2$; 3 layers at r =44, 73, 102 mm	48M	$[0, 1.5]$
	FPIX	n^+-in-n silicon pixel	pixel size: $100 \times 150\ \mu m^2$; 2 disks at $\|z\|$ =345, 465 mm	18M	$[1.5, 2.5]$
Tracker	TIB	p-in-n silicon strip	strip pitch: 80 μm (L1,L2), 120 μm (L3,L4); 4 layers at r =255,339, 418.5, 498 mm		$[0, 1.5]$
	TID	p-in-n silicon strip	strip pitch: 100-141 μm; 3 disk at $\|z\|$ =800-900 mm	9.3M	$[1.5, 2.5]$
	TOB	p-in-n silicon strip	strip pitch: 183 μm (L1-L4), 122 μm (L5,L6); 6 layers at r =608, 692, 780, 868, 965, 1080 mm		$[0, 1.5]$
	TEC	p-in-n silicon strip	strip pitch: 97-184 μm; 9 disk at $\|z\|$ =1240-2800 mm		$[1.5, 2.5]$
ECAL	EB	homogeneous calo. ($PbWO_4$ crystals)	$25X_0$ and $1\lambda_I$	61.2k	$[0, 1.48]$
	EE	homogeneous calo. ($PbWO_4$ crystals)	$26X_0$ and $1\lambda_I$	$2 \cdot 7234$	$[1.48, 3]$
	PS	sampling calo. (lead-silicon stirp)	2 strip layers alternated with 2 absorber layers; $3X_0$	137.7k	$[1.6, 2.6]$
HCAL	HB	sampling calo. (brass-scintillator)	16 alternated layers of scintillator and absorber; $6\lambda_I$		$[0, 1.3]$
	HE	sampling calo. (brass-scintillator)	16 alternated layers of scintillator and absorber; $6\lambda_I$		$[1.3, 3]$
	HF	Cherenkov calo. (steel-quartz fibers)	grooved absorber interlayered with quartz fibers	9k	$[3, 5]$
	HO	sampling calo. (scintillator)	2 layers (central ring), 1 layer ($\pm1, \pm2$ rings), using the coil as absorber		$[0, 1.3]$
Muon system	MB	DT	section: 4.2×1.3; 4 layers	195k	$[0, 1.2]$
	ME	CSC	strip pitch: 8-16 mm; 4 layers	500k	$[0.9, 2.4]$
	RB	RPC	avalanche mode; pitch: 1 cm; 6 layers	192k	$[0, 1.2]$
	RE	RPC	avalanche mode; pitch: 1 cm; 4 layers		$[0.9, 1.6]$

LHC distirbutions: cross sections, pileup

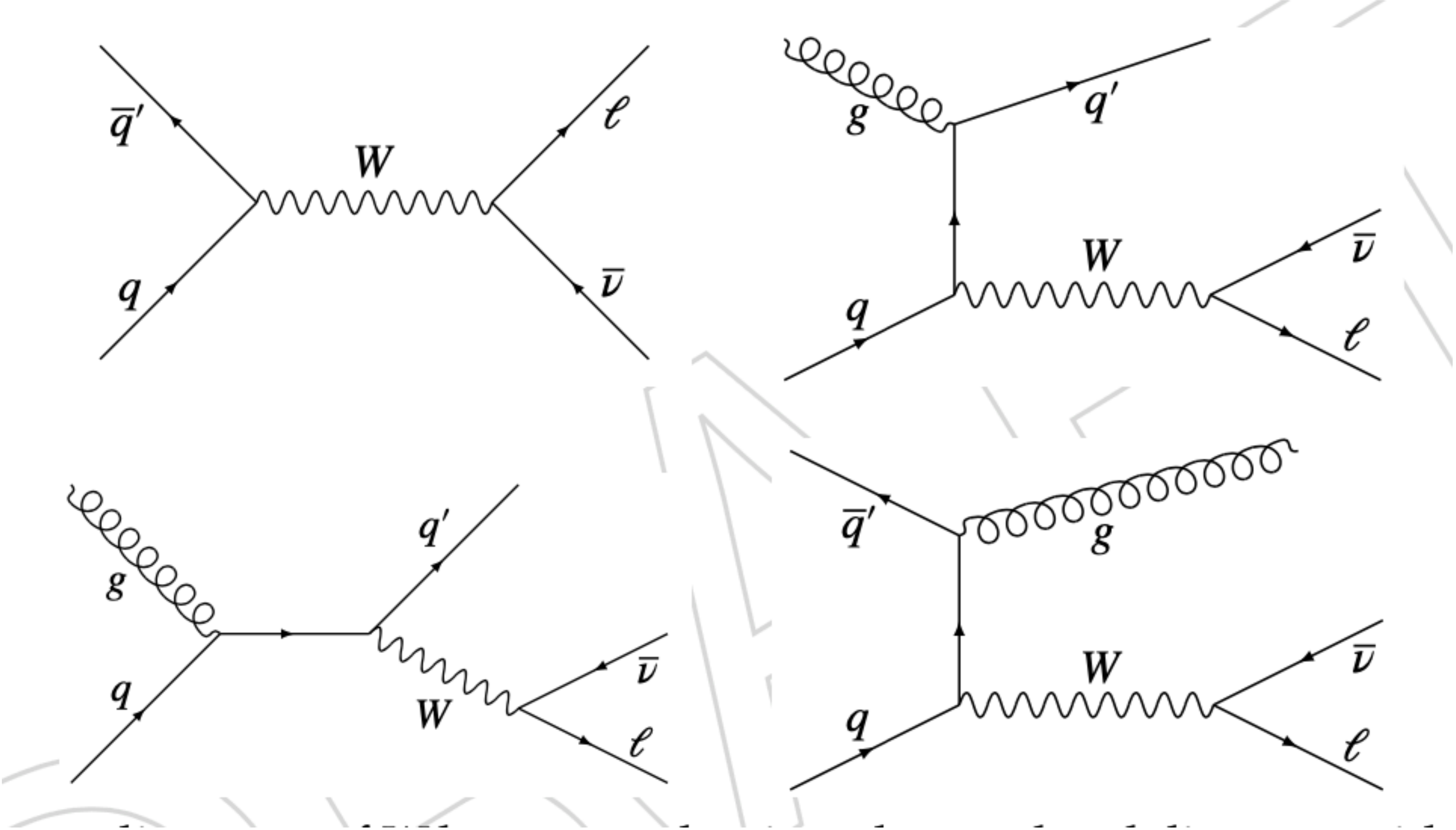






- $\mathscr{L}_{int}(\text{Run2}) \simeq 150\,\text{fb}^{-1}$
- $\sigma_{W(\to \ell\nu)+J} \simeq 61$ nb

W boson production main diagrams



W mass systematics

Table 1: Summary of systematic uncertainties for m_W measurement at hadron collider. All the values are reported in MeV (from [15]).

Experiment	CDF		ATLAS	
Source	p_T^ℓ	m_T	p_T^ℓ	m_T
Statistical	16	15	7.2	9.6
W transverse momentum	9	3	8.3	9.6
PDFs (W rapidity, polarizazion)	9	10	9	10.2
Higher order corrections	4	4	5.7	3.4
Lepton momentum calibration (Scale and Resolution)	7	7	6.5	6.5
Recoil (Scale and Resolution)	5.5	6	2.5	13
Backgrounds	4	3.5	4.6	8.3

https://doi.org/10.1140/epjc/s10052-019-7324-0

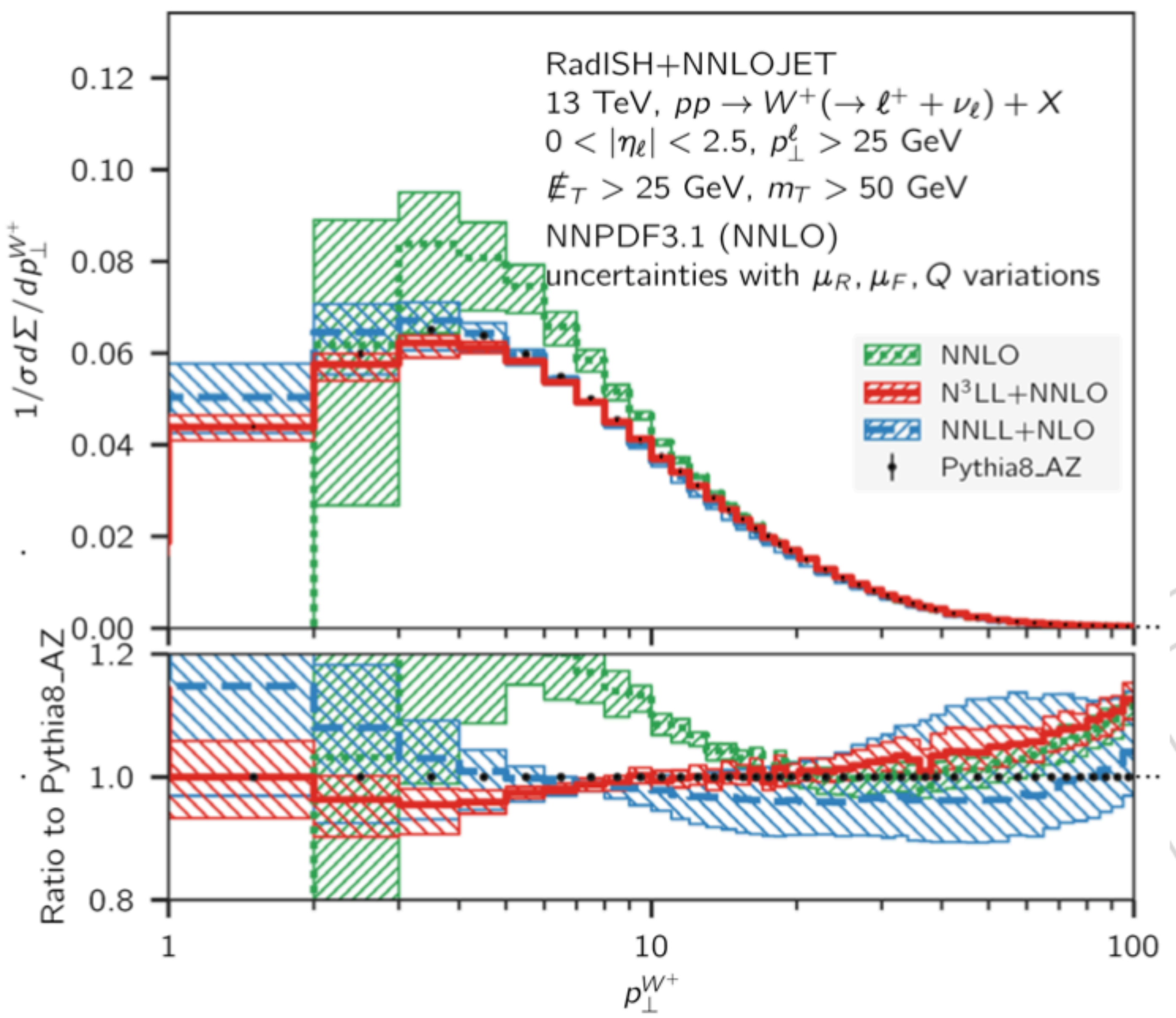
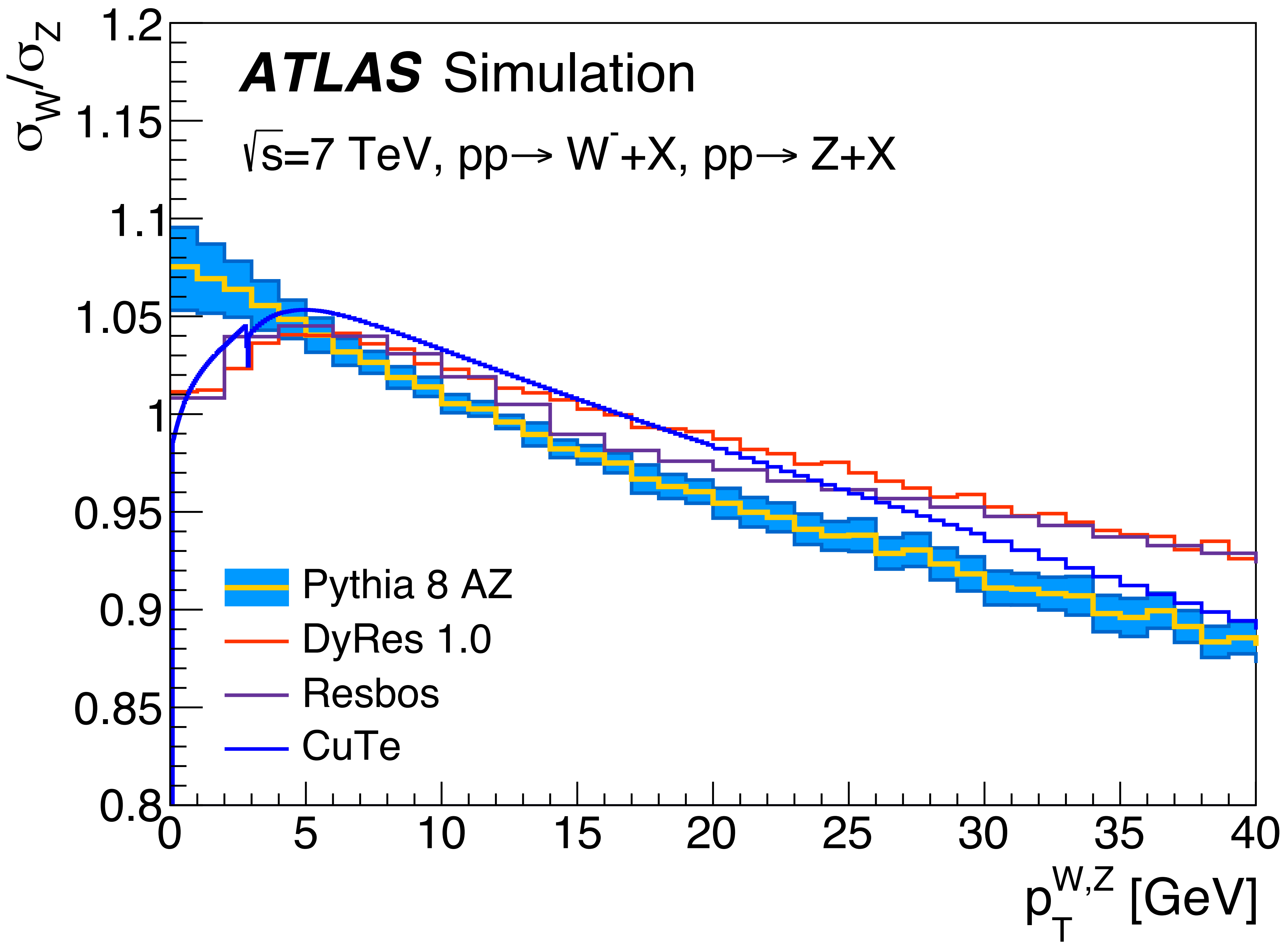


Figure 3: Comparison of the normalized q_T^W distribution for W^+ at $\sqrt{13}$ TeV at NNLO, NNLL+NLO and N^{3}LL+NNLO, and the PYTHIA AZ tune. The fiducial selection $p_T^\ell >$ 25 GeV, $p_T^{\text{miss}} > 25$ GeV, $|\eta^\ell| < 2.5$, $m_T > 50$ GeV is applied (from Ref. [19]).

ATLAS m_W measurement: q_T^W issues

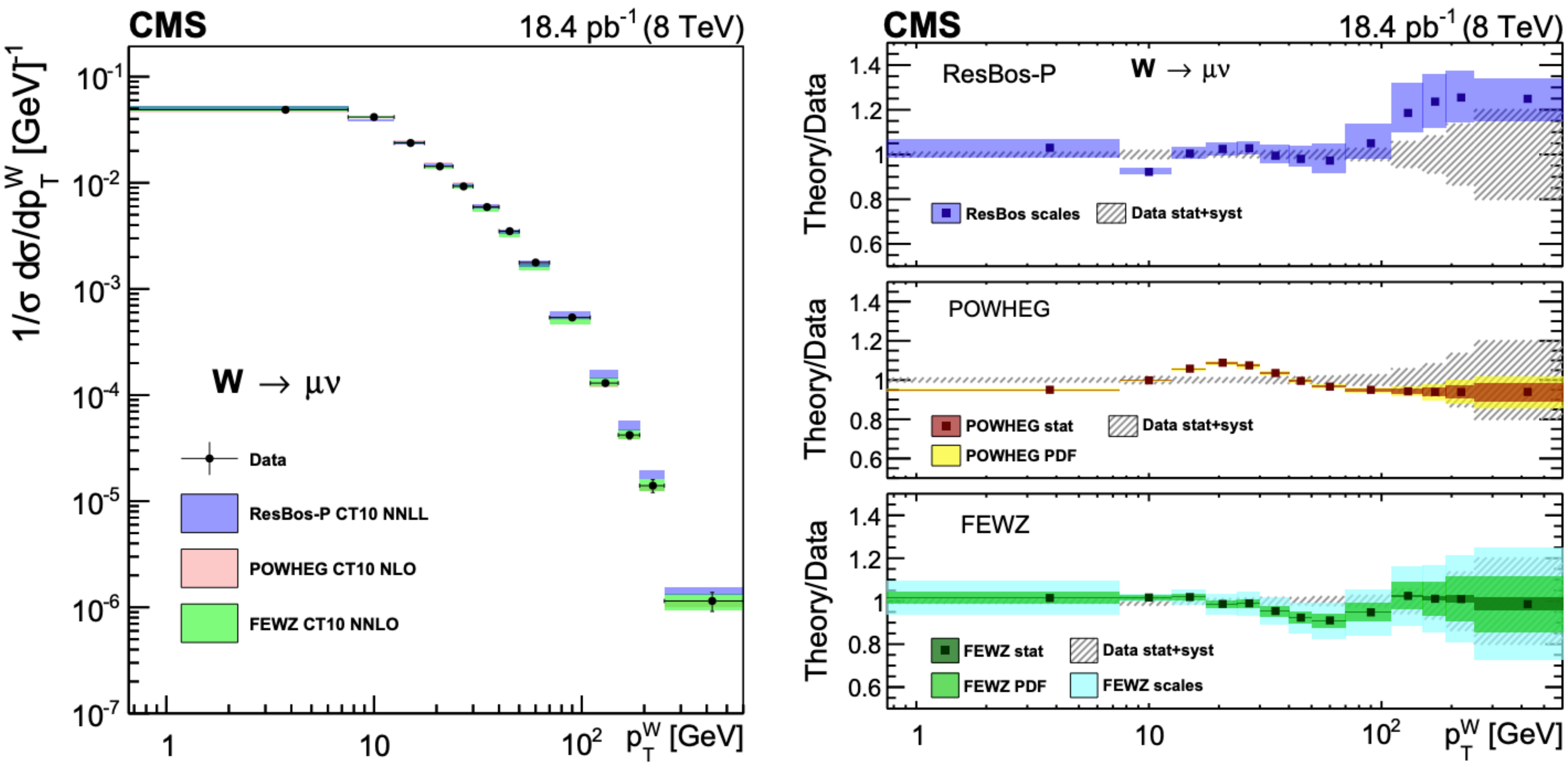
- q_T^W modeling using Pythia tuning
- calibration on q_T^Z
- syst on porting to W:
  - mass c,b
  - factorization scale of PS
  - PDF
- Problem: discrepancy with other model larger than uncertainties

https://doi.org/10.1140/epjc/s10052-017-5475-4

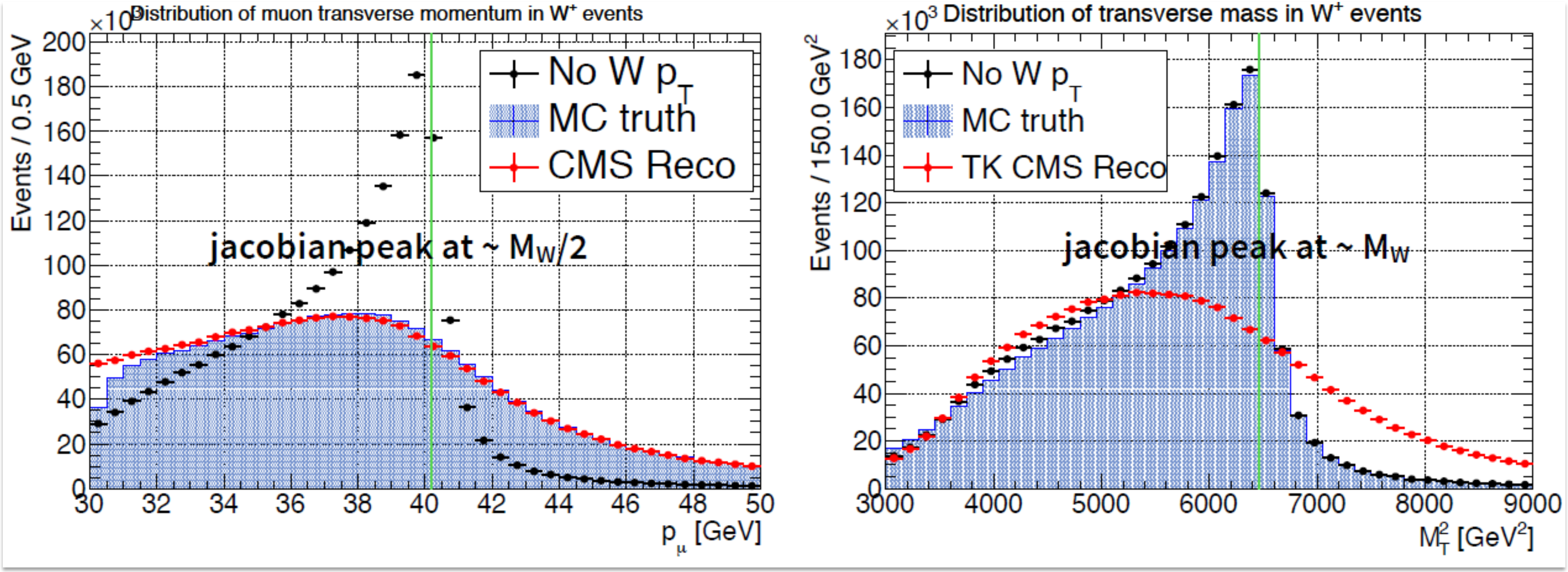


CMS 8 TeV q_T^W measurement

https://doi.org/10.1007/JHEP02(2017)096



W mass variables



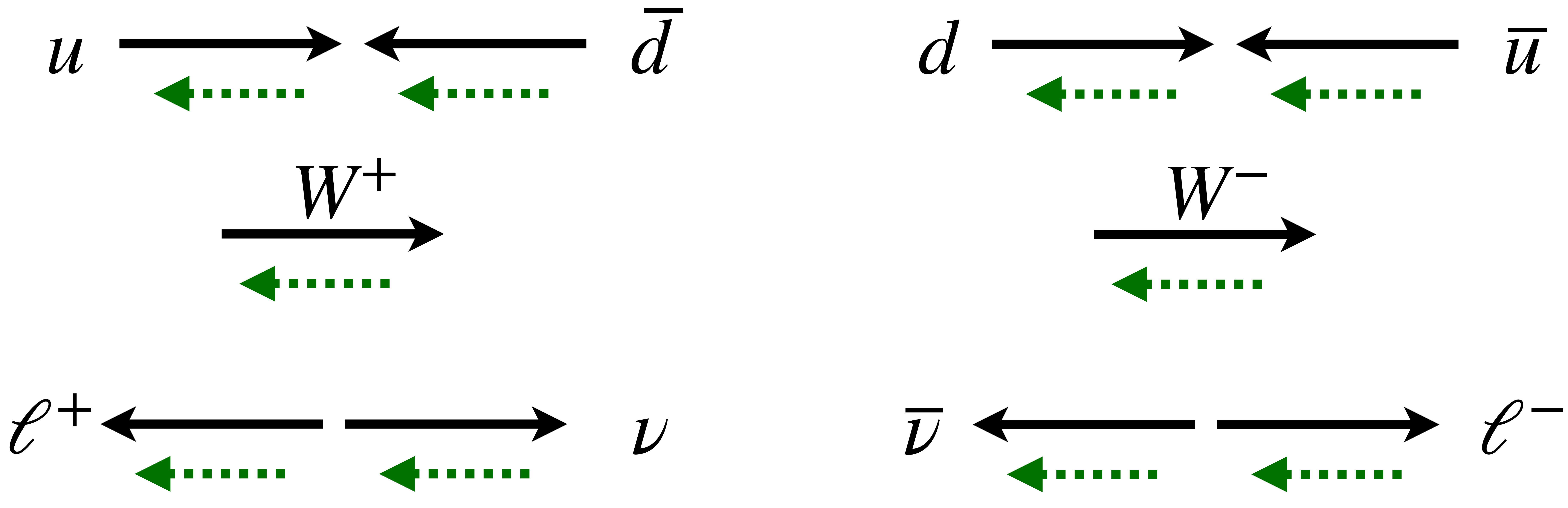
[From N. Foppiani, CERN-THESIS-2017-125]

Spin Correlation

Partons (initial state)

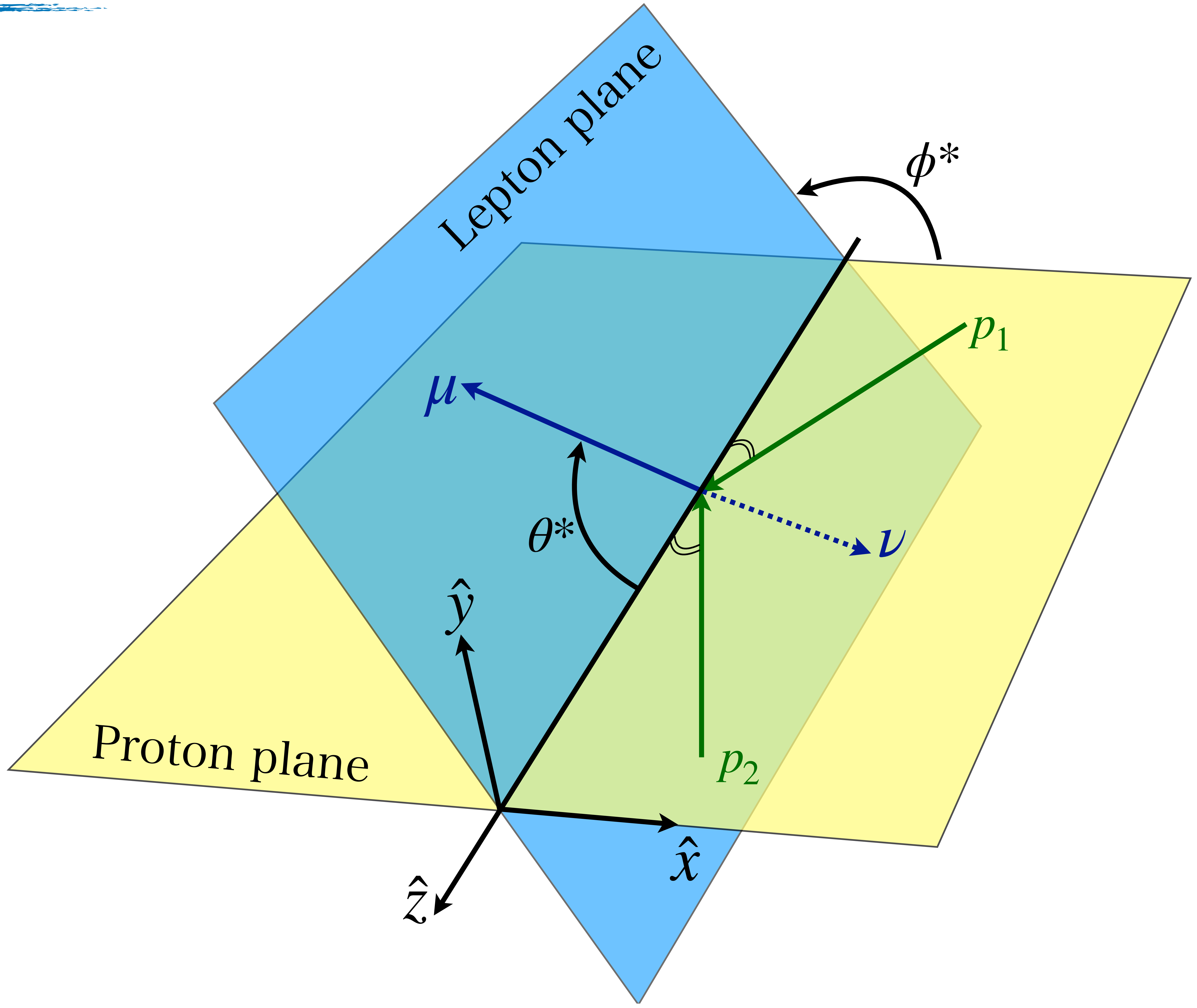
Boson

Leptons (final state)



Collins-Soper frame

- frame where the lepton pair is at rest
- z axis
  - bisect direction of p_1 and -p_2
  - sign=sign q_z^W in lab frame
- x axis:
  - orthogonal to z and in $p_1 \times p_2$ plane
  - direction of q_T^W in lab frame
- y axis: to complete a right-handed coordinate system (—>orthogonal to the plane $p_1 \times p_2$)
- ϕ=x-muon direction projected on $x \times y$ plane
- $\theta =$ z-muon direction



Helicity cross sections

$$\frac{d\sigma}{dq^2_{T,W}dY_W d\cos\theta^*_\mu d\phi^*_\mu} = \frac{3}{16\pi}\sum_\alpha \frac{d\sigma_\alpha}{dq^2_{T,W}dY_W}P_\alpha(\cos\theta^*\mu, \phi^*_\mu),$$

with $\alpha \in \{U+L, L, I, T, A, P, 7, 8, 9\}$. The σ_α are defined from the following relations:

$$A_0 \equiv 2\frac{d\sigma^L}{d\sigma^{U+L}}, \quad A_3 \equiv 4\sqrt{2}\frac{d\sigma^A}{d\sigma^{U+L}}, \quad A_6 \equiv 4\sqrt{2}\frac{d\sigma^8}{d\sigma^{U+L}},$$

$$A_1 \equiv 2\sqrt{2}\frac{d\sigma^I}{d\sigma^{U+L}}, \quad A_4 \equiv 2\frac{d\sigma^P}{d\sigma^{U+L}}, \quad A_7 \equiv 4\sqrt{2}\frac{d\sigma^9}{d\sigma^{U+L}},$$

$$A_2 \equiv 4\frac{d\sigma^T}{d\sigma^{U+L}}, \quad A_5 \equiv 2\frac{d\sigma^7}{d\sigma^{U+L}},$$

- $q_T^W = 0$ —> only A4
- $O(\alpha_s)$ —> A0,A1,A2,A3,A4 + Lam-Tung relation (A0=A2)
- $O(\alpha_s^2)$—> A5,A6,A7 + Broken Lam-Tung

Input samples

Process	Sample
$W(\to \ell\nu)$+jets	privately produced
$Z(\to \ell\ell)$	/DYJetsToLL_M-50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7_ext2-v1/NANOAODSIM
$Z(\to \ell\ell)$,m10-50	/DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
	/DYJetsToLL_M-10to50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7_ext1-v1/NANOAODSIM
$t\bar{t}(\ell)$	/TTJets_SingleLeptFromTbar_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
	/TTJets_SingleLeptFromTbar_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7_ext1-v1/NANOAODSIM
$t\bar{t}(\ell\ell)$	/TTJets_DiLept_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
	/TTJets_DiLept_TuneCUETP8M1_13TeV-madgraphMLM-pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7_ext1-v1/NANOAODSIM
t (t-channel)	/ST_t-channel_top_4f_inclusiveDecays_13TeV-powhegV2-madspin-pythia8_TuneCUETP8M1/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
$\bar{t}$ (t-channel)	/ST_t-channel_antitop_4f_inclusiveDecays_13TeV-powhegV2-madspin-pythia8_TuneCUETP8M1/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
top (s-channel)	/ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
tW	/ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7_ext1-v1/NANOAODSIM
	/ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7_ext1-v1/NANOAODSIM
WW	/WW_TuneCUETP8M1_13TeV-pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
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WZ	/WZ_TuneCUETP8M1_13TeV-pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
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ZZ	/ZZ_TuneCUETP8M1_13TeV-pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
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QCD	/QCD_Pt-1000toInf_MuEnrichedPt5_TuneCUETP8M1_13TeV_pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
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	/QCD_Pt-120to170_MuEnrichedPt5_TuneCUETP8M1_13TeV_pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_backup_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
	/QCD_Pt-15to20_MuEnrichedPt5_TuneCUETP8M1_13TeV_pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
	/QCD_Pt-170to300_MuEnrichedPt5_TuneCUETP8M1_13TeV_pythia8/RunIISummer16NanoAODv6-PUMoriond17_Nano25Oct2019_102X_mcRun2_asymptotic_v7-v1/NANOAODSIM
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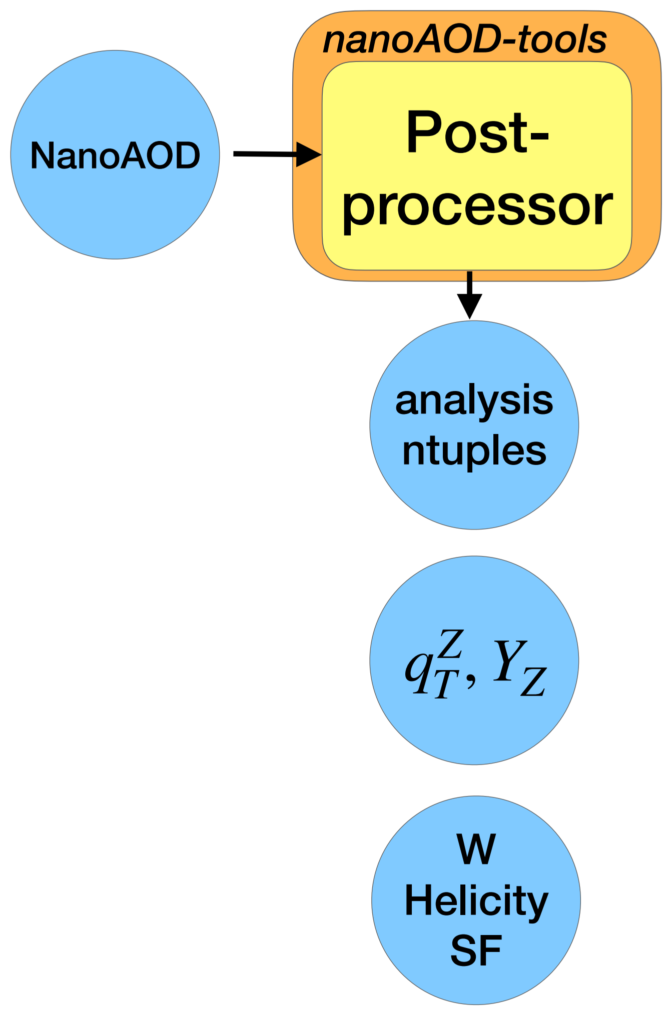
Input



Process	σ [pb]	$\mathcal{L}_{\text{int}}^{\text{eq}}$ [fb^{-1}]	generator
$W(\to \ell\nu)$+jets	61526.70	4.7	MadGraph_aMC@NLO
$Z/\gamma^*(\to \ell\ell)$, $m_{\ell\ell} > 50$ GeV	6025.20	9.1	MadGraph_aMC@NLO
$Z/\gamma^*(\to \ell\ell)$, 10 GeV $< m_{\ell\ell} <$ 50 GeV	1093.00	29.1	MadGraph_aMC@NLO
$t\bar{t}(\ell)$	182.00	623.6	Madgraph, LO
$t\bar{t}(\ell\ell)$	95.02	319.2	Madgraph, LO
t (t-channel)	136.20	493.3	POWHEG, NLO
$\bar{t}$ (t-channel)	80.95	479.4	POWHEG, NLO
top (s-channel)	3.68	105.5	POWHEG, NLO
tW	35.60	195.3	POWHEG, NLO
WW	115.00	69.4	Madgraph, LO
WZ	47.13	84.8	Madgraph, LO
ZZ	16.50	59.9	Madgraph, LO

<u>Data and MC samples</u>

- NanoAOD-V6
- Legacy re-reco
  - MC: RunIISummer16
  - GT: 102X mcRun2 asymptotic v7
  - CMSSW_10_2_18
- Data: 2016, B to H eras
- Lumi = 35.9 fb^{-1}

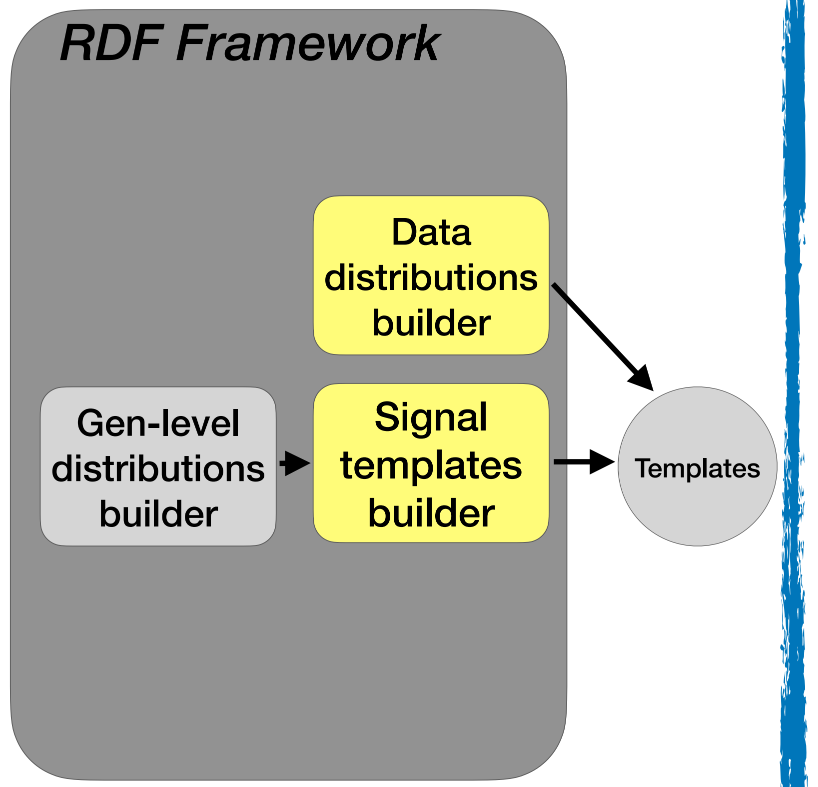
<u>Efficiency Scale Factors</u>

- from SMP-18-012 *[https://doi.org/10.1103/PhysRevD.102.092012]*
- Standard Tag and Probe technique
- $\text{SF} = \text{SF}_{\text{sel}} \cdot \text{SF}_{\text{trig}}$, with: $\text{SF}_{\text{sel}} \equiv \frac{\varepsilon^{\text{data}}_{\text{sel}}}{\varepsilon^{\text{MC}}_{\text{sel}}}$, $\text{SF}_{\text{trig}} \equiv \frac{\varepsilon^{\text{data}}_{\text{trig}}}{\varepsilon^{\text{MC}}_{\text{trig}}}$, where sel=ID*ISO
- smoothed with ERF in p_T^μ, range: 25-55 GeV
- fine binned in η^μ ($\Delta\eta^\mu = 0.1$). range: -2.4-2.4

<u>Z distributions</u>

- From SMP-17-010 *[https://doi.org/10.1007/JHEP12(2019)061]*
- reweighing the Z/W MC for measured q_T^Z (Z also for Y_Z)

Signal templates - Selection



Selection

- trigger: `HLT_IsoMu24_v*` OR `HLT_IsoTkMu24_v*`
- Exactly one muon in the event, identified as:
  - Muon Medium ID
  - $d_{xy} < 0.05$ cm, $d_z < 0.2$ cm
  - $p_T^\mu > 25$ GeV, $|\eta^\mu| < 2.4$
- additional lepton veto:
  - muon: loose muon ID, $p_T^\mu > 10$ GeV
  - electron: GSF-electon, veto electron iD, $p_T^e > 10$ GeV, RelIso<0.3, $d_{xy} < 0.05$ cm, d_z<0.1 (0.2) cm barrel (endcap)
- Primary vertex position: z<24 cm, xy<2 cm
- MET-filters applied
- $m_T > 40$ GeV
- RelIso < 0.15

} Easily relaxable

MC weights:

- PU weights
- L1 trigger prefire weights
- Efficiency SF
- (q_T^Z, Y_Z, q_T^W for bkg)

$$w_{\text{tot}} = (w_Y \cdot w_{q_T}) \cdot w_{\text{PU}} \cdot w_{\text{prefire}} \cdot w_{\text{SF}} \cdot w_{\mathcal{L}}.$$

Object Calibration

- p_T^μ scale and resolution: Rochester corrections
- MET: recommended JEC from Jet-MET POG

Isolation variable

- $\text{Iso}_{\text{PF}} = \text{Iso}_{\delta\beta} \equiv \sum_{x^{\pm}_{\text{PV}}} p_T + \max\left(0, \sum_{\gamma} p_T + \sum_{h^0} p_T - \frac{1}{2} \sum_{x^{\pm}_{\text{PU}}} p_T\right),$
- Relative Isolation: $\text{RelIso}^{\mu}_{\text{PF}} \equiv \text{Iso}_{\text{PF}}/p^{\mu}_T$
- counting in cone of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.4$

Muon reconstruction and ID

- **Standalone Muons:** muon sistem only
- **Global Muons:** standalone muons matched with a track from the tracker (out —>in geometrical matching)
- **Tracker muons:** inner tracker tracks extrapolated outward

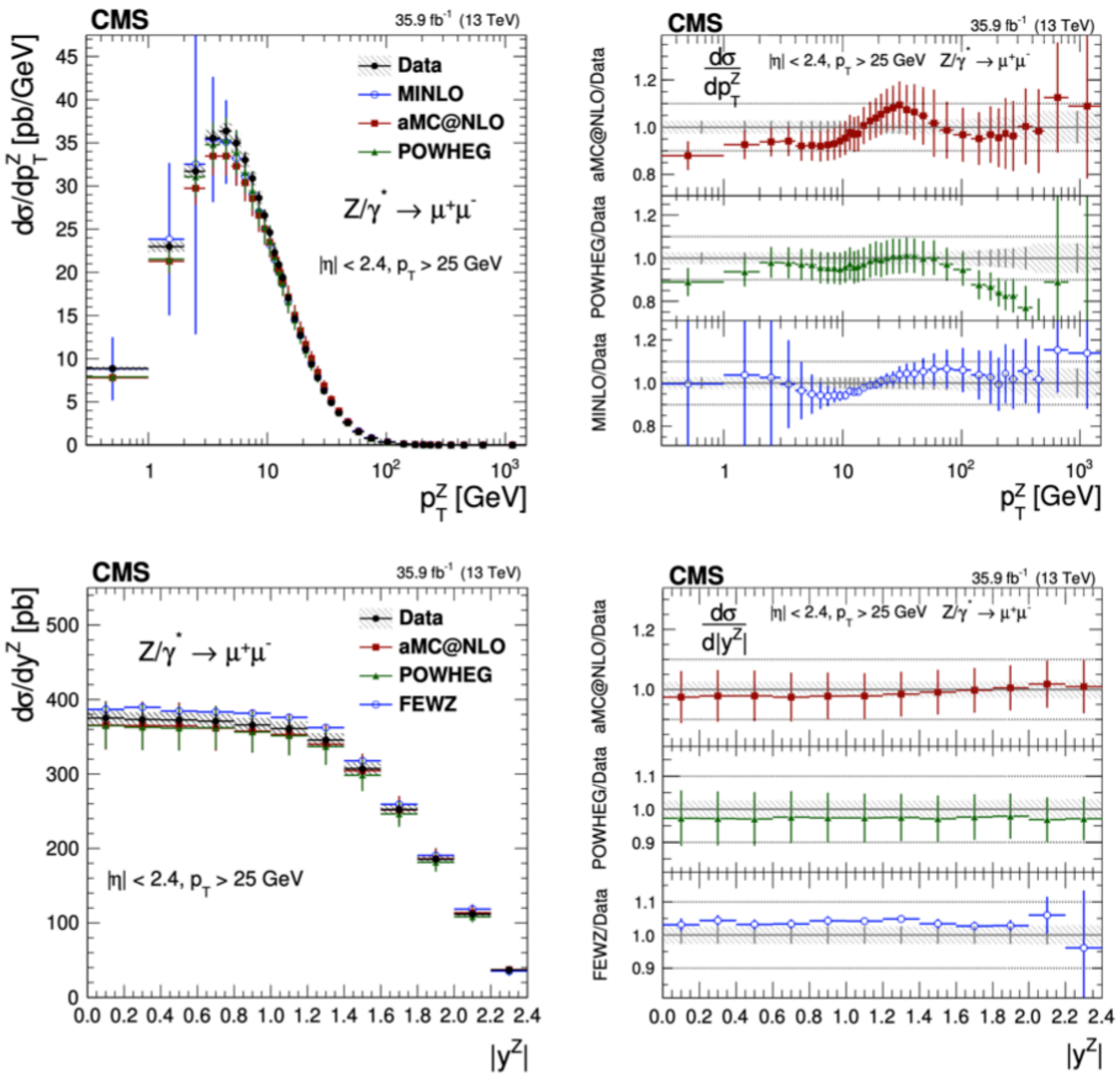
- **Medium ID:** global muon, hits in 80% of silicon layers, compatibility with muon segments, high quality in fit χ^2 , low material effect.

q_T^Z and Y_Z from SMP-17-010

$$w_Y = \frac{(d\sigma_Z/dY)^{\mathrm{meas}}}{(d\sigma_Z/dY)^{\mathrm{MC}}} \cdot \frac{\int (d\sigma_Z/dY)^{\mathrm{MC}} dY}{\int (d\sigma_Z/dY)^{\mathrm{meas}} dY},$$

$$w_{q_T} = \frac{(d\sigma_Z/dq_T)^{\mathrm{meas}}}{(d\sigma_Z/dq_T)^{\mathrm{MC}}} \cdot \frac{\int (d\sigma_Z/dq_T)^{\mathrm{MC}} dq_T}{\int (d\sigma_Z/dq_T)^{\mathrm{meas}} dq_T}$$

- w_{qT} applied to Z and W MC
- w_Y applied to Z MC



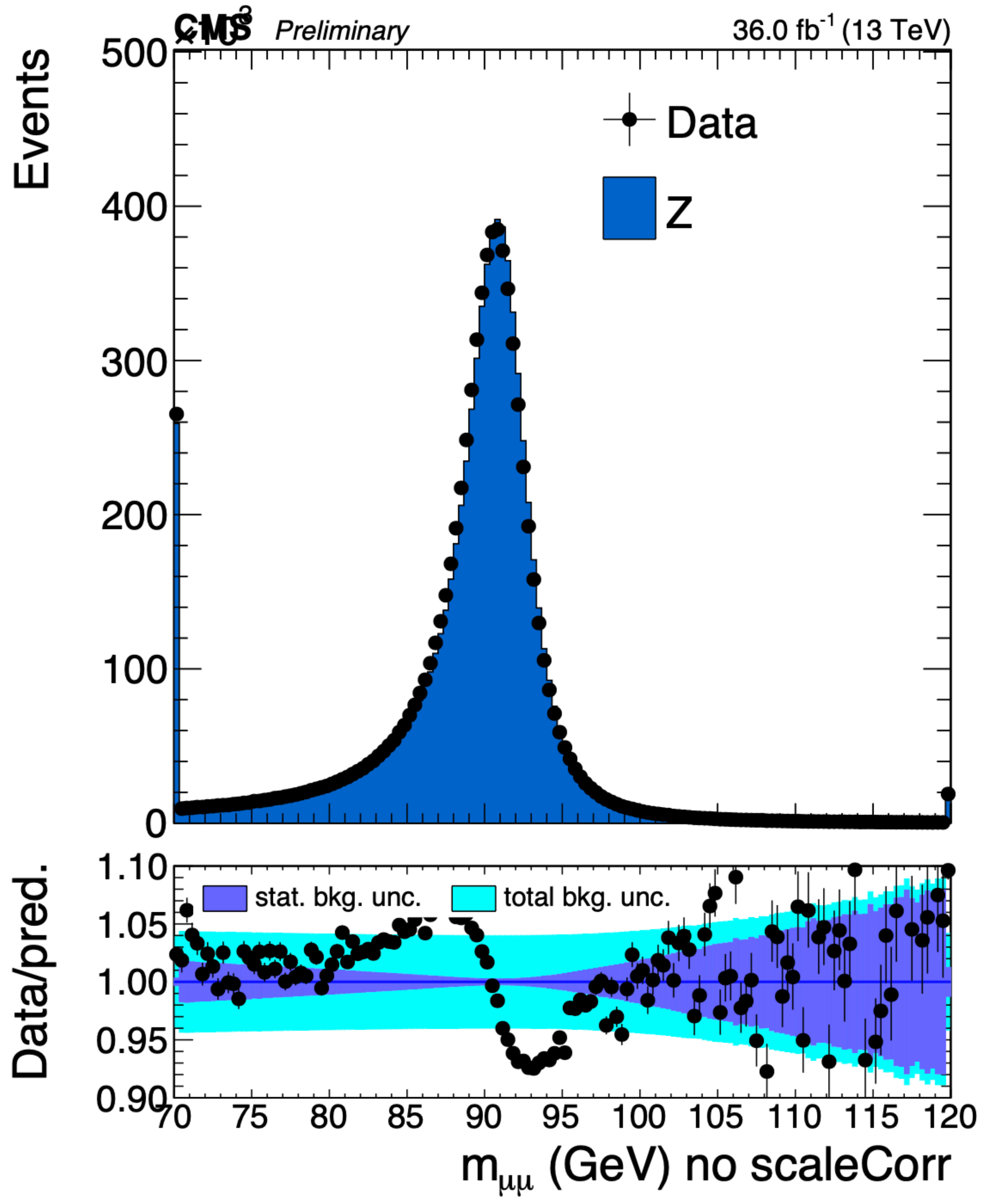
Tag & Probe Method

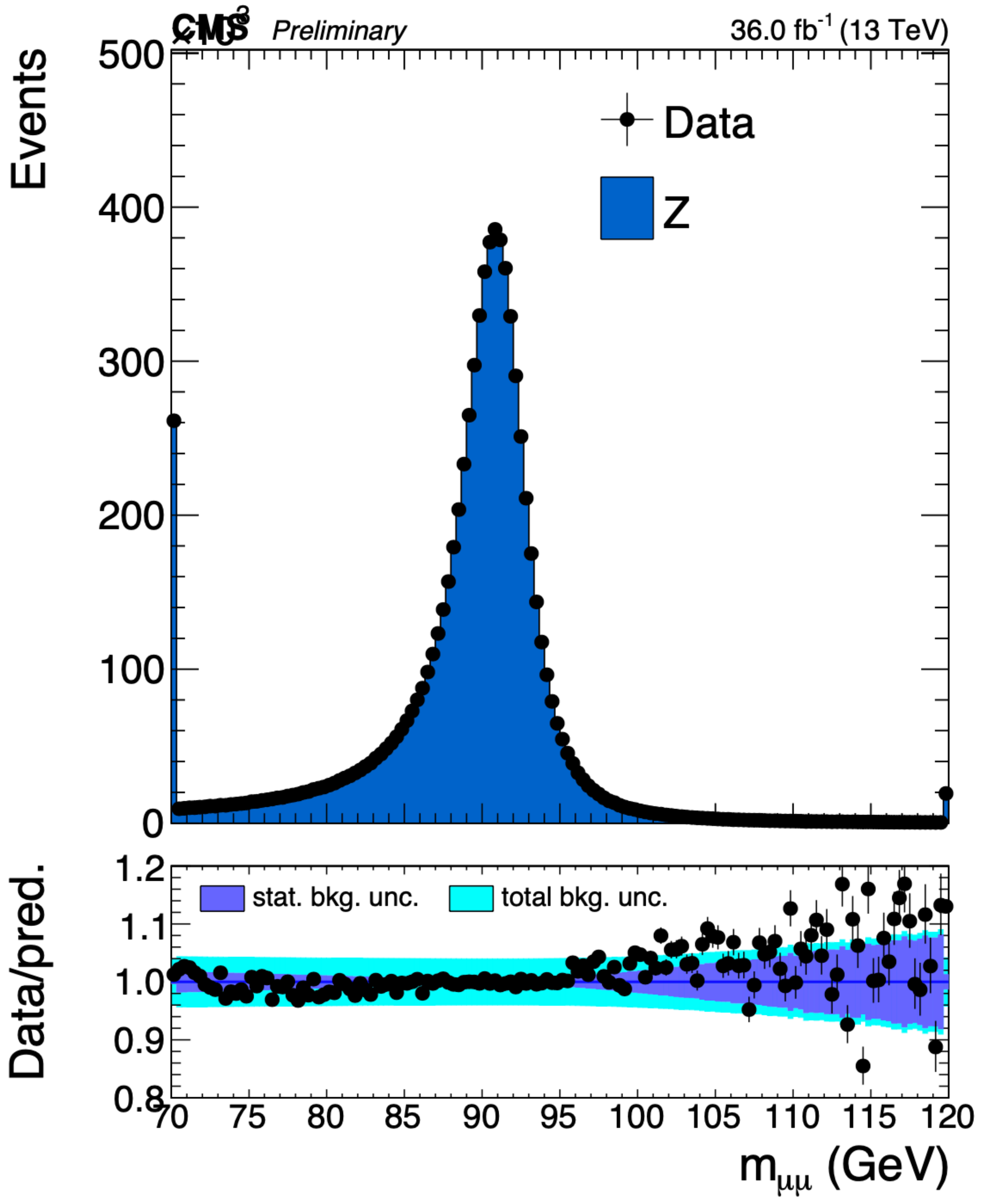
- Purpose: efficiency measurement on data, unbiased from MC and models
- Select di-leptons decays (eg. $Z \to \mu\mu$) with a loose invariant mass selection
  - Tag lepton: very tight selection
  - Probe Lepton: relaxed selection, which not include X (selection related to efficiency to measure)
- ε_X = fraction of probes which overcame selection X over the total number of probes
- lineshape fit to remove background
- Muon efficiency: $\varepsilon_\mu = \varepsilon_{\text{tracking}} \cdot \varepsilon_{\text{reco+ID}} \cdot \varepsilon_{\text{iso}} \cdot \varepsilon_{\text{trig}}$

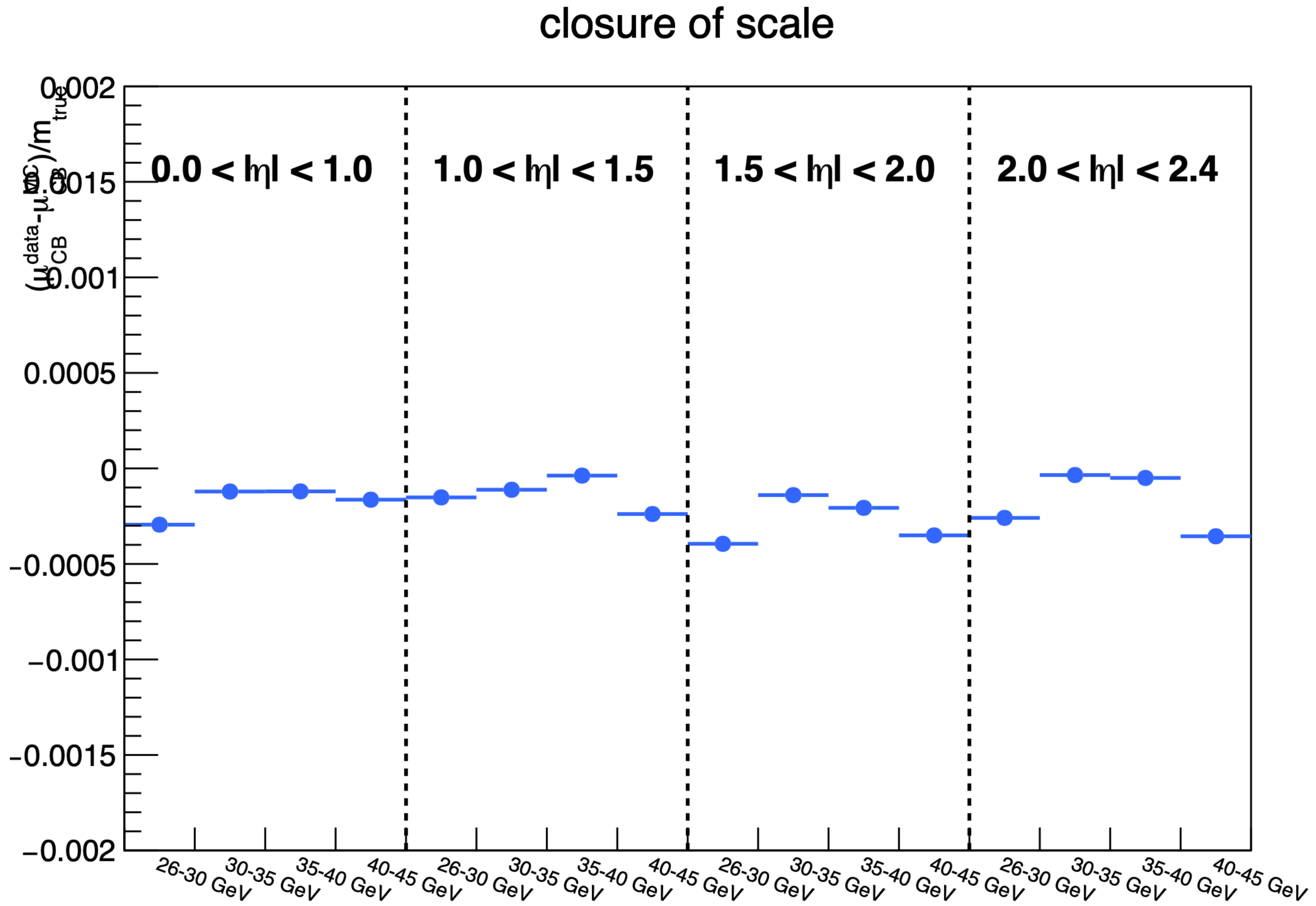
Rochester Corrections

- references: [Note] [TWiki] [Bodek et al, EPJC, 72,2194 (2012)]
- $Z \to \mu\mu$ events to calibrate muon scale and resolution
- $Z \to \mu\mu$ MC, with perfect aligned reference
- correction from comparison of $\langle 1/p_T \rangle (p_T, \eta)$ between sample and reference
  - multiplicative term (magnetic field), additive term (misaligment), extra term to match the Z peak
  - iteration until good agreement, data and MC separately
- residual discrepancy for trigger and reco. efficiency modelling (to select $Z \to \mu\mu$)—> $\langle m_{\mu\mu} \rangle (p_T, \eta)$ discrepancy
  - $\langle 1/p_T \rangle$correction with $1 + 2\Delta M^Z / m_Z^{\text{data}}, M_Z = m_Z^{\text{measured}} - m_Z^{\text{expected}}$ term
- resolution corrected using $m_{\mu\mu}$ between data and MC
- Summary: $1/p_T^{\text{RC}} = \kappa(\eta, \phi)\dfrac{1}{p_T} + q\lambda(\eta, \phi), \quad \sigma_{p_T}^{\text{RC}} = \sigma_{p_T}/\kappa_{\text{res}}(|\eta|)$

Rochester corrections plots







- reconstructed $m_{\mu\mu}$ before and after
- residual muon momentum scale calibration

Scale Factors from SMP-18-012

$$\mathrm{SF} = \mathrm{SF}_{\mathrm{sel}} \cdot \mathrm{SF}_{\mathrm{trig}}, \quad \text{with: } \mathrm{SF}_{\mathrm{sel}} \equiv \frac{\varepsilon^{\mathrm{data}}_{\mathrm{sel}}}{\varepsilon^{\mathrm{MC}}_{\mathrm{sel}}}, \quad \mathrm{SF}_{\mathrm{trig}} \equiv \frac{\varepsilon^{\mathrm{data}}_{\mathrm{trig}}}{\varepsilon^{\mathrm{MC}}_{\mathrm{trig}}}.$$

$$\varepsilon^{\eta,q}_{\text{step, kind}}(p_T) = p_0 \mathrm{erf}\left(\frac{p_T - p_1}{p_2}\right), \quad \mathrm{erf}(x) \equiv \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy,$$

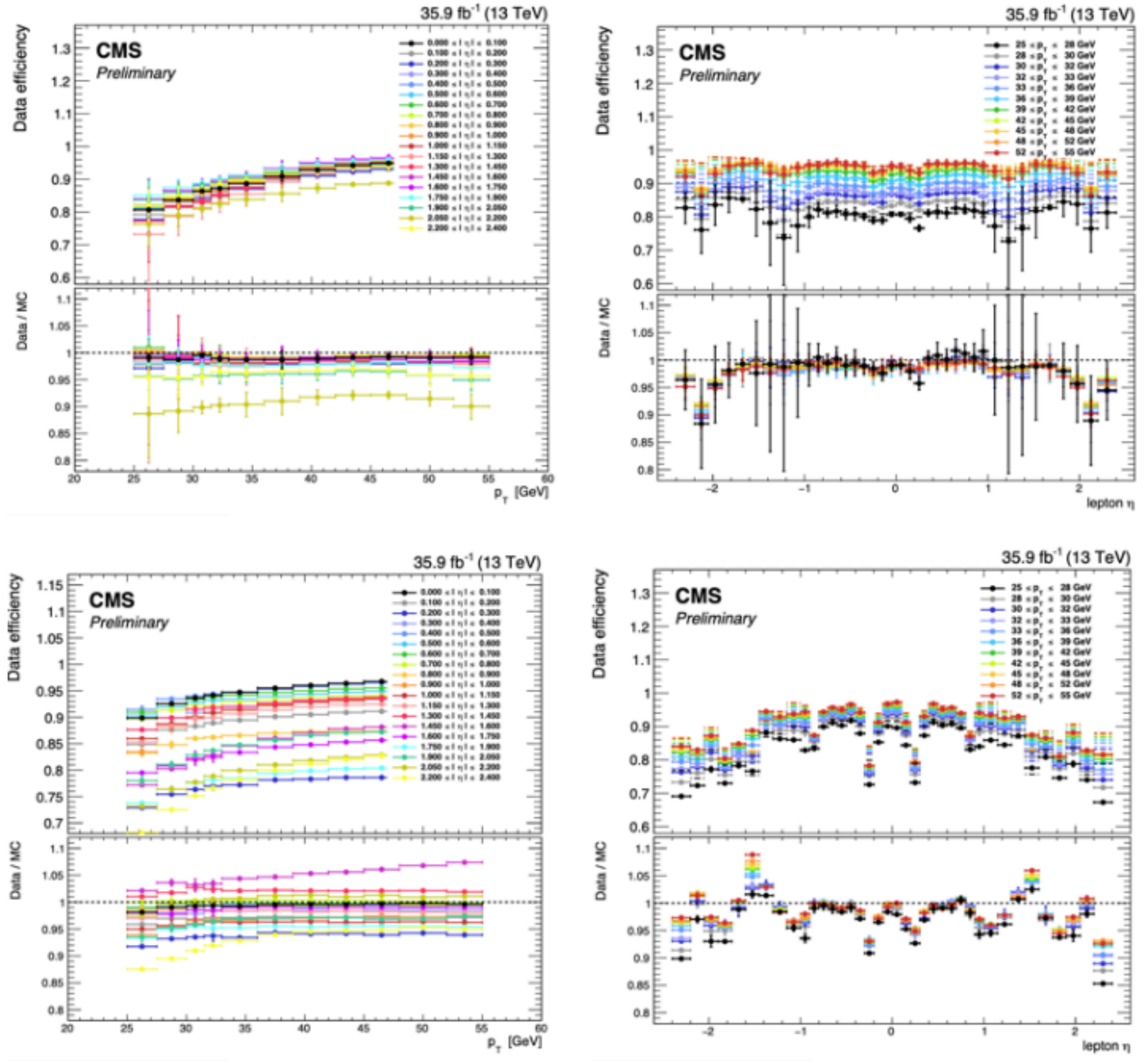


Figure 2.18. *Values of the selection (upper plots) and trigger-μ^+ (lower plots) efficiencies measured on data as a function of p_T^μ (left plots) or η^μ (right plots) before the application of the smoothing. The SFs are reported in the panels below each plot (from Ref. [105]).*

Scale Factors from SMP-18-012 (cont'd)

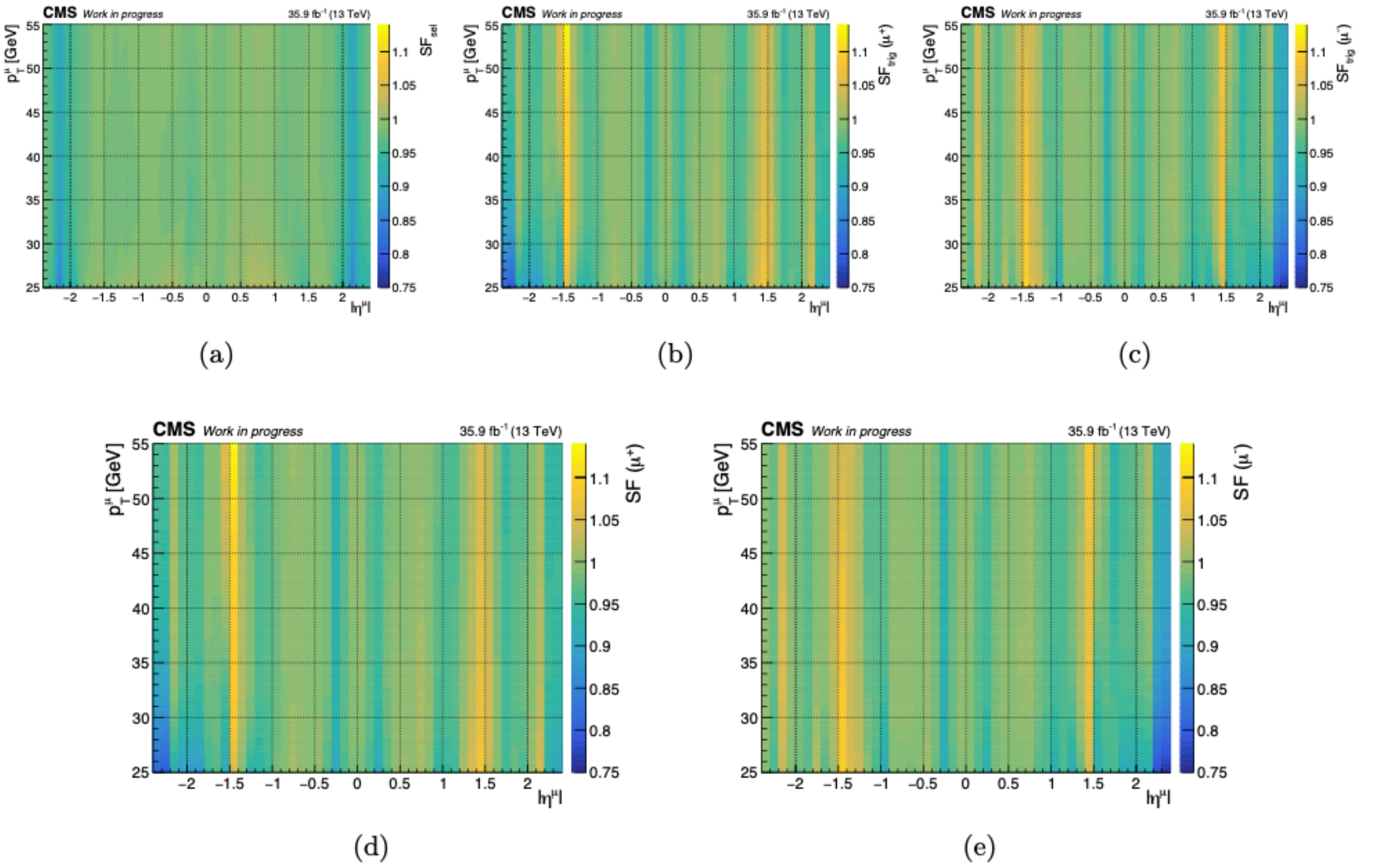
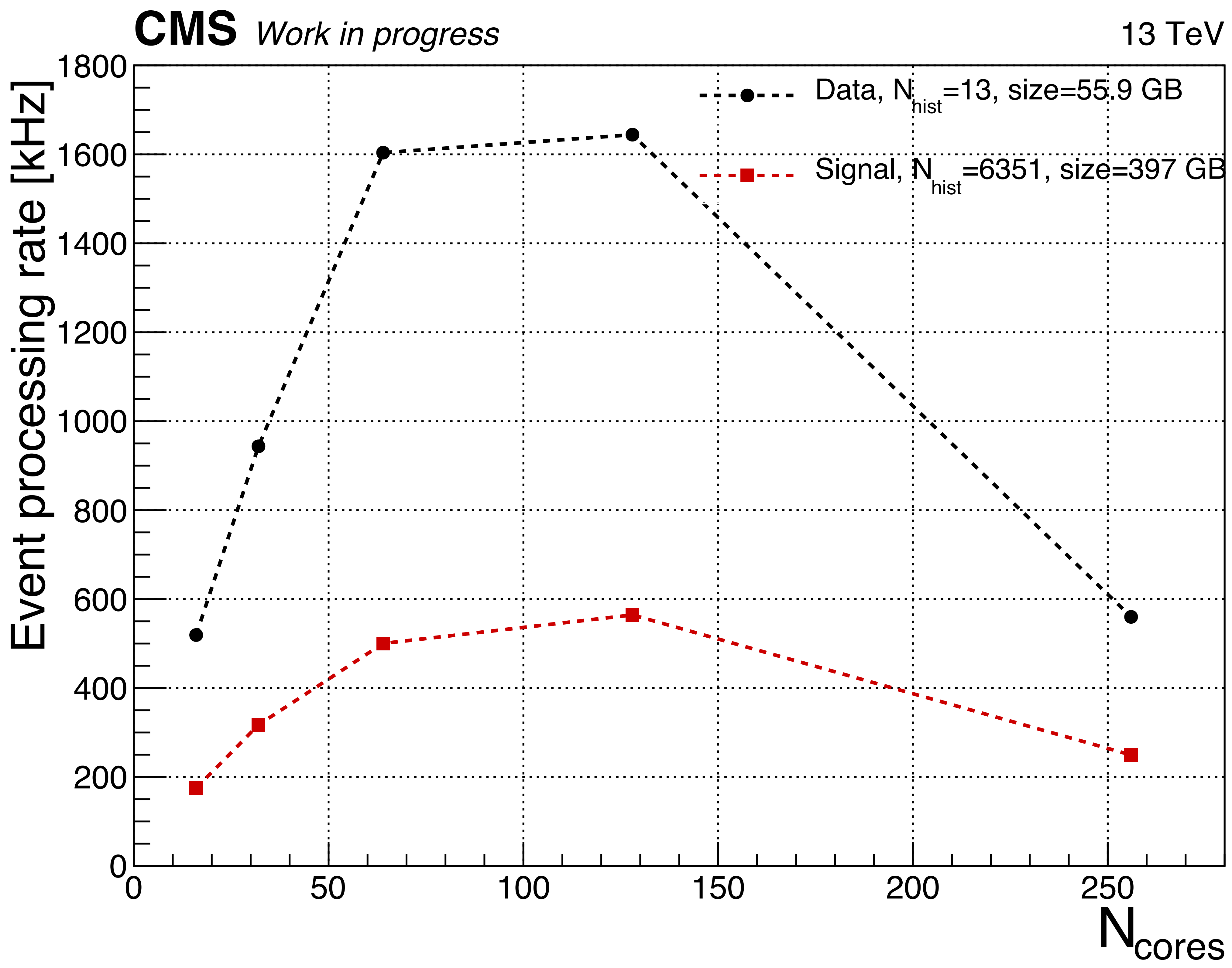


Figure 2.19. *Values of the selection scale factor (a) and trigger scale factor for μ^+ and μ^- (b and c, respectively) on the $\eta^\mu \times p_T^\mu$ plane. This is the result of the ratio of data and MC efficiency p_T-smoothed (trigger) or p_T and η-smoothed (selection). The total SF, as defined in Eq. 2.7 in (d) and (e) for μ^+ and μ^-, respectively.*

Framework performance

- Framework performance (December 2020)
- AMD EPYC 7742 processor, 256 cores, 2TB memory (DDR4, 3200 MHz) and a SSD-nvme disk of 54 TB



Template ϕ^* folding

- Explicit CS->lab trasformation:

$$p_T^\mu = \frac{1}{2}\sqrt{(E_T^W \cos\phi^* \sin\theta^* - q_T)^2 + (m_W \sin\phi^* \sin\theta^*)^2},$$

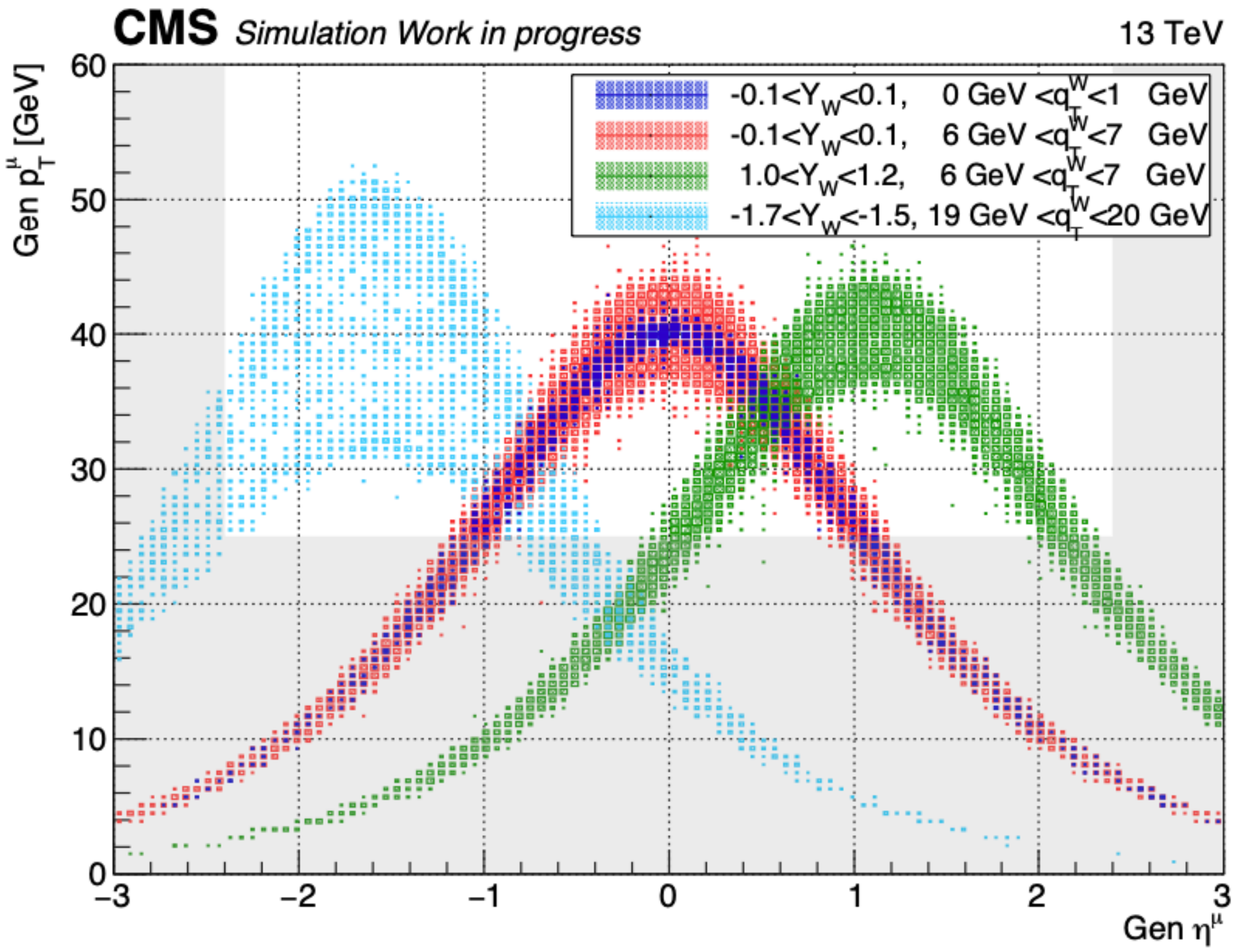
$$\eta^\mu = -\ln\left[\frac{p_T^\mu}{E_\mu + p_z^\mu}\right] = -\ln\left[\frac{\frac{1}{2}\sqrt{(E_T \cos\phi^* \sin\theta^* - q_T^W)^2 + (m_W \sin\phi^* \sin\theta^*)^2}}{\cosh y(1-\tanh y)(\frac{E_T^W}{m_W} - \frac{q_T^W}{m_W}\cos\phi^* \sin\theta^* + \cos\phi^*)}\right]$$

- only ϕ^*-even terms

- In lab only (where $\phi = \phi^\mu - \phi^W$)

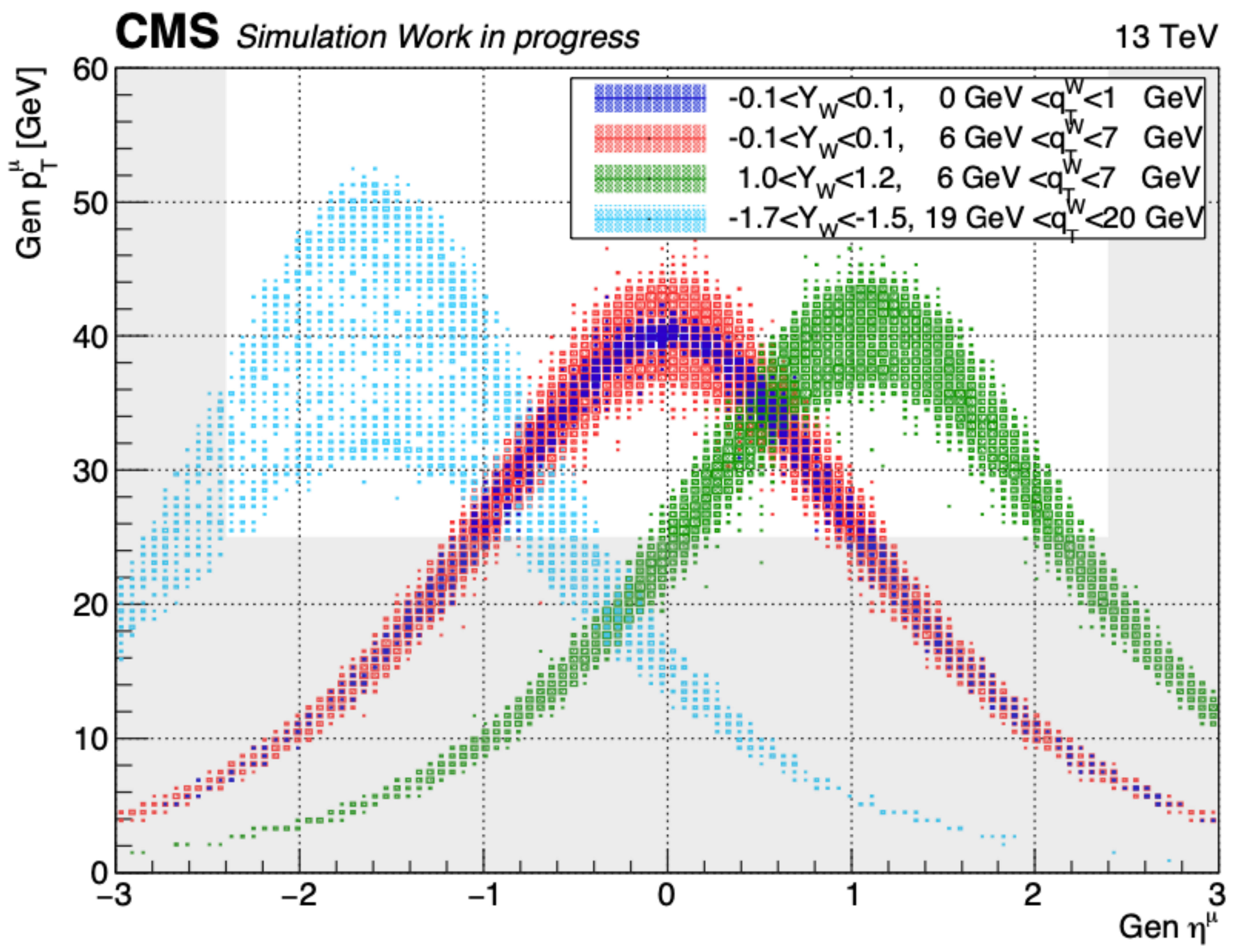
$$p_T^\mu = \frac{m_W^2/2}{E_T^W \cosh(Y_W - \eta^\mu) - q_T^W \cos\phi}, \quad \text{with: } E_T^W = \sqrt{m_W^2 + (q_T^W)^2}$$

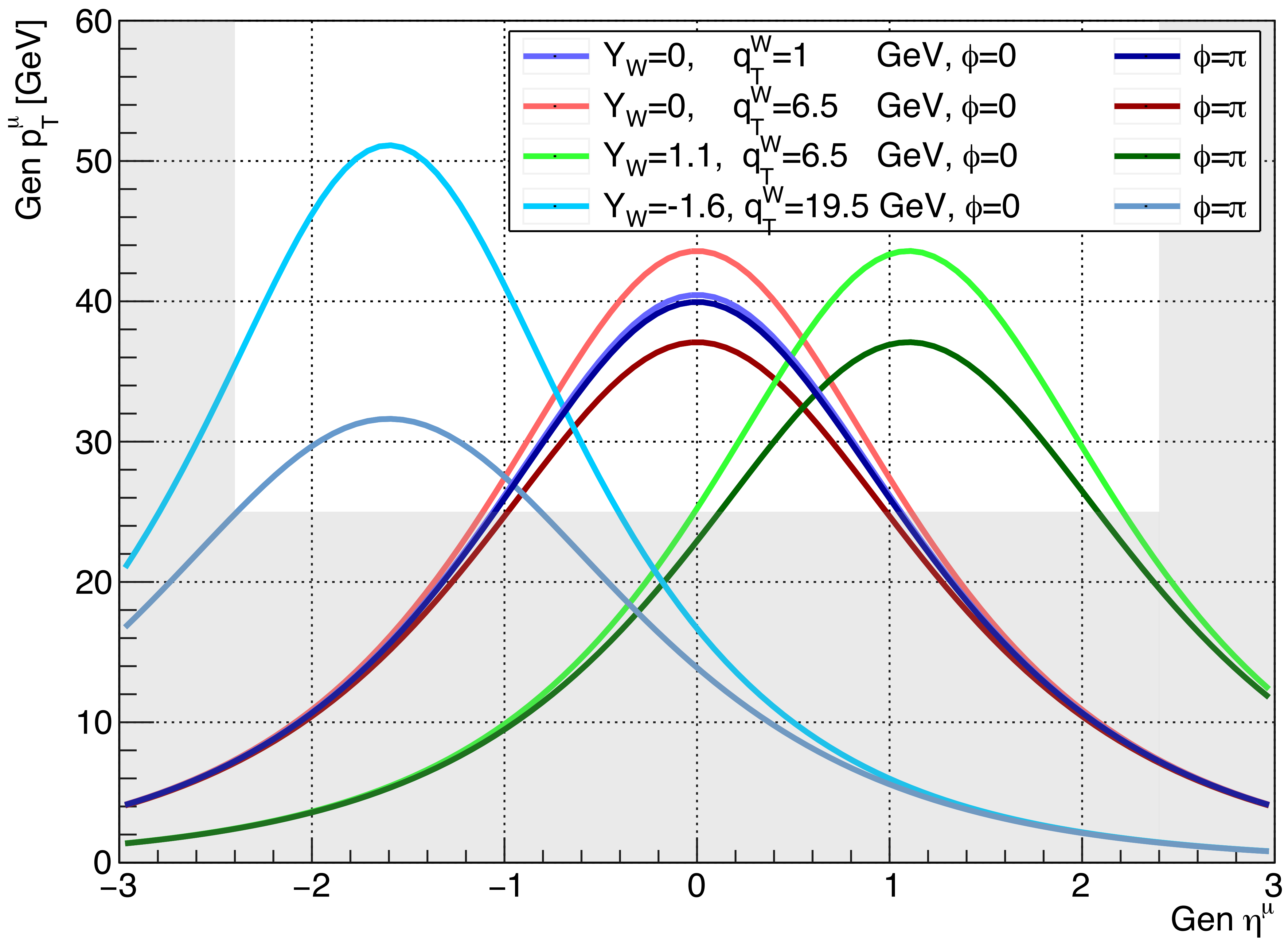
- A_5, A_6, A_7 templates cancel out because:
  - their harmonic functions are odd in ϕ^*
  - The templates are integrated in ϕ, and the acceptance in $+\phi^*$ is the same of $-\phi^*$



templates analytic formula

$$p_T^\mu = \frac{m_W^2/2}{E_T^W \cosh(Y_W - \eta^\mu) - q_T^W \cos\phi}, \quad \text{with: } E_T^W = \sqrt{m_W^2 + (q_T^W)^2}$$



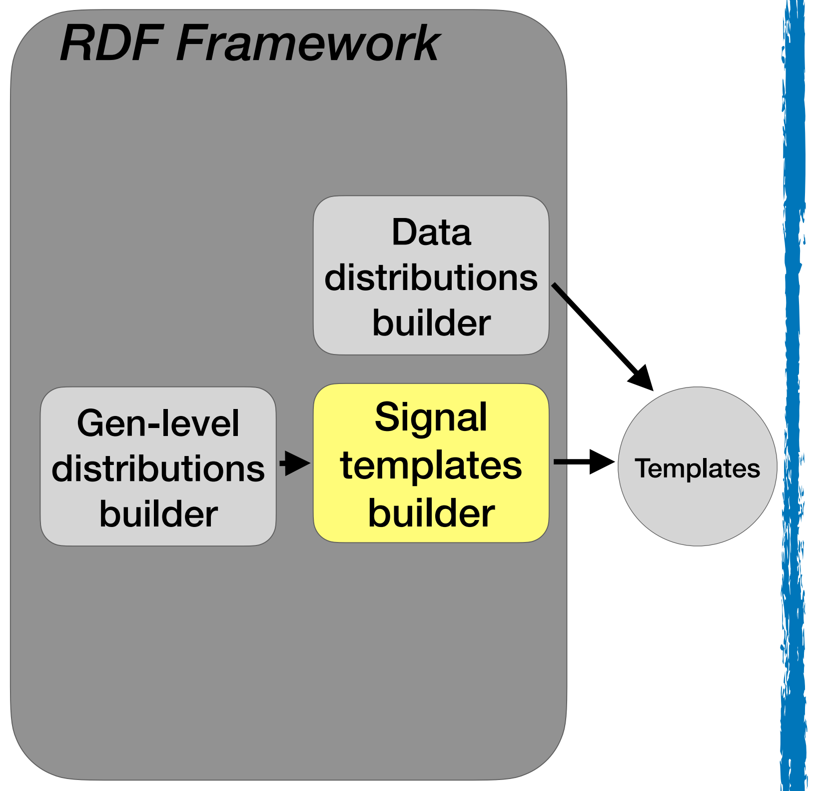


Final State Radiation syst

- We are independent from W production, but we completely rely on muon propagation
- it must be well described in the MC
- A syst. must be assessed
- Previous work:
  - W-Helicity: 0.1-3% on A4 or Y
  - Atlas: 3-6 MeV on W-mass
  - Theory prediction: 1-2 MeV with modern tools

https://doi.org/10.1103/PhysRevD.96.093005

Signal templates - template building



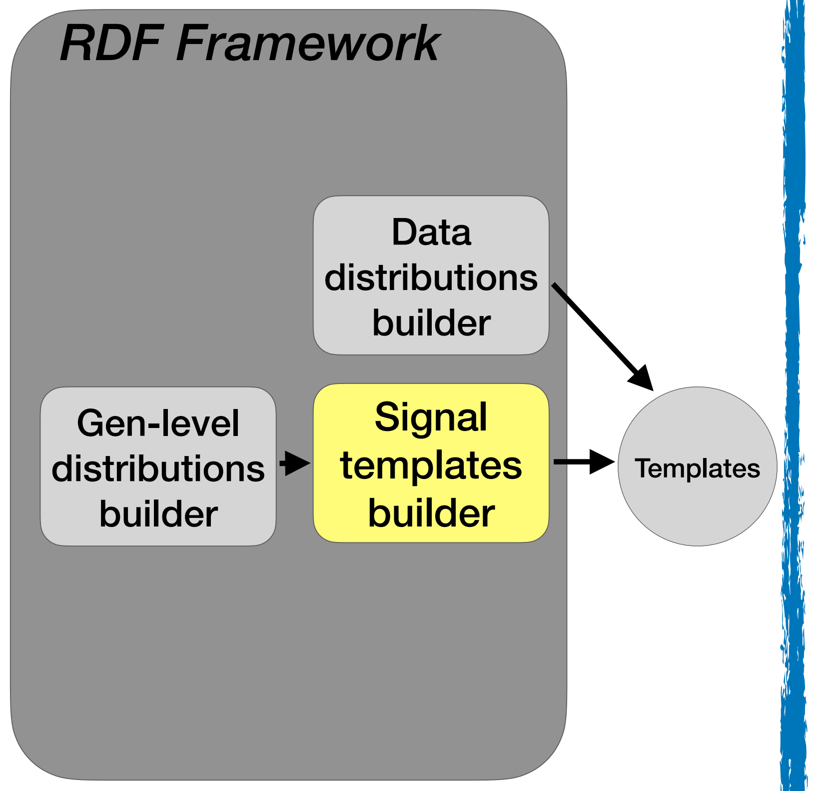
1. from W MC —> get the events in a certain bin of Y_W, q_T^W
2. Reweight the events to make the distribution $(\cos\theta^* \times \phi^*)$ flat. How? method of momenta:
   - momentum of $f(\cos\theta^*, \phi^*)$ defined as:

$$f(\theta^*, \phi^*)\rangle = \frac{\int_{-1}^{1} d\cos\theta^* \int_0^{2\pi} d\phi^* f(\theta^*, \phi^*) d\sigma(\theta^*, \phi^*)}{\int_{-1}^{1} d\cos\theta^* \int_0^{2\pi} d\phi^* d\sigma(\theta^*, \phi^*)}$$

$$\langle\frac{1}{2}(1 - 3\cos^2\theta^*)\rangle = \frac{3}{20}\left(A_0 - \frac{2}{3}\right), \quad \langle\sin\theta^*\cos\phi^*\rangle = \frac{1}{4}A_3, \quad \langle\sin(2\theta^*)\sin\phi^*\rangle = \frac{1}{5}A_6,$$
$$\langle\sin(2\theta^*)\cos\phi^*\rangle = \frac{1}{5}A_1, \quad \langle\cos\theta^*\rangle = \frac{1}{4}A_4, \quad \langle\sin\theta^*\sin\phi^*\rangle = \frac{1}{4}A_7.$$
$$\langle\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)\rangle = \frac{1}{20}A_2, \quad \langle\sin^2\theta^*\sin(2\phi^*)\rangle = \frac{1}{5}A_5,$$

   - apply the weight: $w_\Sigma = \dfrac{1}{\sum_i A_i P_i}$
3. Build now the desired distribution $(\cos\theta^* \times \phi^*)$ with the weight: $w_i = P_i(\cos\theta^*, \phi^*)$
4. for each event fill the proper template $(\cos\theta^* \times \phi^*) \rightarrow (\eta^\mu \times p_T^\mu)$

Signal templates - template building (cont'd)



- The overall normalization of the template rely on the MC, but is left free in the fit —-> no assumption on Y_W, q_T^W

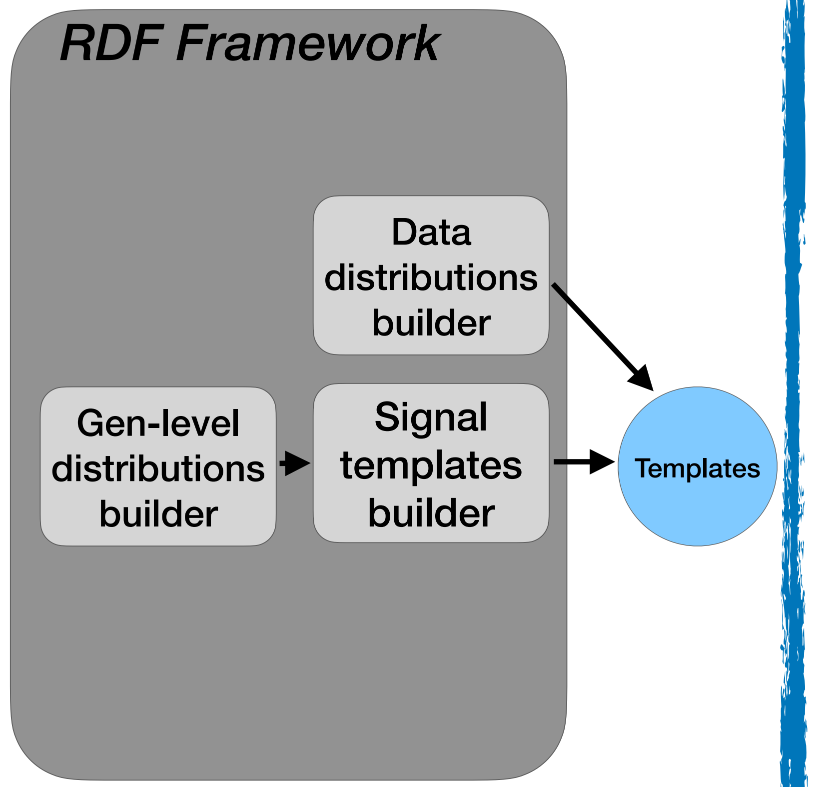
- the mapping $(\cos\theta^* \times \phi^*) \rightarrow (\eta^\mu \times p_T^\mu)$ is 2—>1:

  - $\phi^*, -\phi^*$ go in same (η, p_T) bin

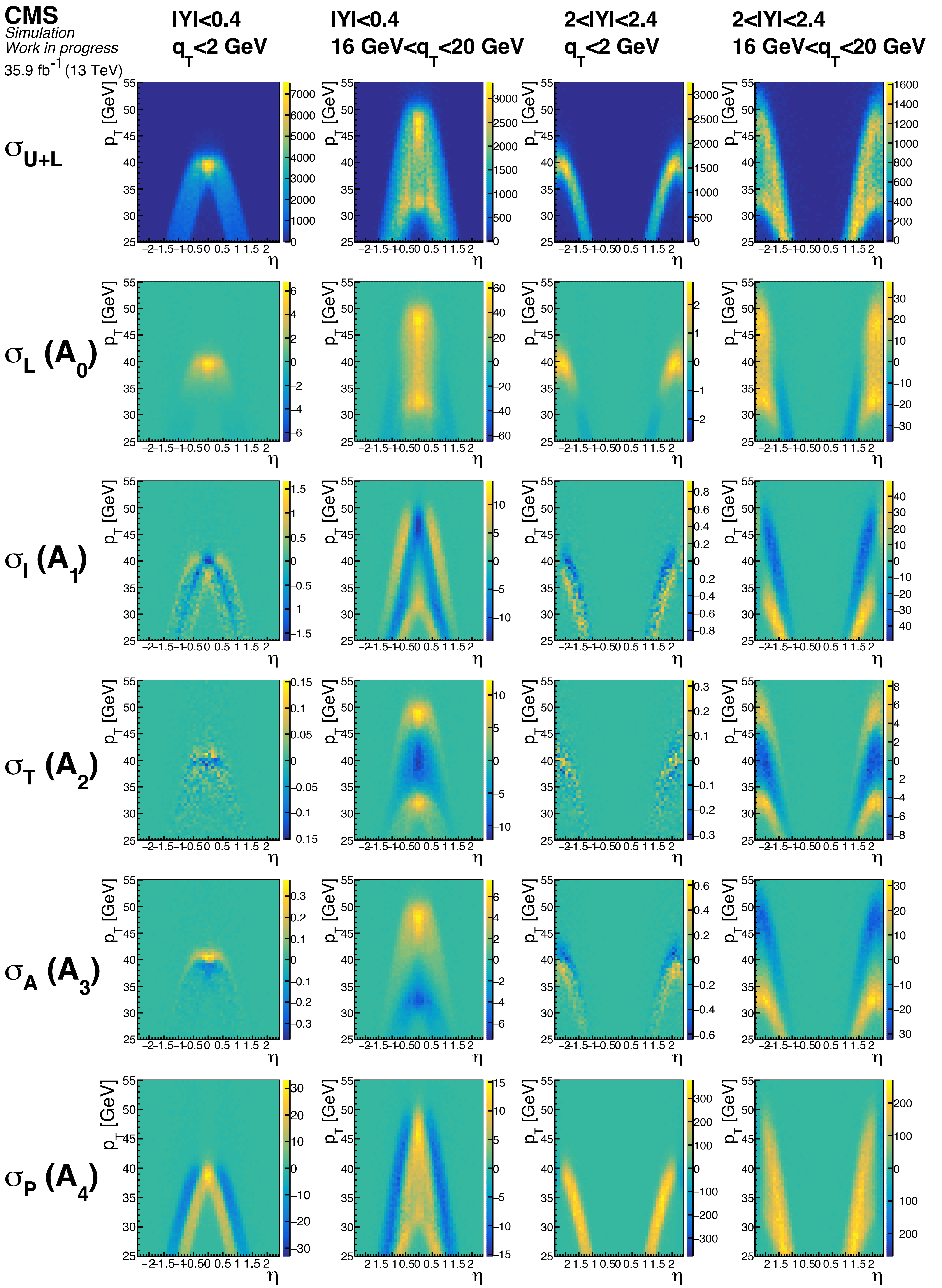
  - A_5, A_6, A_7 template mathematically 0 and they do not affect mass/properties measurement

- The bins should be fine enough to avoid strong variation of Y_W, q_T^W inside the bin

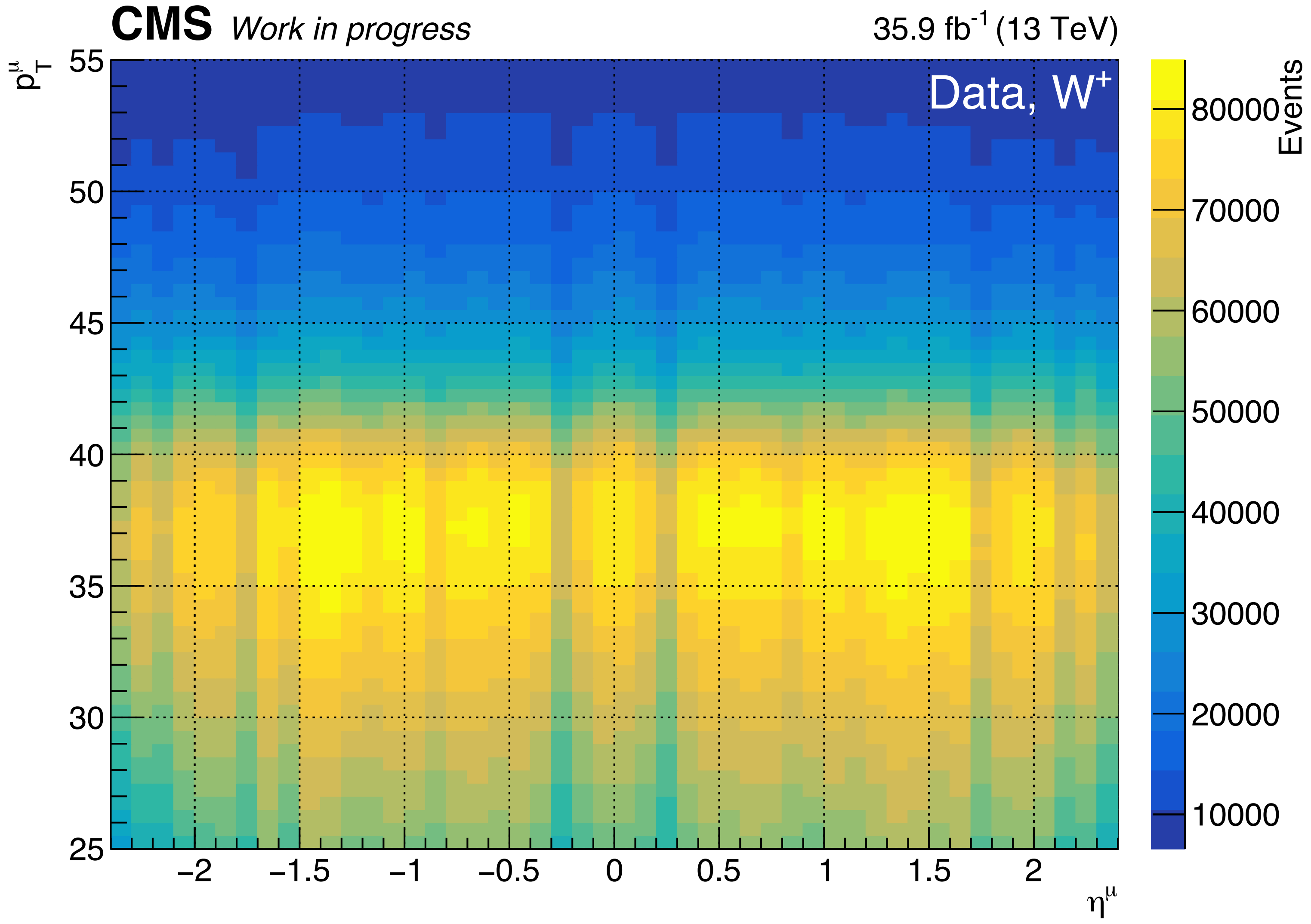
Signal templates - result



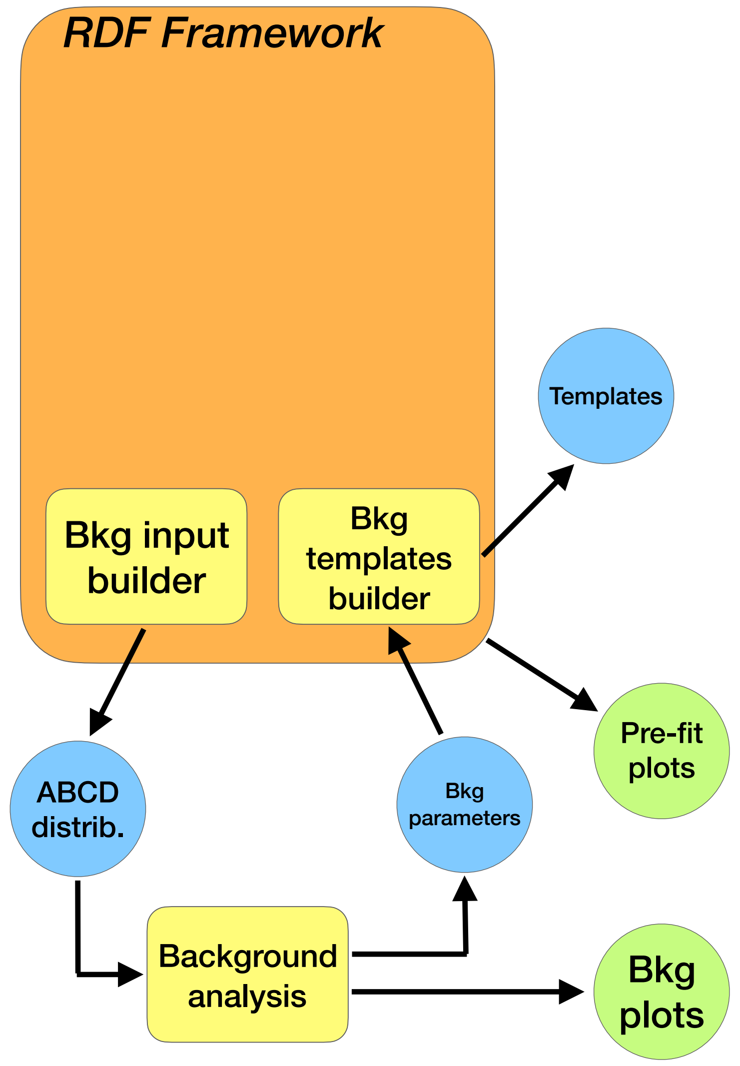
Example of signal templates



Data template



Backgrounds - sources

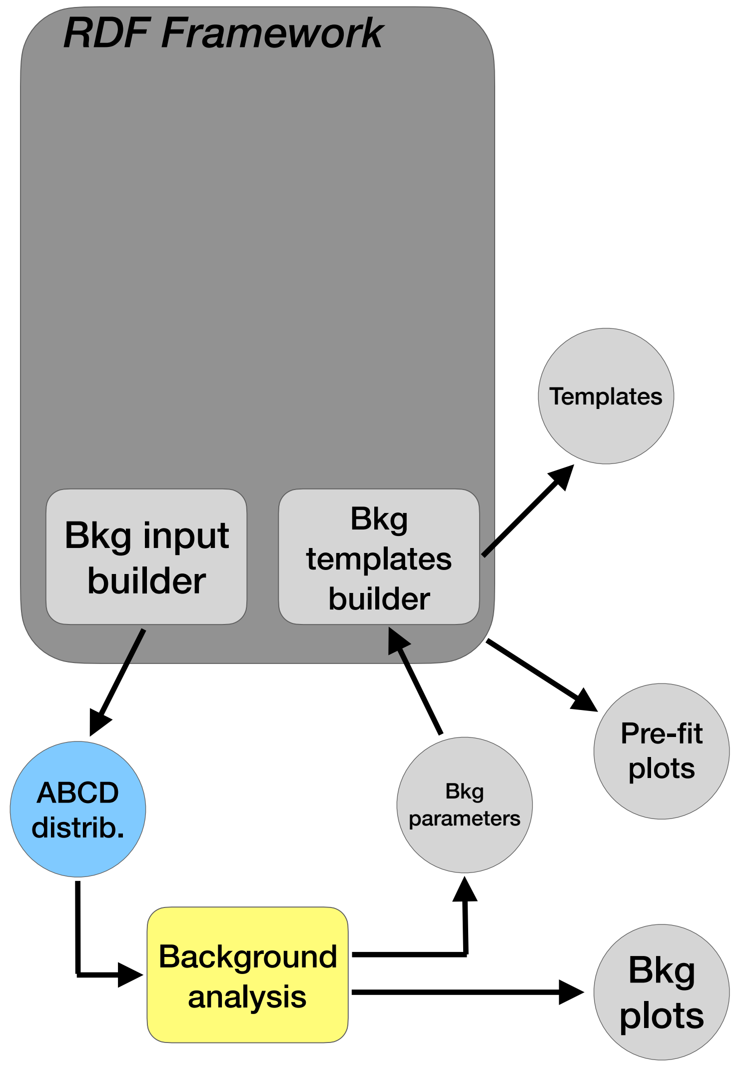


- **EWK**: prompt muons from electroweak channels which mimic the signal —> from MC

- **Low-Acceptance:** $W \to \mu\nu$ events produced outside the $q_T^W \times |Y_W|$ range considered in the fit, which falls in the $p_T^\mu \times \eta^\mu$ range —> from MC

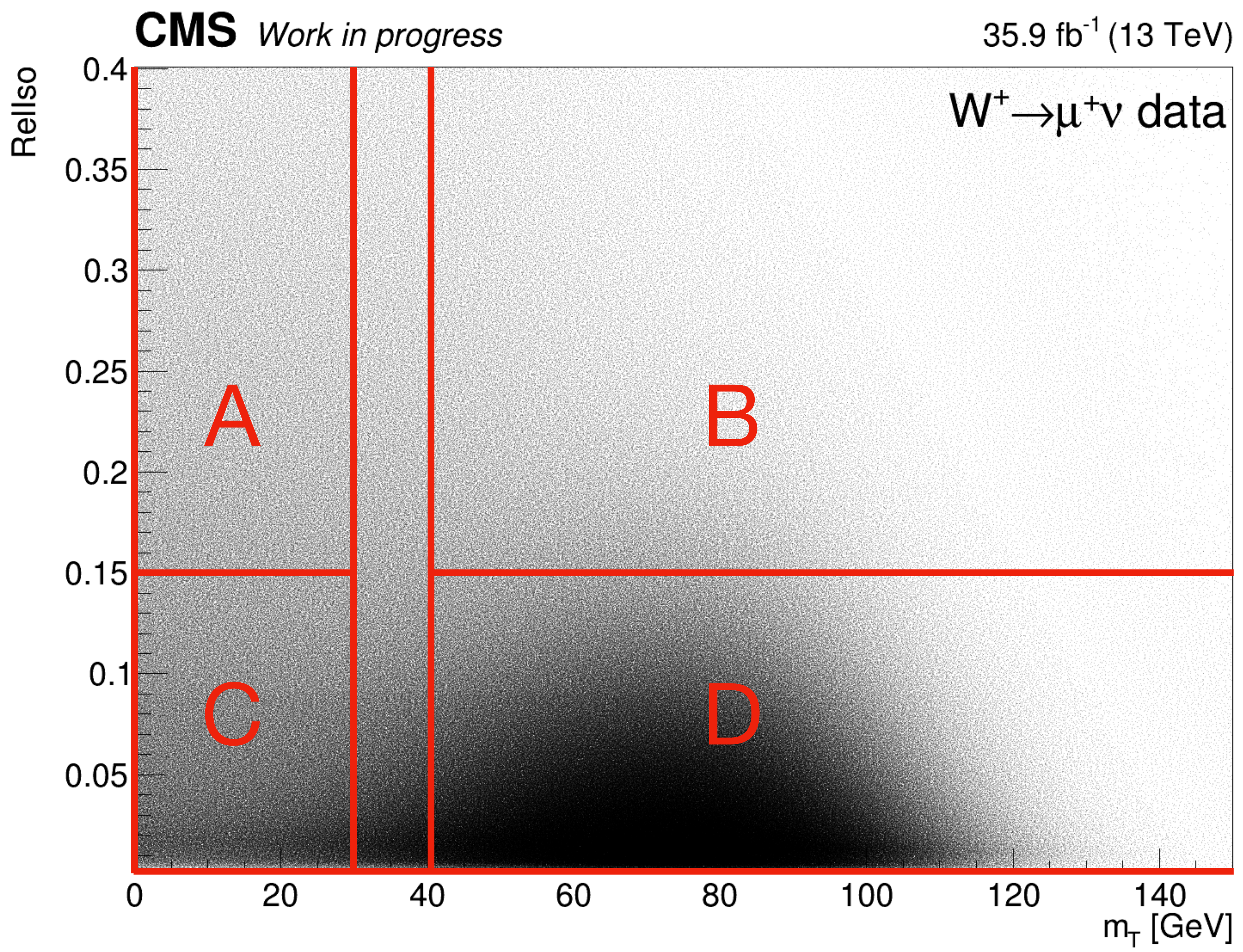
- **QCD**: non-prompt muons from multijet production —> Data driven estimation

Backgrounds - QCD, ABCD method (cont'd)

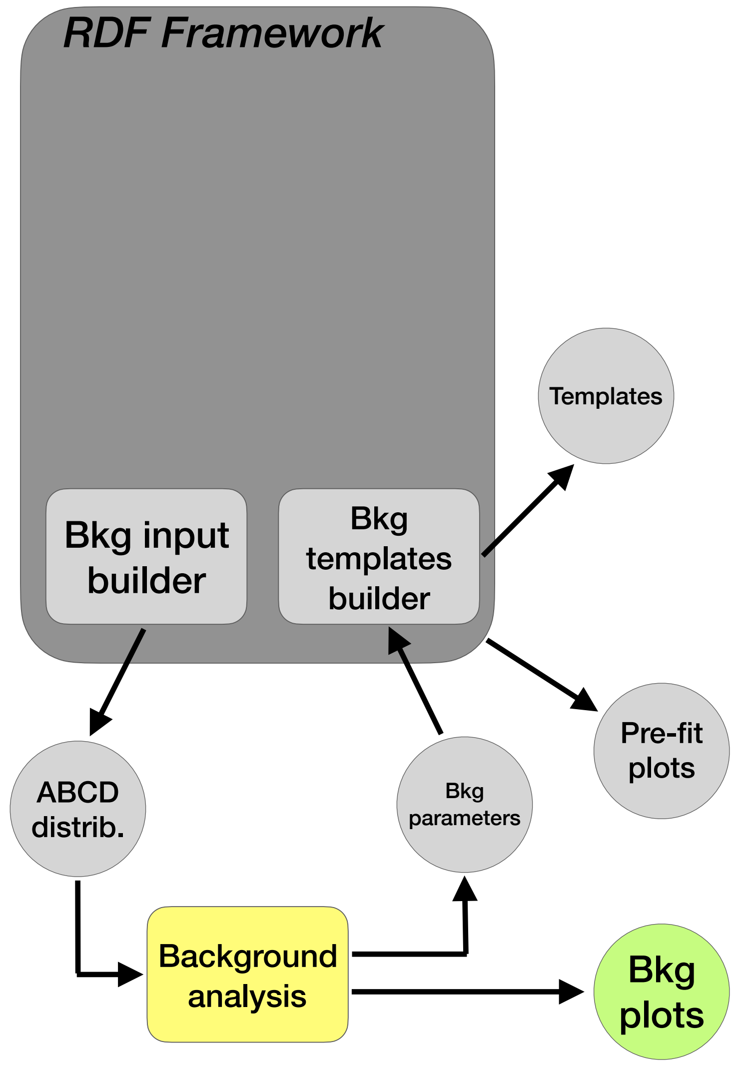


- Measure the fake rate:
  - Select A+C events (binned in p_T^μ and η^μ)
  - measure $f = \dfrac{N_C^{\text{data}} - N_C^{\text{EWK}}}{(N_A + N_C)_{\text{data}} - (N_A + N_C)_{\text{EWK}}}$
  - linear fit of $f(p_T) = m(p_T[\text{GeV}] - 25) + q$
- Measure the prompt rate:
  - select B+D events (binned in p_T^μ and η^μ)
  - measure $p = \dfrac{N_D}{N_D + N_B}\Big|_{\text{EWK}}$
  - error function fit of $p(p_T) = A \cdot \text{erf}(Bp_T + C)$
- Select B+D events (binned in p_T^μ and η^μ)
- Reweight the events to obtain the QCD template:
  - B weight: $\dfrac{f}{p-f}p$
  - D weight: $-\dfrac{f}{p-f}(1-p)$

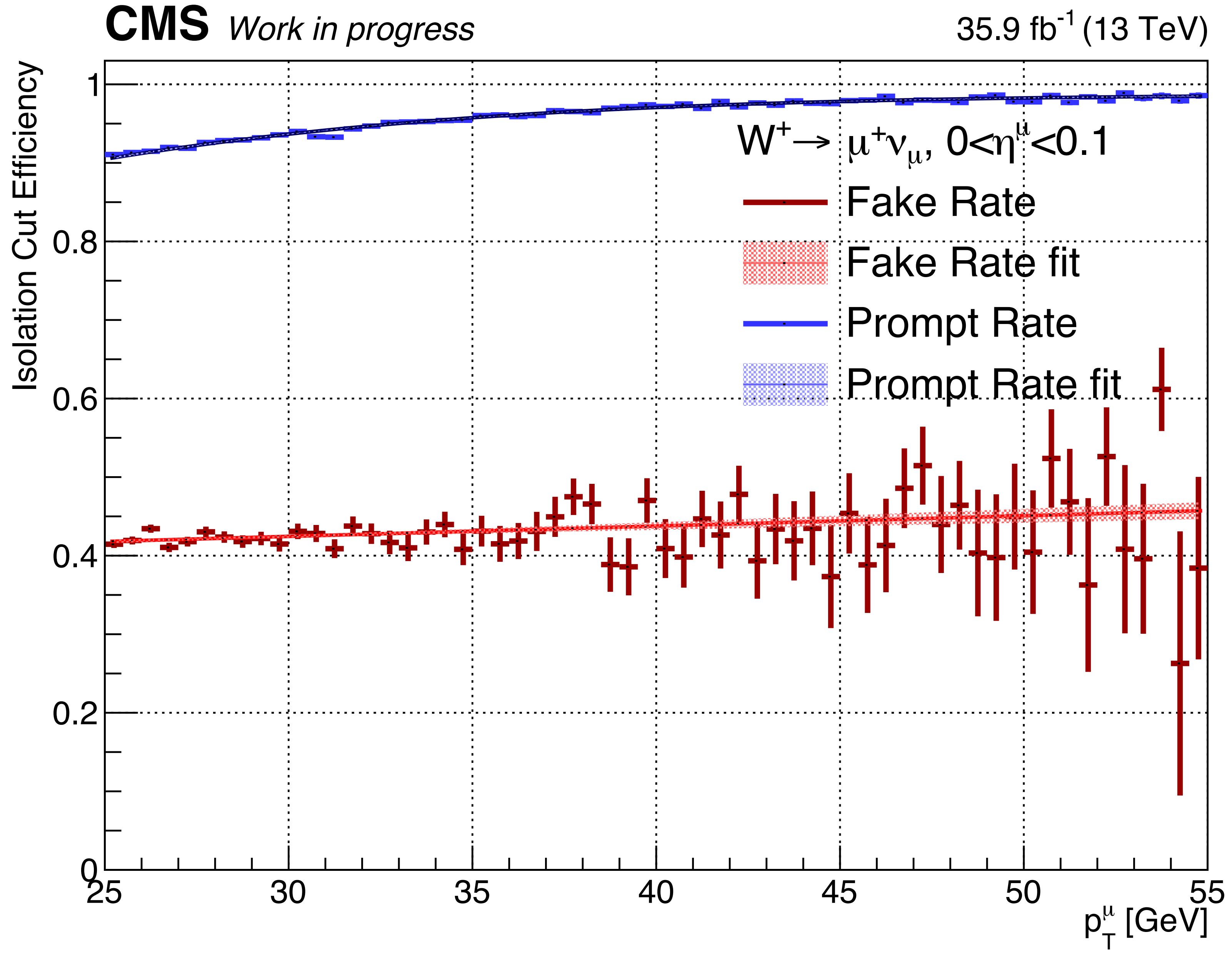
$$N_D^{\text{QCD}} = \frac{f}{p-f}[pN_B^{\text{data}} - (1-p)N_D^{\text{data}}]$$

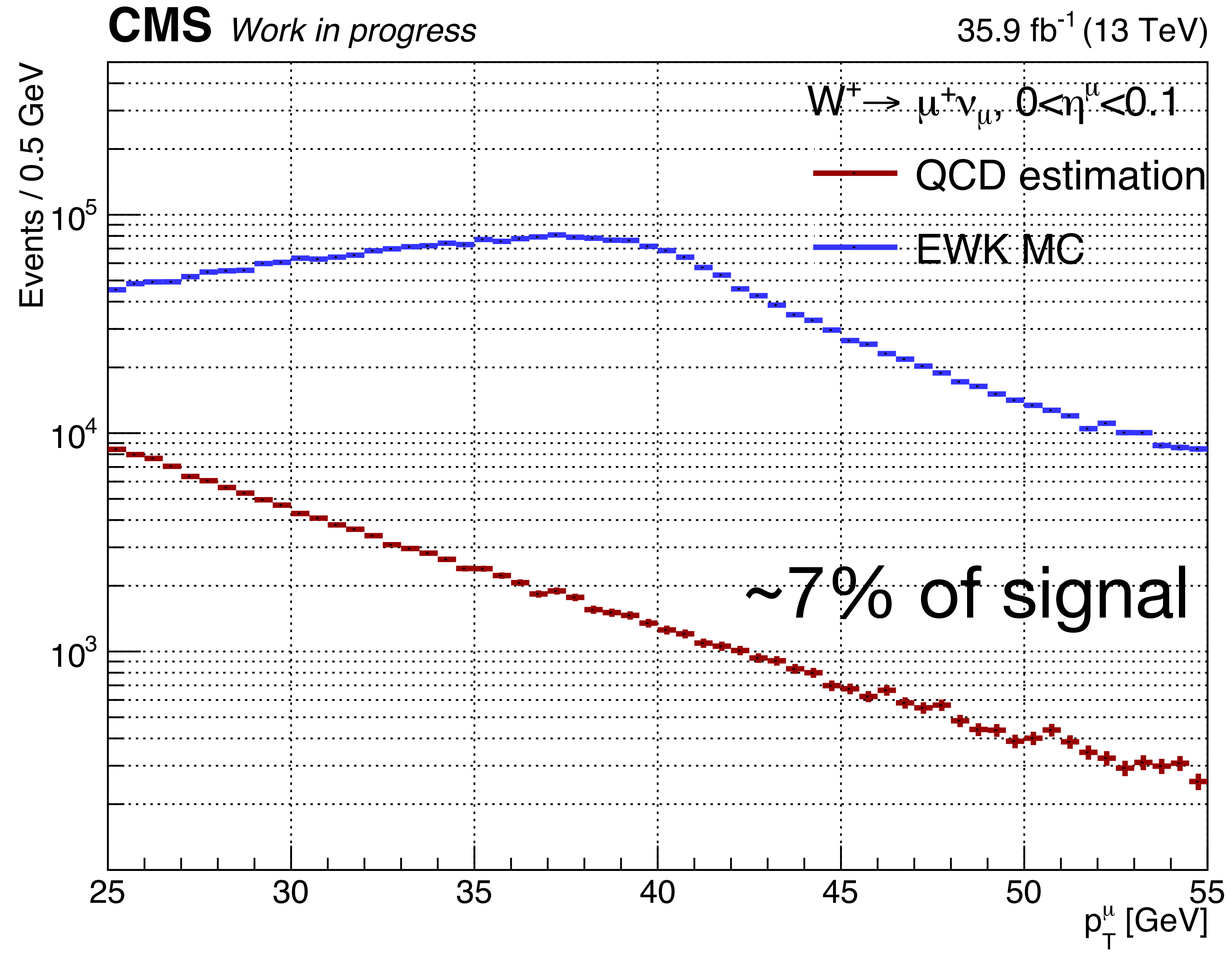


Backgrounds - QCD results

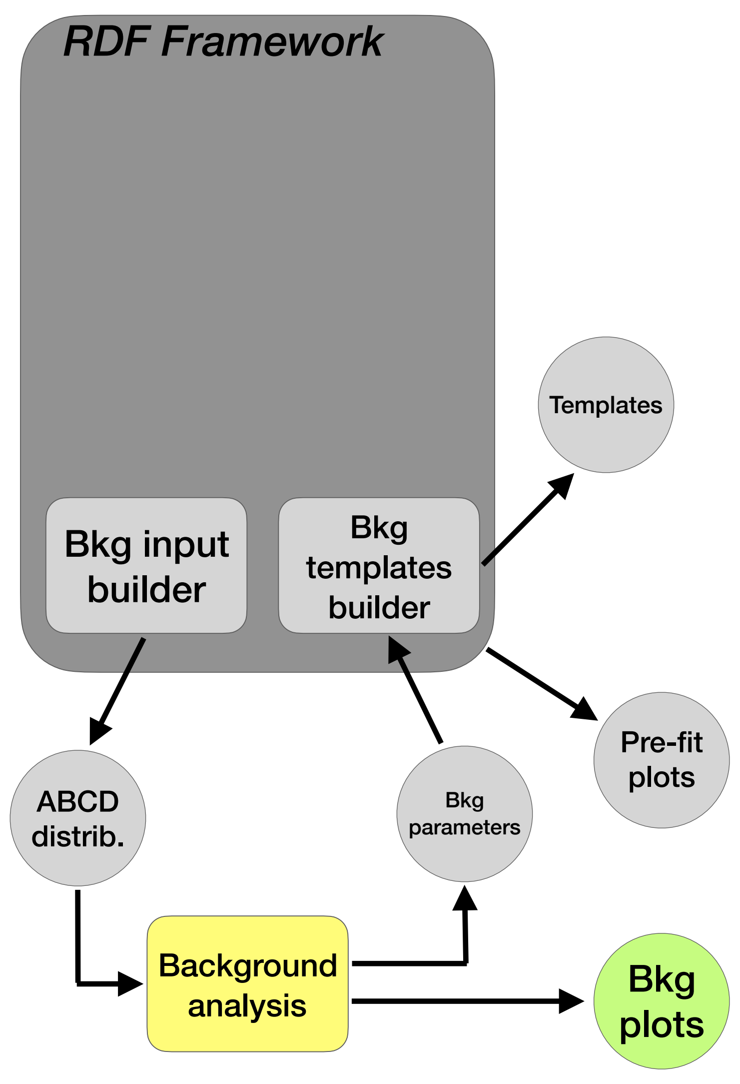


- Measure the fake rate:
  - Select A+C events (binned in p_T^{μ} and η^{μ})
  - measure $f = \dfrac{N_C^{\text{data}} - N_C^{\text{EWK}}}{(N_A + N_C)_{\text{data}} - (N_A + N_C)_{\text{EWK}}}$
  - linear fit of $f(p_T) = m(p_T[\text{GeV}] - 25) + q$
- Measure the prompt rate:
  - select B+D events (binned in p_T^{μ} and η^{μ})
  - measure $p = \dfrac{N_D}{N_D + N_B}\Big|_{\text{EWK}}$
  - error function fit of $p(p_T) = A \cdot \text{erf}(Bp_T + C)$
- Select B+D events (binned in p_T^{μ} and η^{μ})
- Reweight the events to obtain the QCD template:
  - B weight: $\dfrac{f}{p-f}p$
  - D weight: $-\dfrac{f}{p-f}(1-p)$





Backgrounds - QCD systematic uncertainties



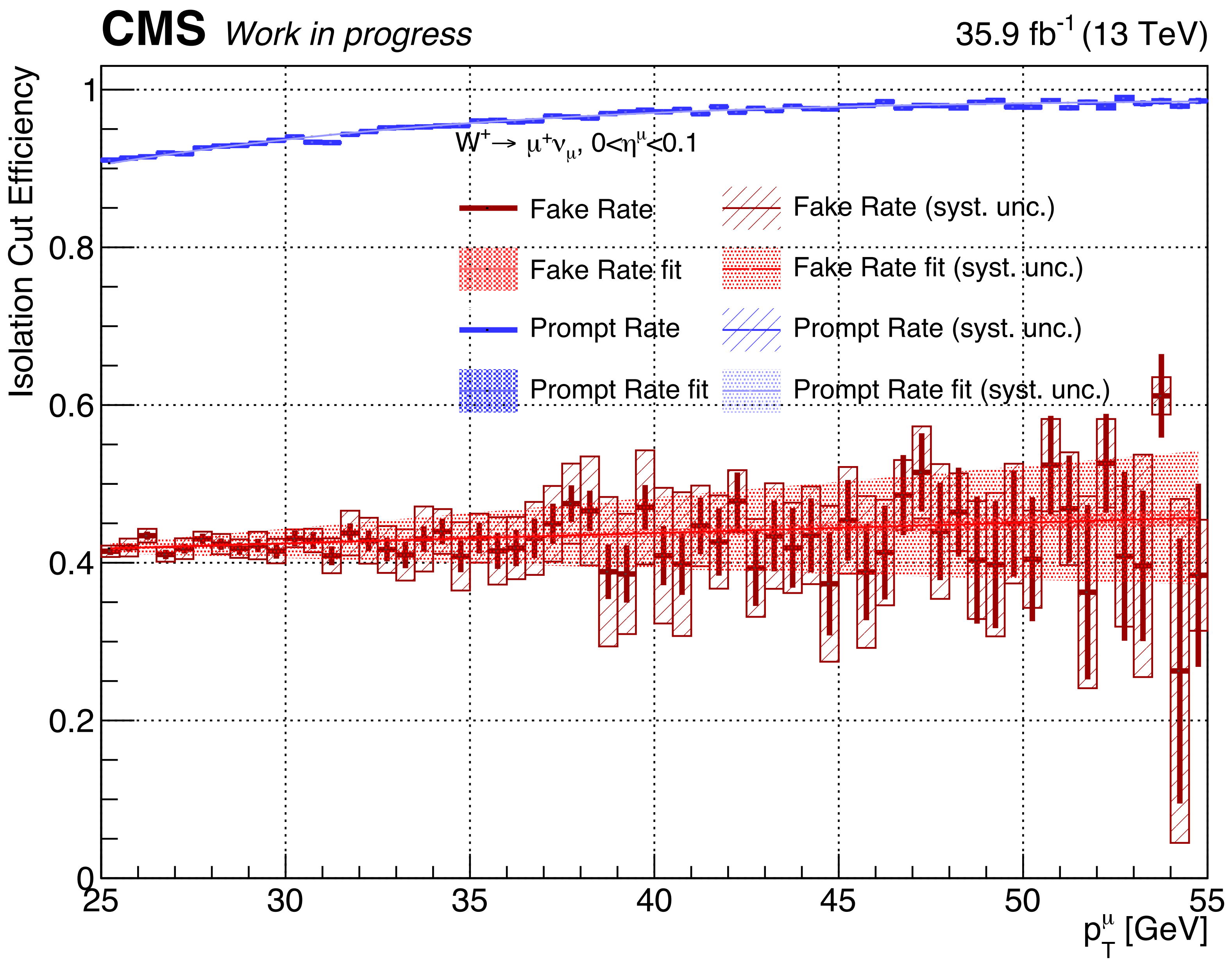
Variation of input variables propagated to fake and prompt rate and then to QCD yield estimation

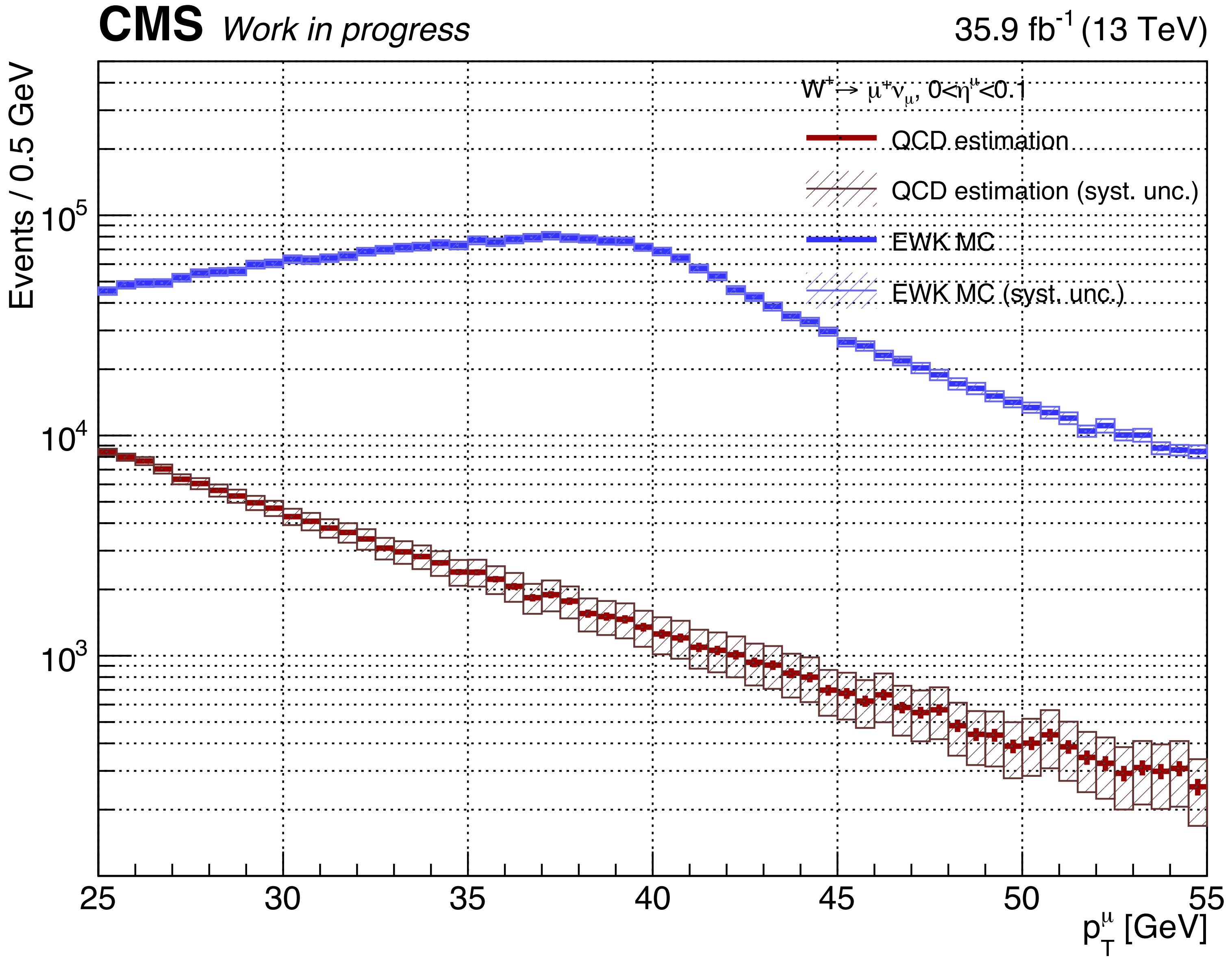
Systematic uncertainties:

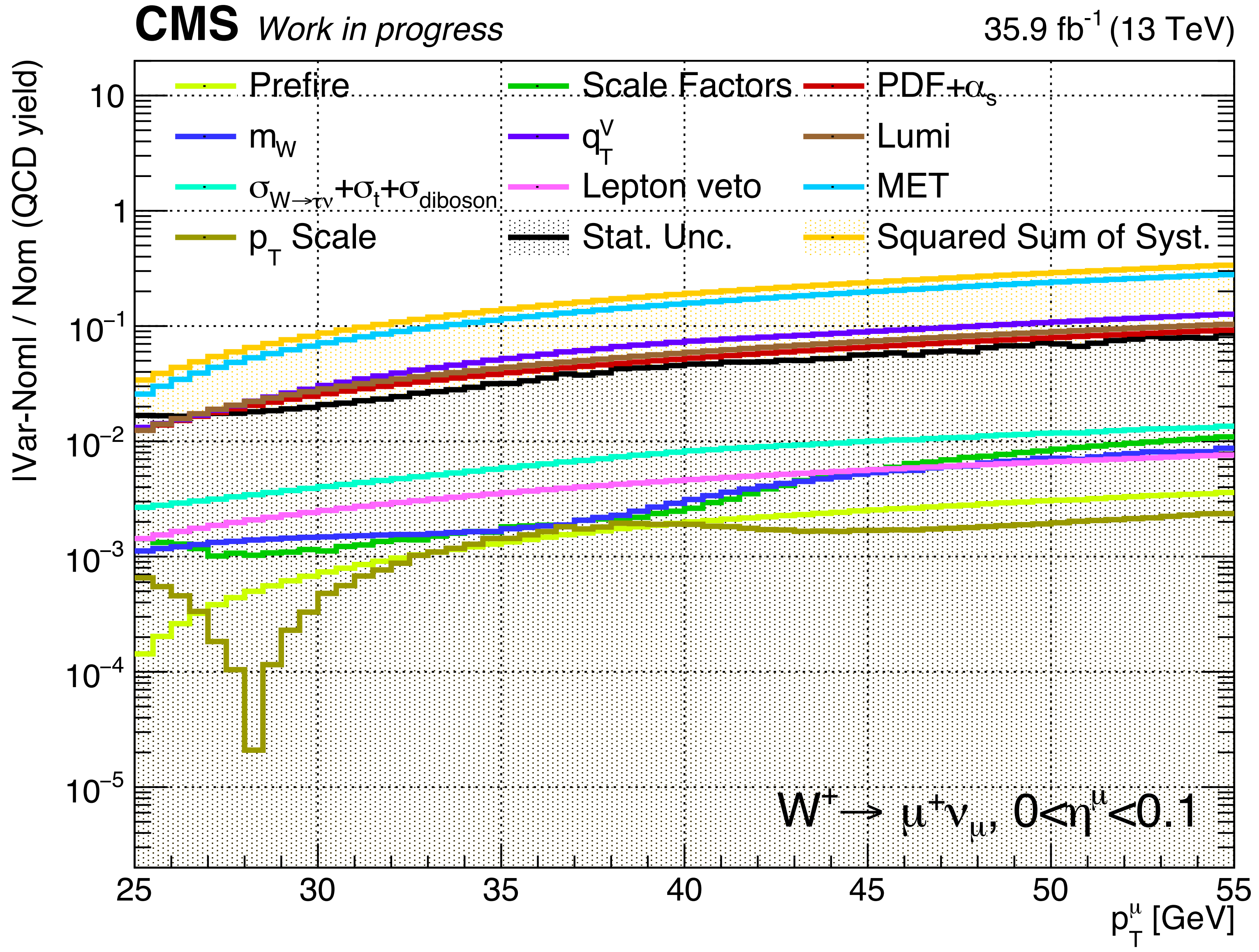
- Experimental: MET, p_T^{μ} scale, Scale Factors, Prefire
- Theoretical: PDF+α_S, q_T^W

Uncertainty on QCD:

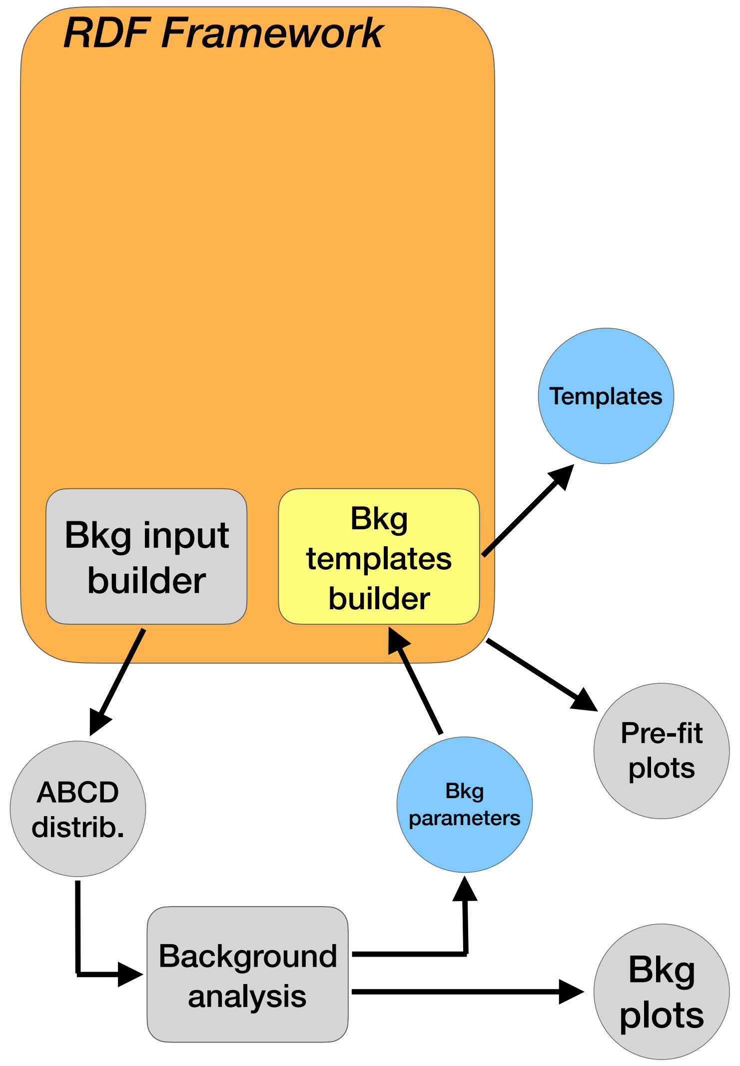
- Statistic: up to 10%
- Systematic: up to 20%



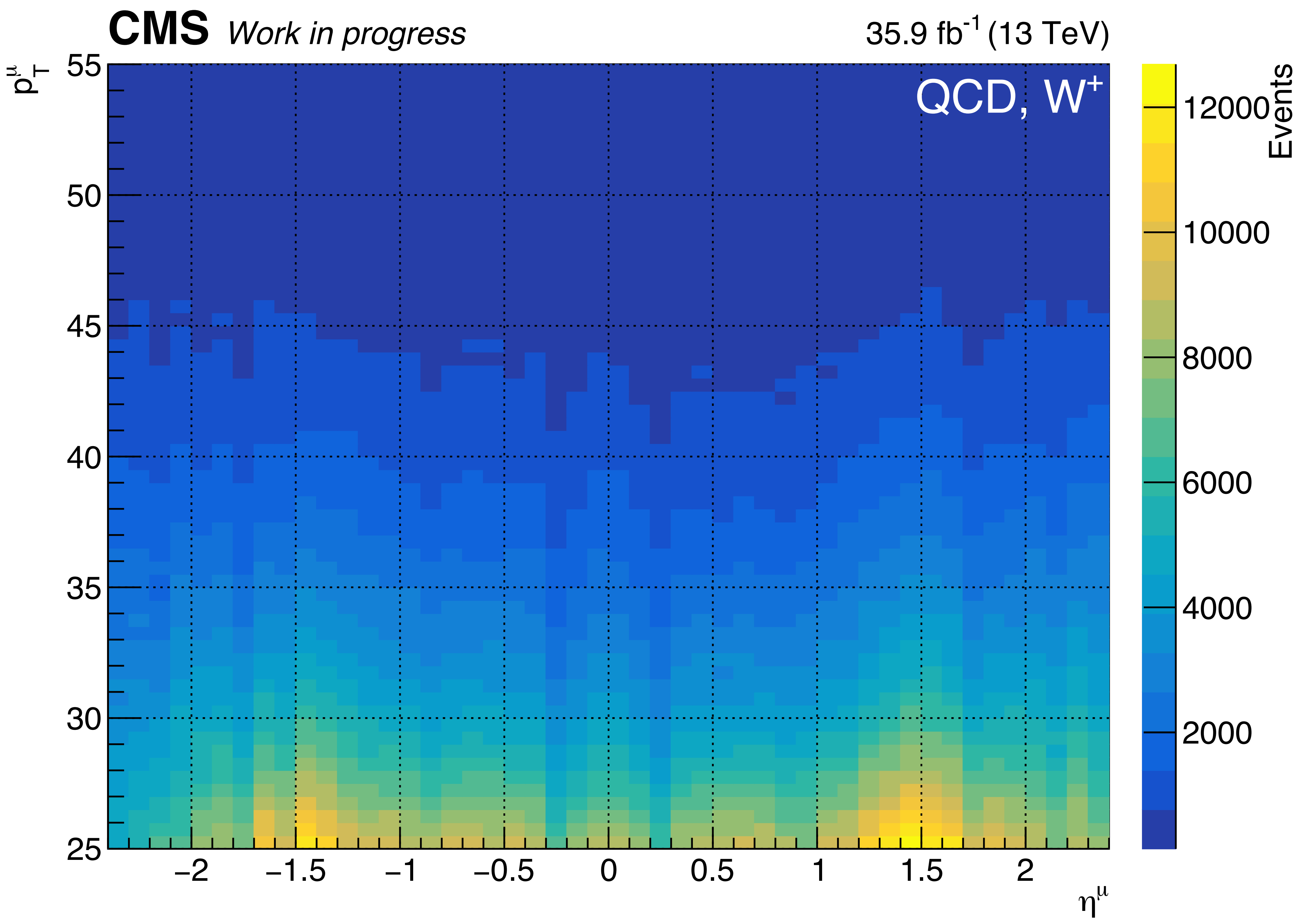


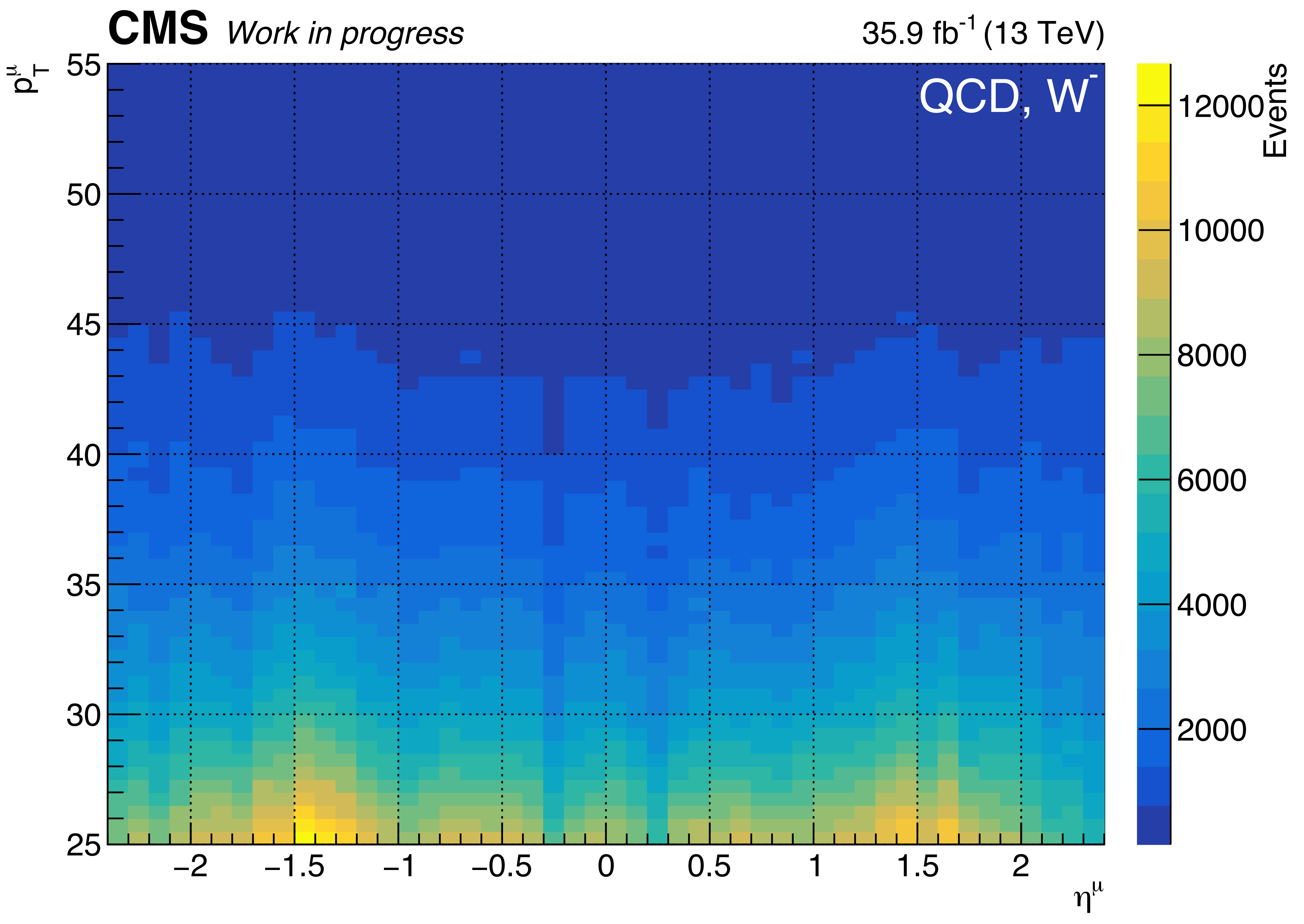


Backgrounds - QCD templates



Using the fake rate and prompt rate parameters —> built the QCD bkg templates





Background yield and syst

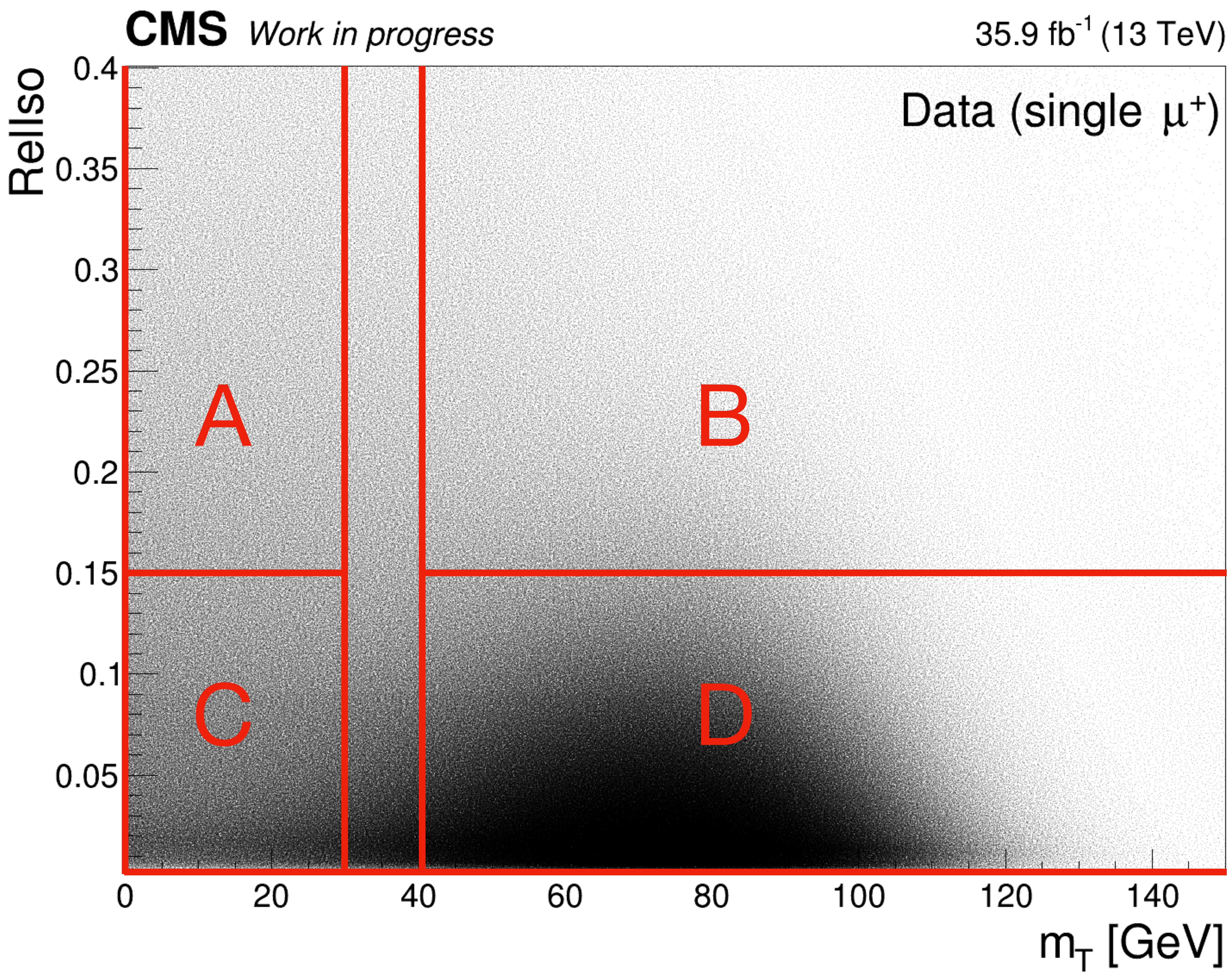
	Events/10^6		Bkg/Signal	
	W^+	W^-	W^+	W^-
Data	132.68	104.13	-	-
$W \to \mu\nu_\mu$	117.94	90.13	-	-
$W \to \tau\nu_\tau$	3.32	2.75	2.82%	3.05%
Drell-Yan $(Z/\gamma*)$	5.75	5.13	4.87%	5.69%
Top	0.77	0.72	0.65%	0.80%
Diboson	0.12	0.11	0.10%	0.12%
QCD	7.27	6.86	6.17%	7.61%

Table 7: Summary of the systematic uncertainty which affect the background estimation and the relative induced variation; the statistical uncertainty is reported for comparison.

Assumption	Approach	yield variation (%)				
		QCD	$Z/\gamma*$	$W \to \tau\nu_\tau$	Top	Diboson
Exp. - p_T^{miss}	input variation	2-30	1	0.5	0.5	0.5
Exp. - p_T^μ scale	input variation	0.1-2	0.01	0.01	0.01	0.01
Exp. - Efficiency SF	input variation	0.1-5	0.5-1	0.5-1	0.5-1	0.5-1
Exp. - L1 Trigger Prefire	input variation	0.1-2	0.1-0.5	0.1-0.5	0.5-1	0.1-0.5
Exp. - Lepton Veto	input variation	0.1-1	2	-	-	-
Exp. - Luminosity	input variation	1-10	2.5	2.5	2.5	2.5
Theo. - PDF, α_s	input variation	1-10	2	2	-	-
Theo. - m_W	input variation	0.1-1	-	-	-	-
Theo. - $q_T^{W,Z}$	input variation	2-15	5	3	-	-
Theo. - σ_t, σ_τ, $\sigma_{diboson}$	input variation	0.1-1	-	4	6	16
$f(M_T) = $ const	extrapolation study	0-10	-	-	-	-
$f(p_T) =$linear	function variation	0	-	-	-	-
$p(p_T) =$erf	function variation	0	-	-	-	-
finite data statistics	uncertainity propagation	2-10	1-5	2	6	20

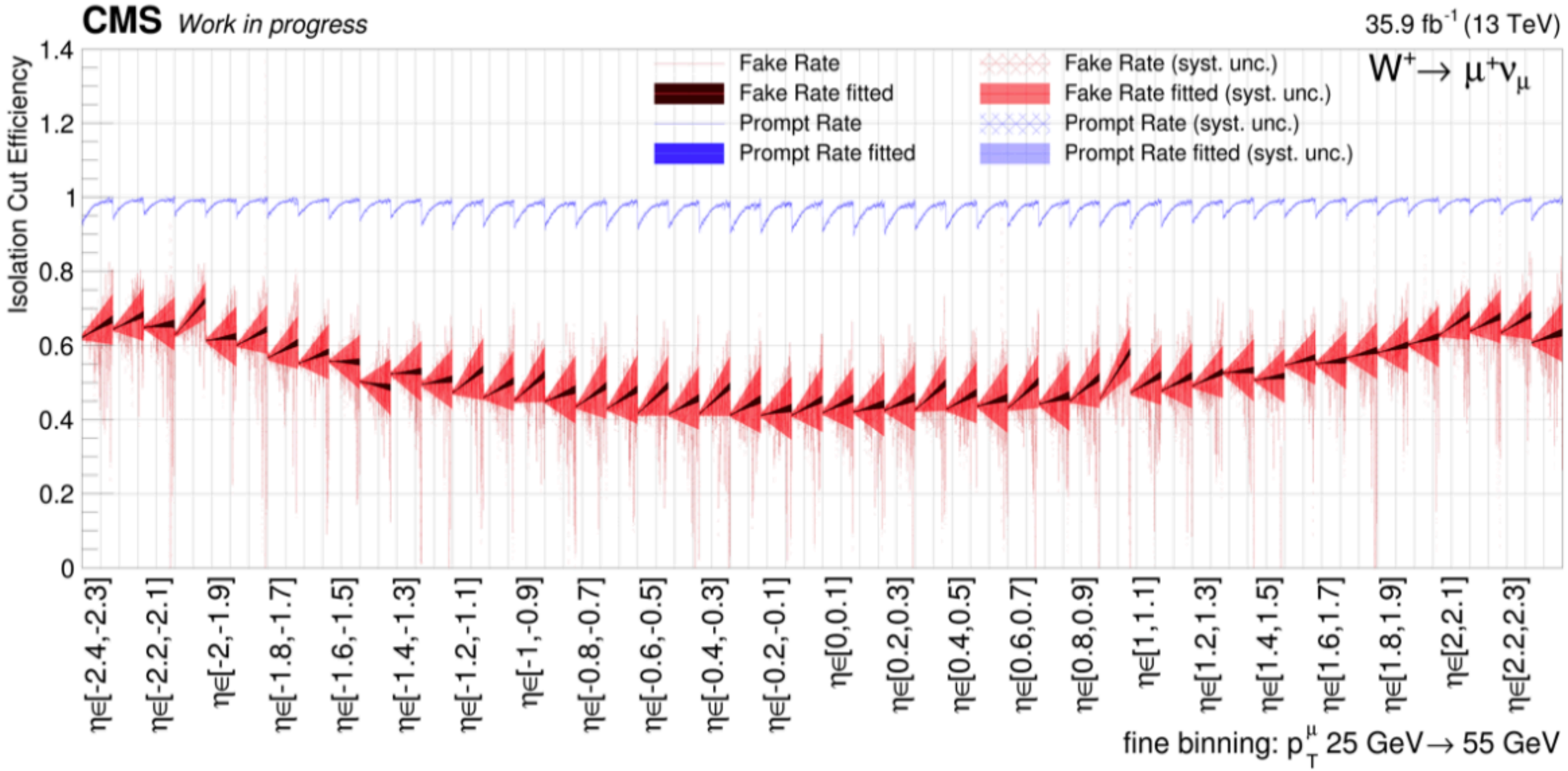
Backgrounds - ABCD derivation

$$
\begin{aligned}
N_D^{\text{QCD}} &= f(N_D + N_B)_{\text{QCD}} \\
&= f(N_D + N_B)_{\text{data}} - f(N_B + N_B)_{\text{EWK}} \\
&= f(N_D + N_B)_{\text{data}} - \frac{f}{p} N_D^{\text{EWK}} \\
&= f(N_D + N_B)_{\text{data}} - \frac{f}{p} (N_D^{\text{data}} - N_D^{\text{QCD}}), \\
N_D^{\text{QCD}} (\frac{p-f}{p}) &= f\left[N_B^{\text{data}} + N_D^{\text{data}} (\frac{p-1}{p})\right], \\
N_D^{\text{QCD}} &= \frac{f}{p-f}\left[p N_B^{\text{data}} - (1-p) N_D^{\text{data}}\right].
\end{aligned}
$$

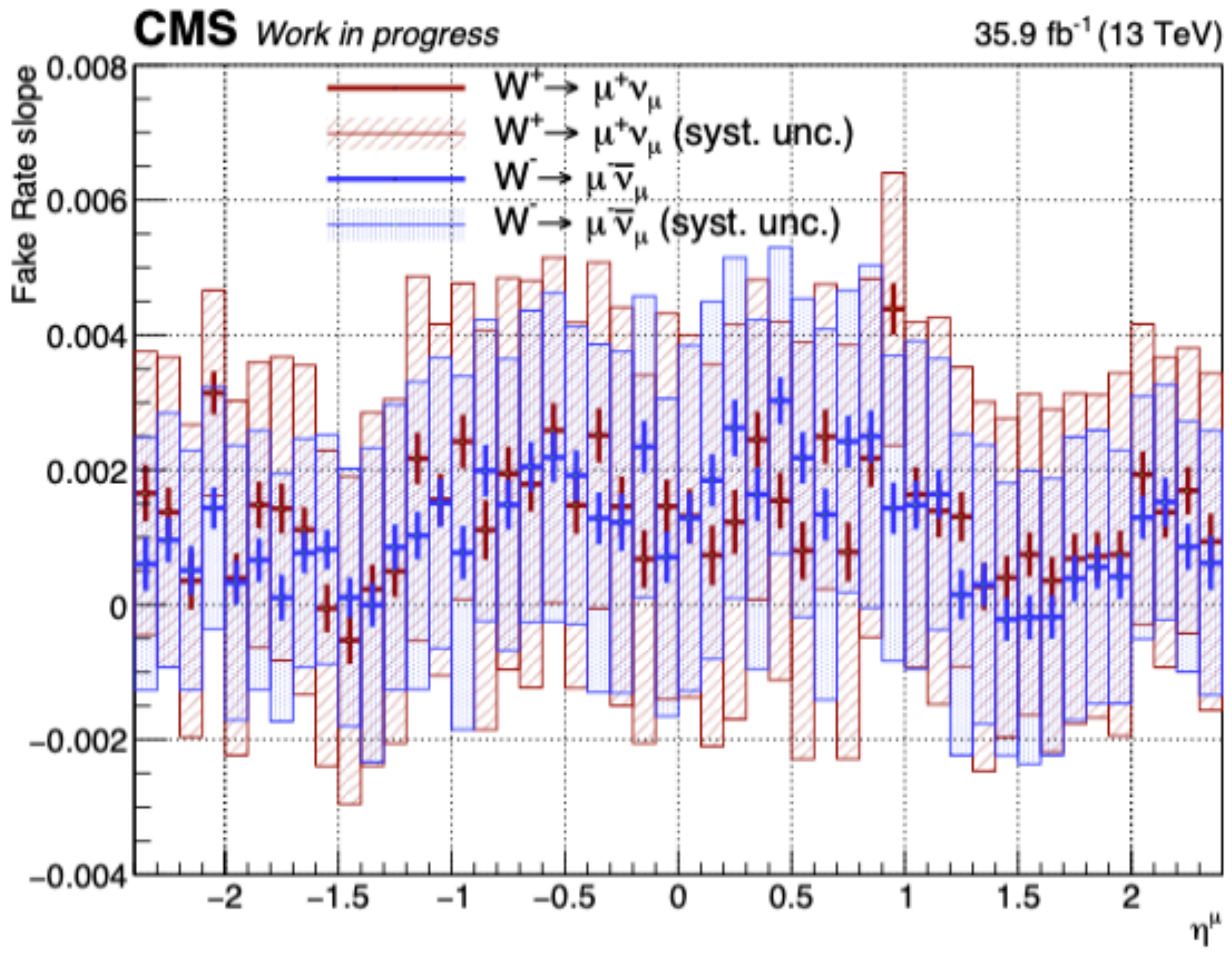


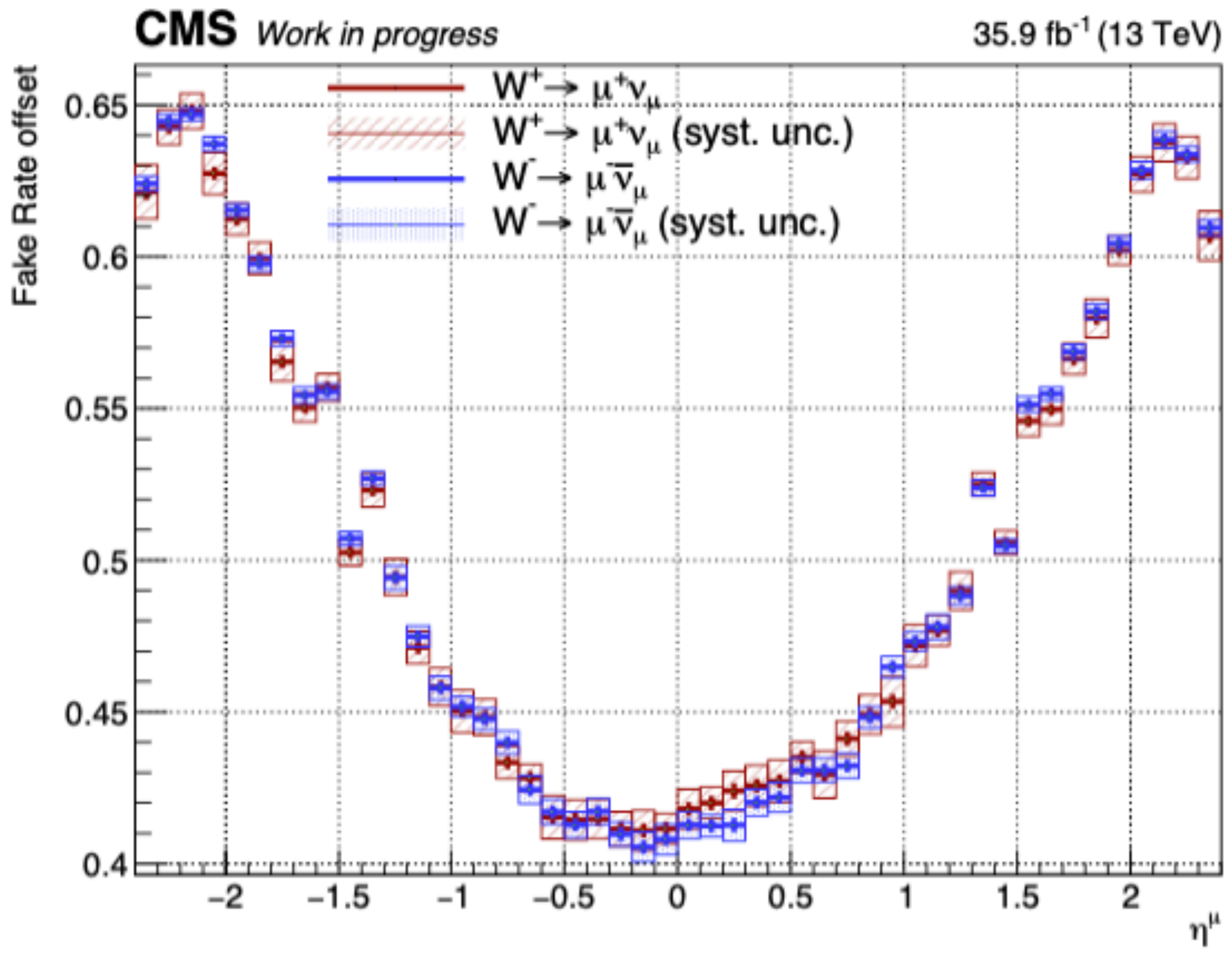
Prompt rate fit: $p(p_T) = A \frac{2}{\sqrt{\pi}} \int_0^{Bp_T + C} e^{-t^2} dt$

QCD bkg - unrolled fake and prompt rate

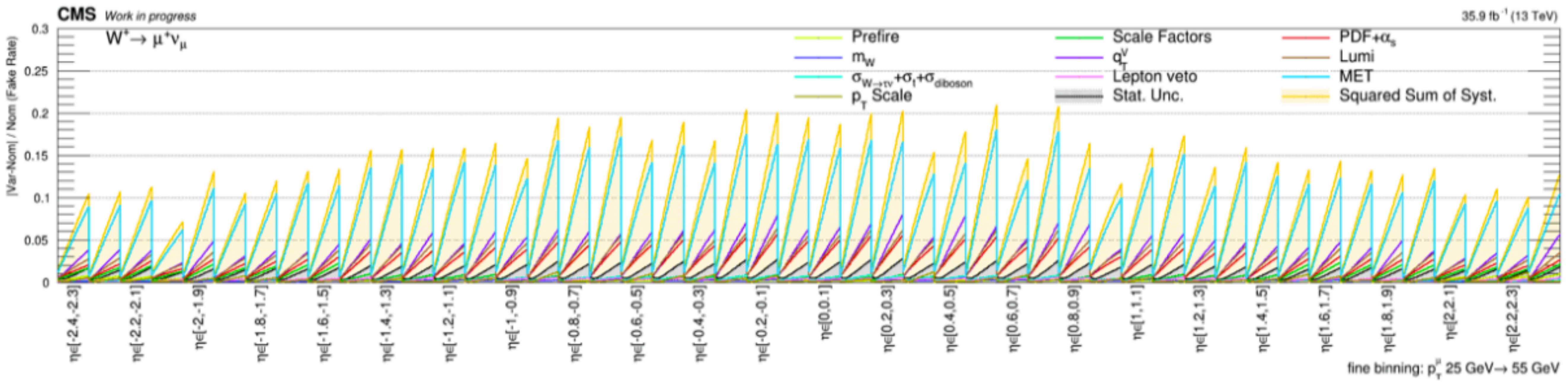


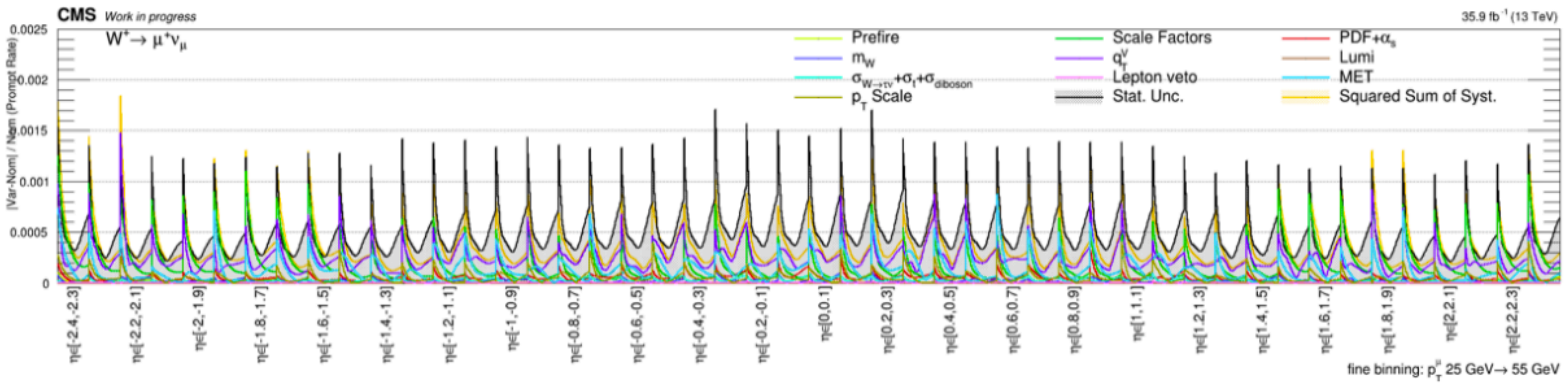
QCD bkg -fake rate parameters

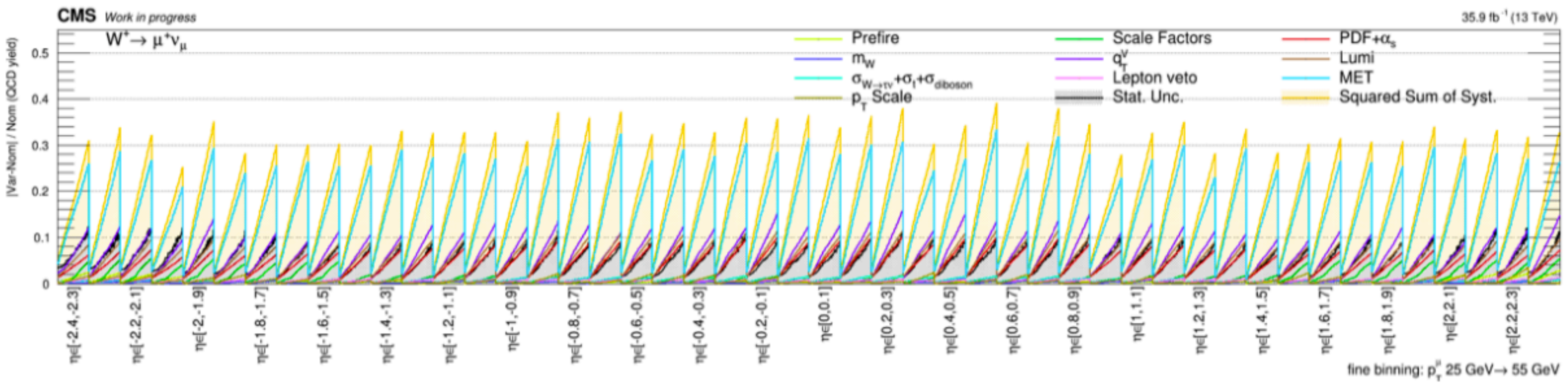




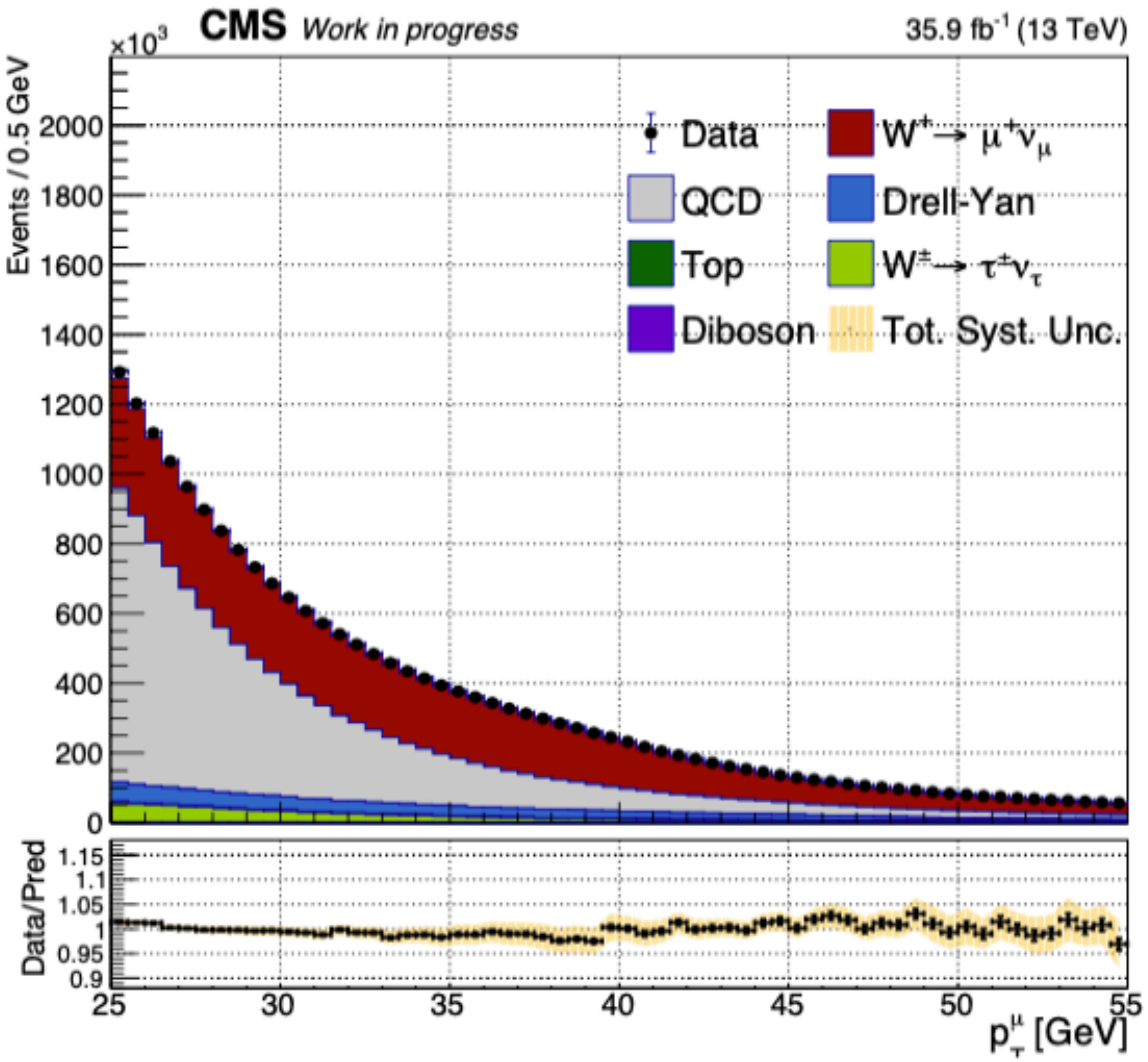
QCD bkg - unrolled syst

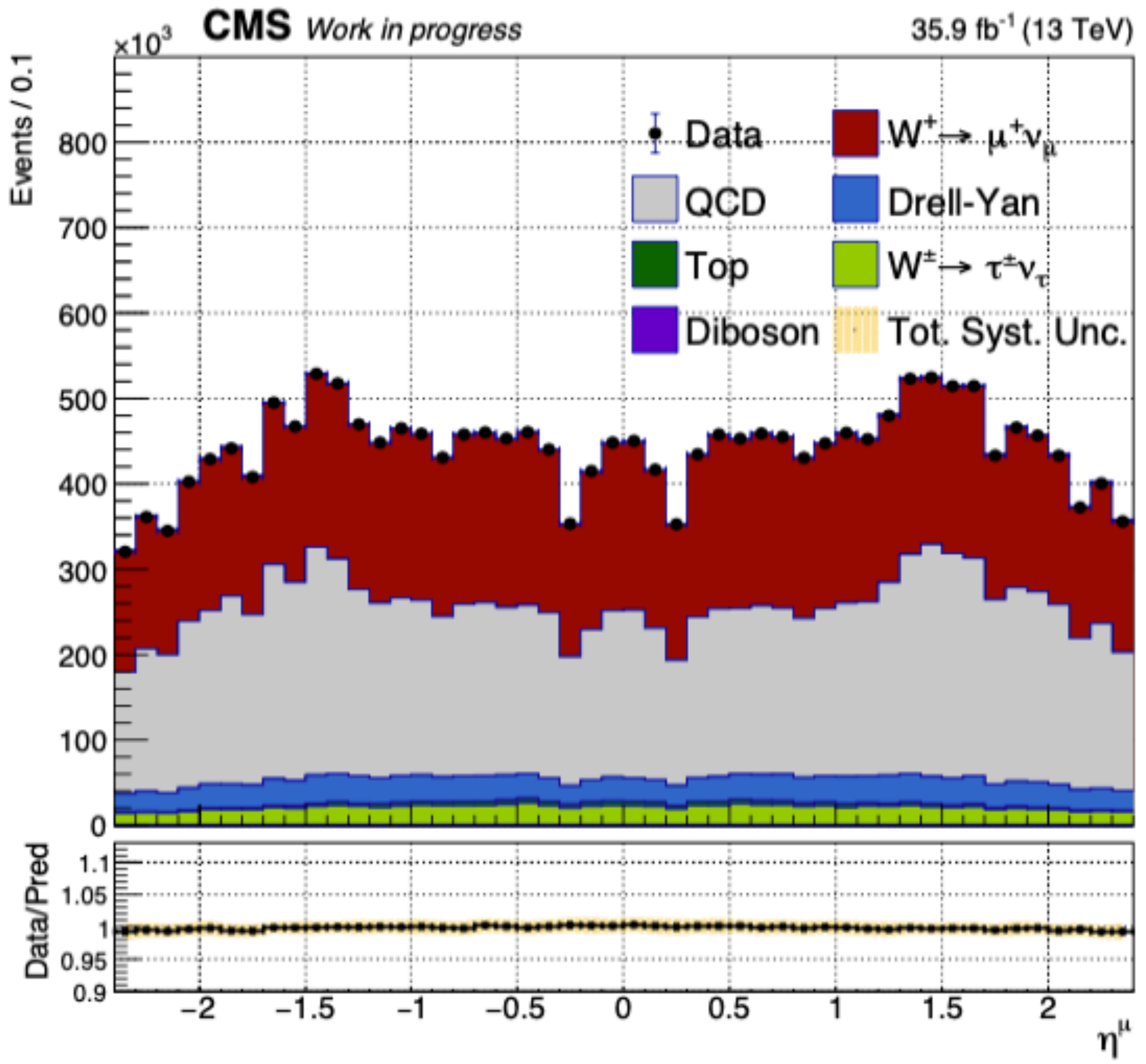






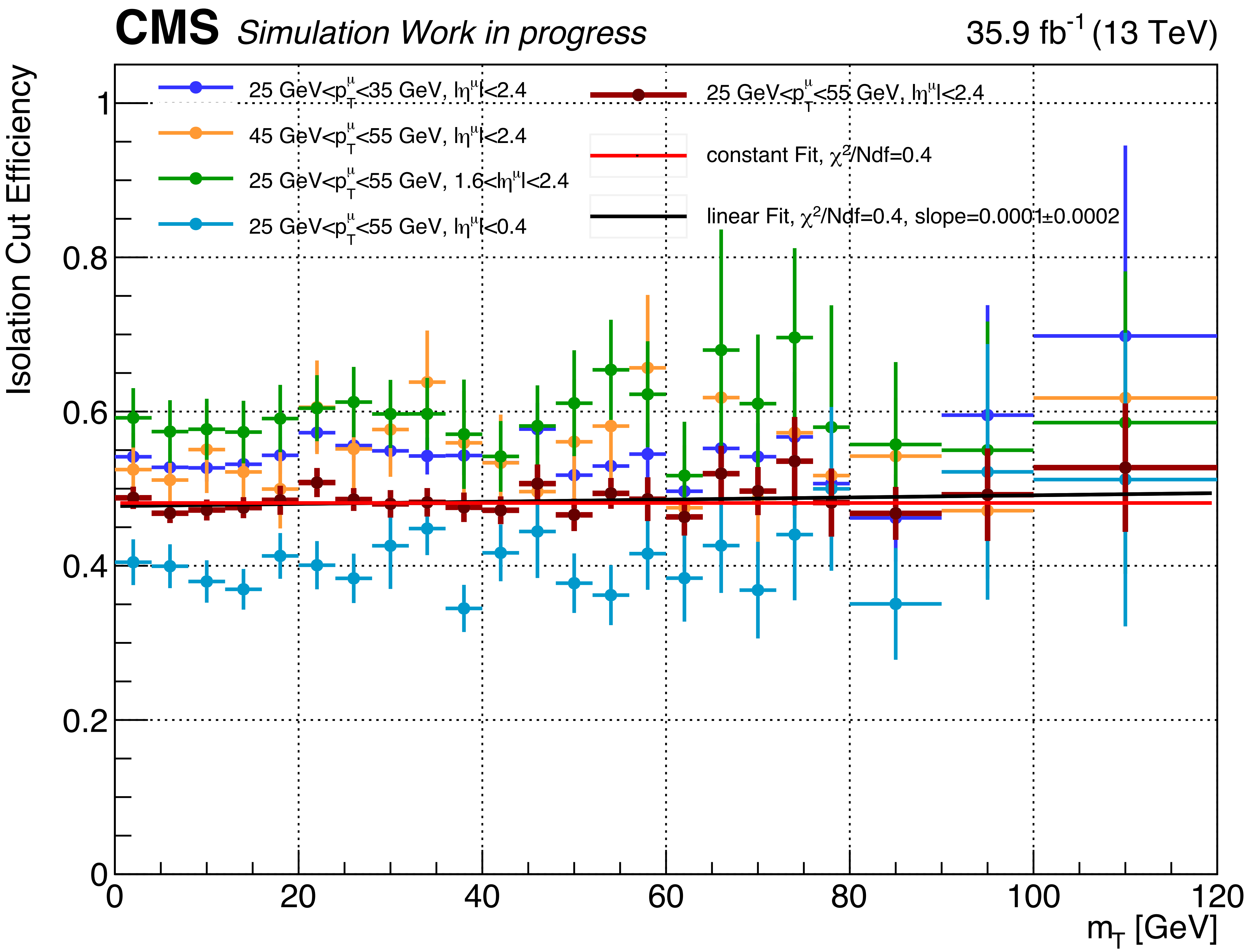
QCD bkg - closure in sideband





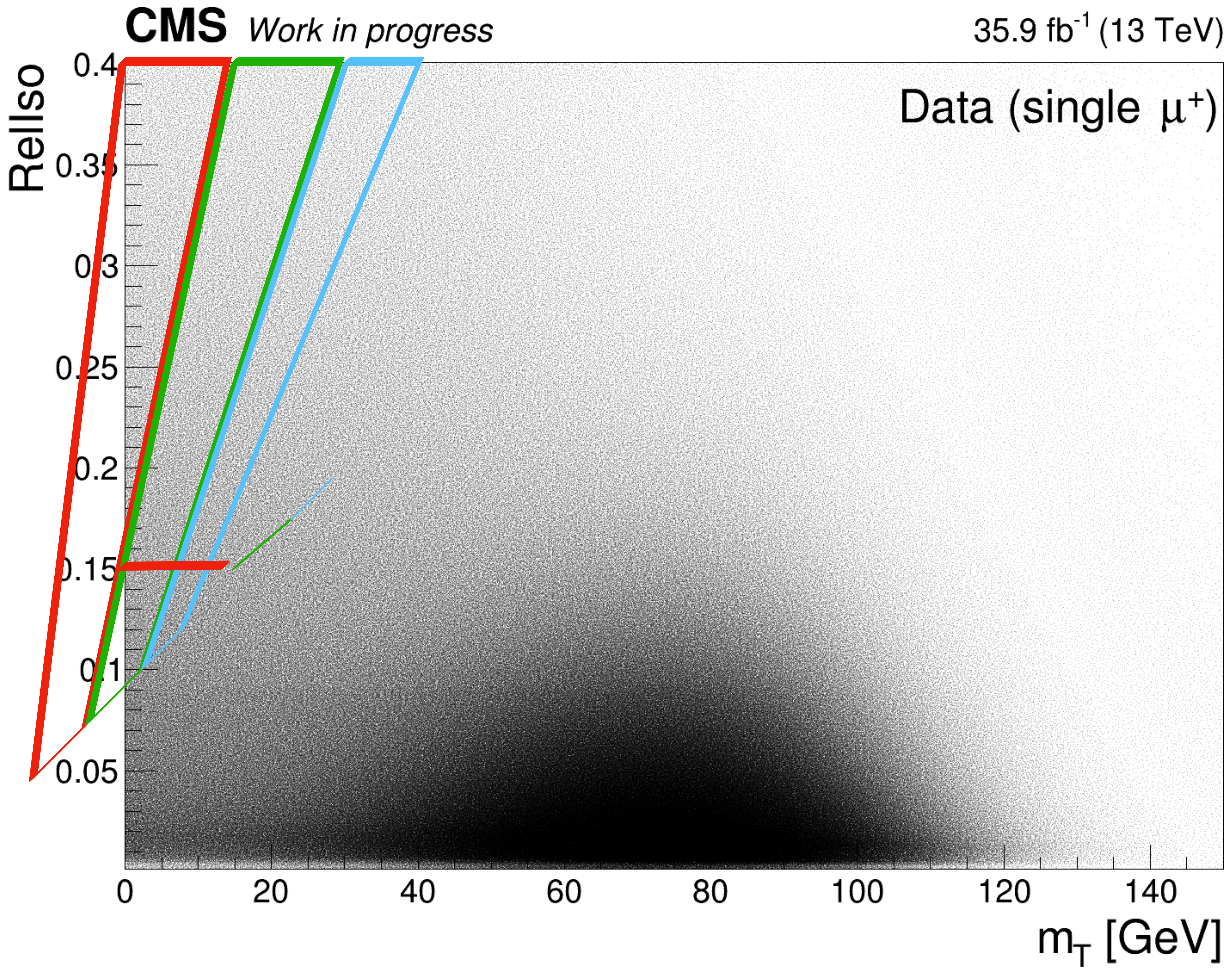
Bkg - validity of ABCD - MC check

- If MT dependence of RelIso?
- evaluated fake rate on QCD MC, only to check the not-correlation
- Different p_T^μ and η^μ bin plotted vs m_T
- linear fit—> slope~0
- constant fit—-> ok!



Bkg - validity of ABCD - data check

- If MT dependence of RelIso?
- evaluated fake rate in slice of m_T using usual data-driven technique
- extrapolated in signal region
- discrepancy at 5-10% compared estimate done for signal region (i.e. measuring fake rate 0-30 GeV)
- Discrepancy covered by uncertainties

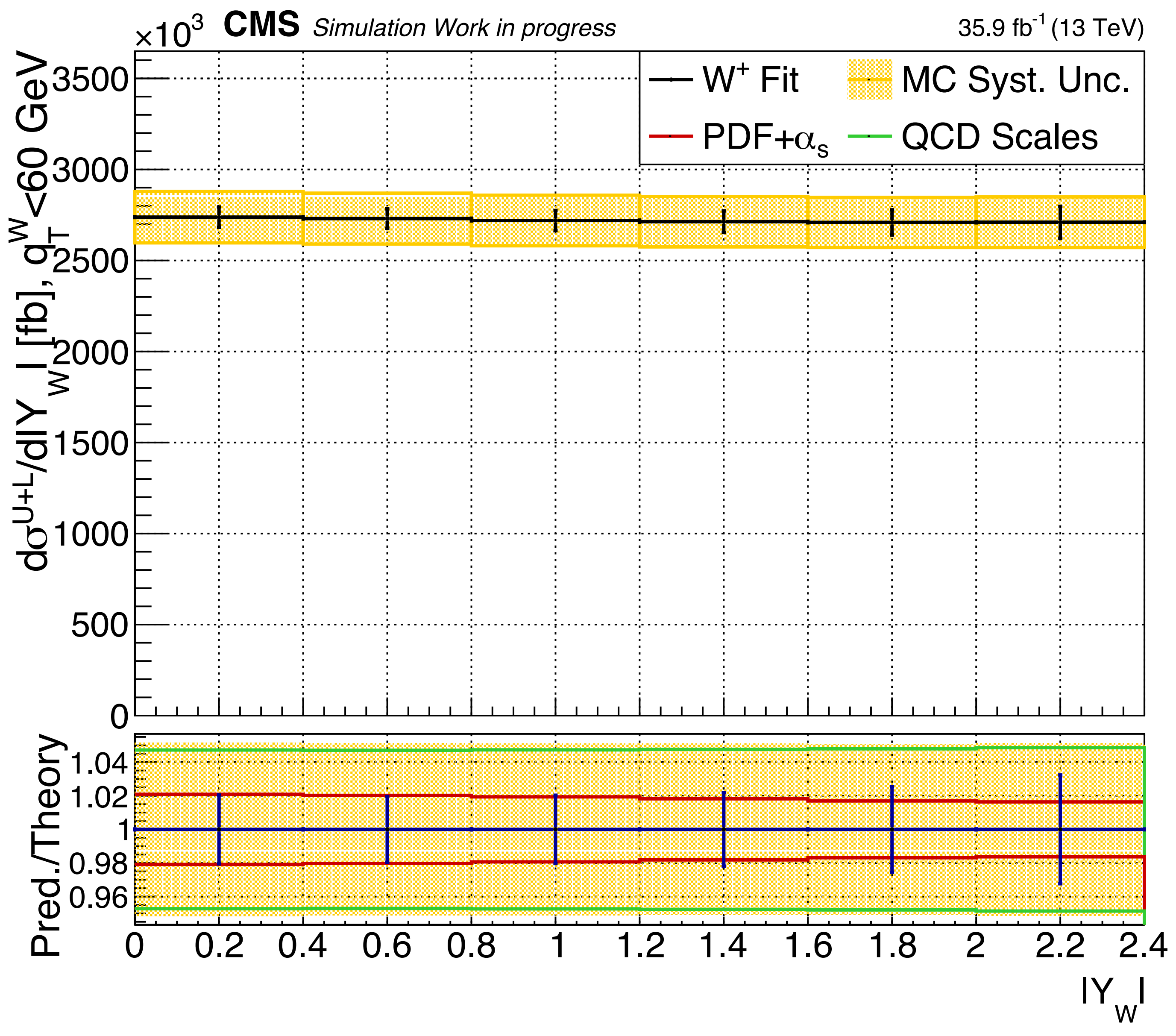


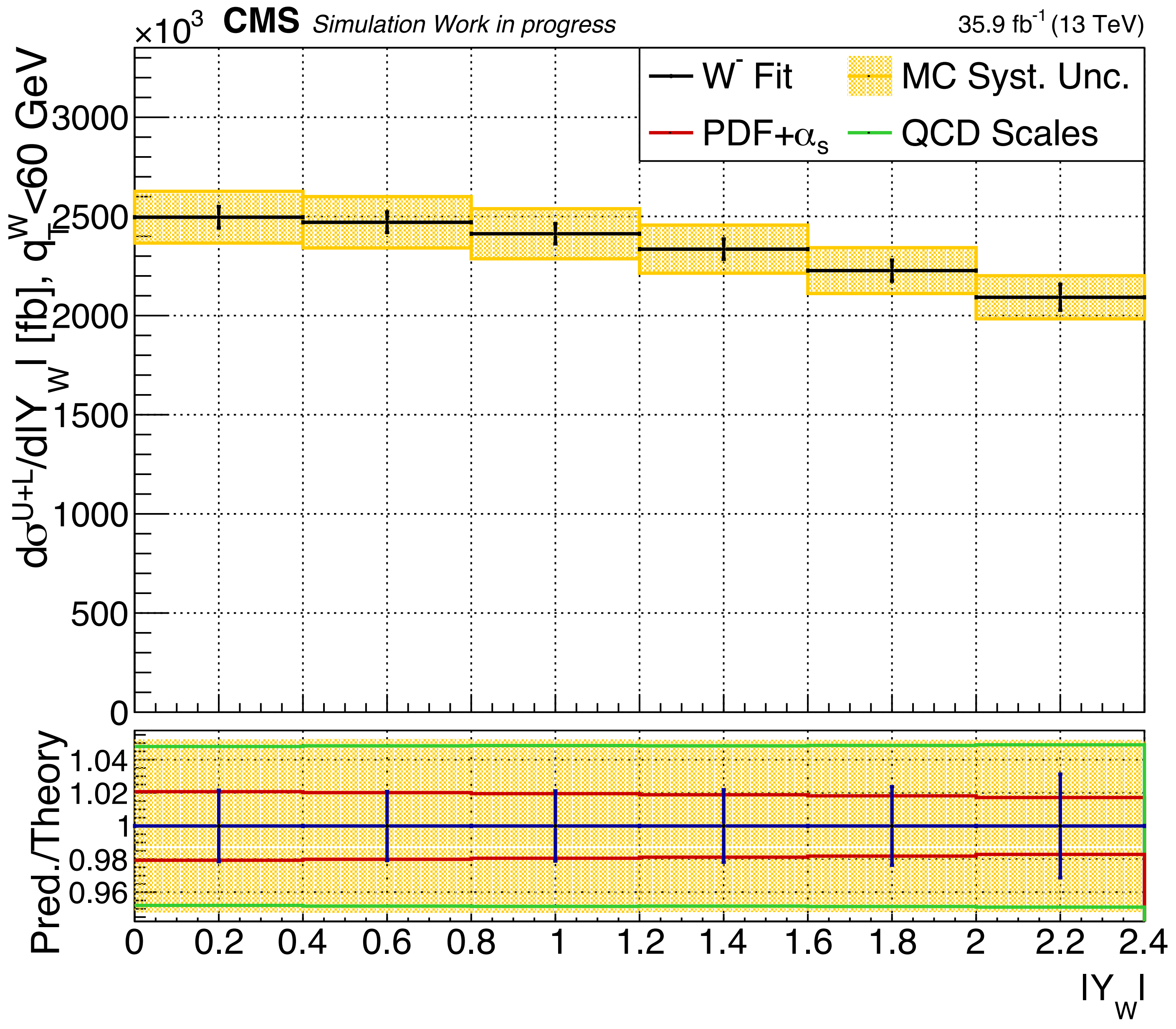
Fit - Asimov dataset results - A_4

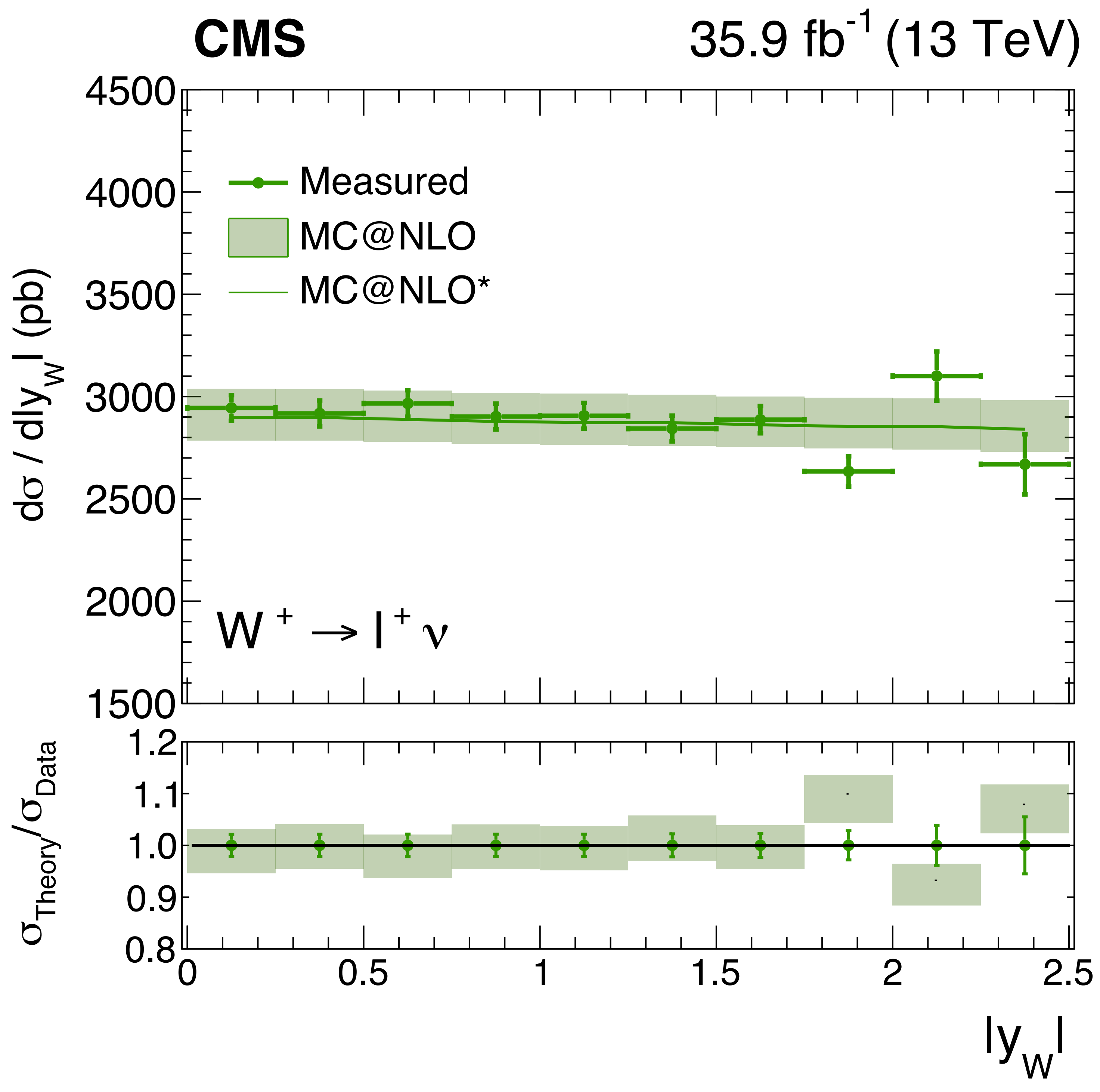
Nuisances impacts similar to σ^{U+L}

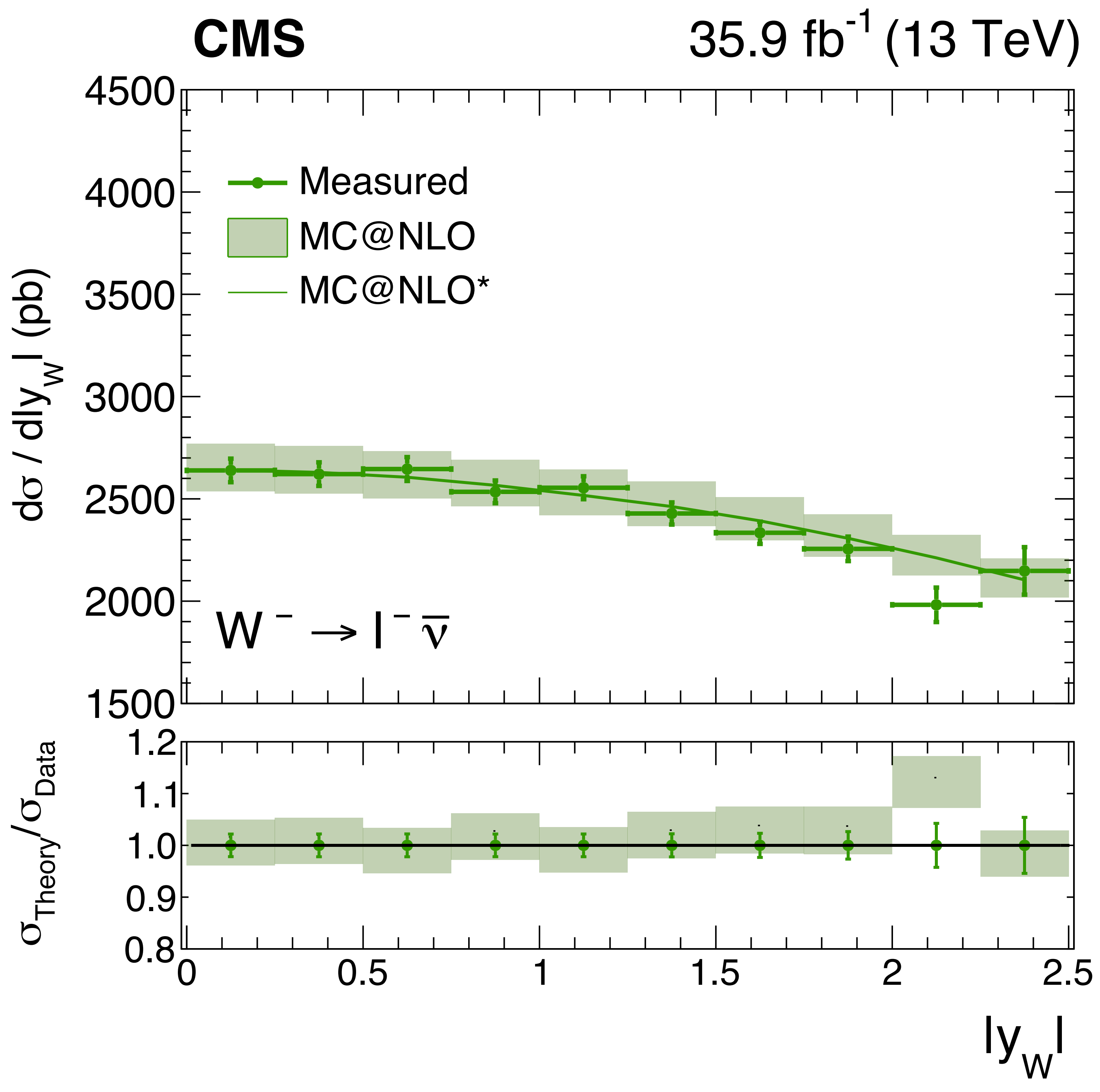
SMP-18-012 comparison

NB: discrepancies for $q_T^W < 60$ GeV cut





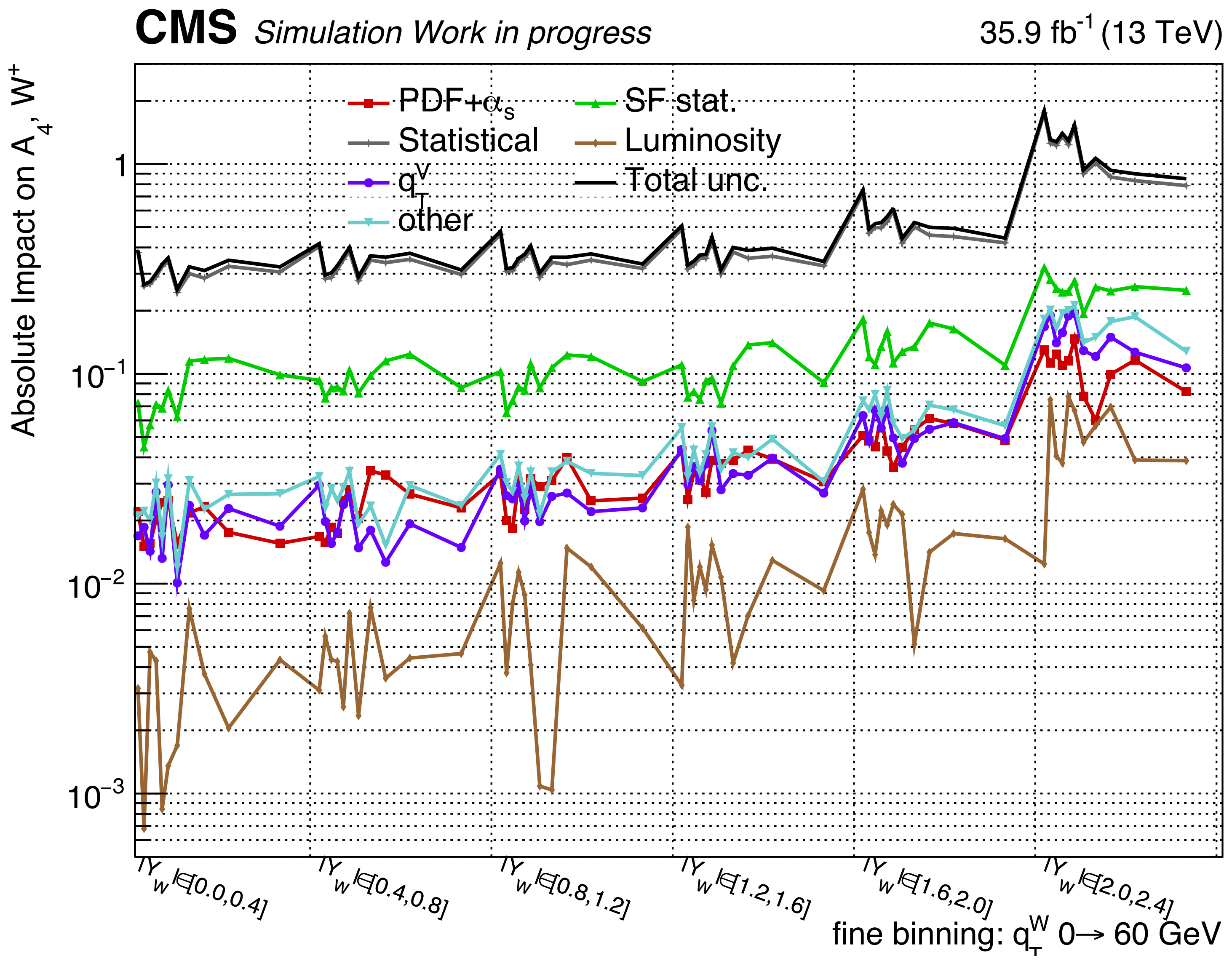




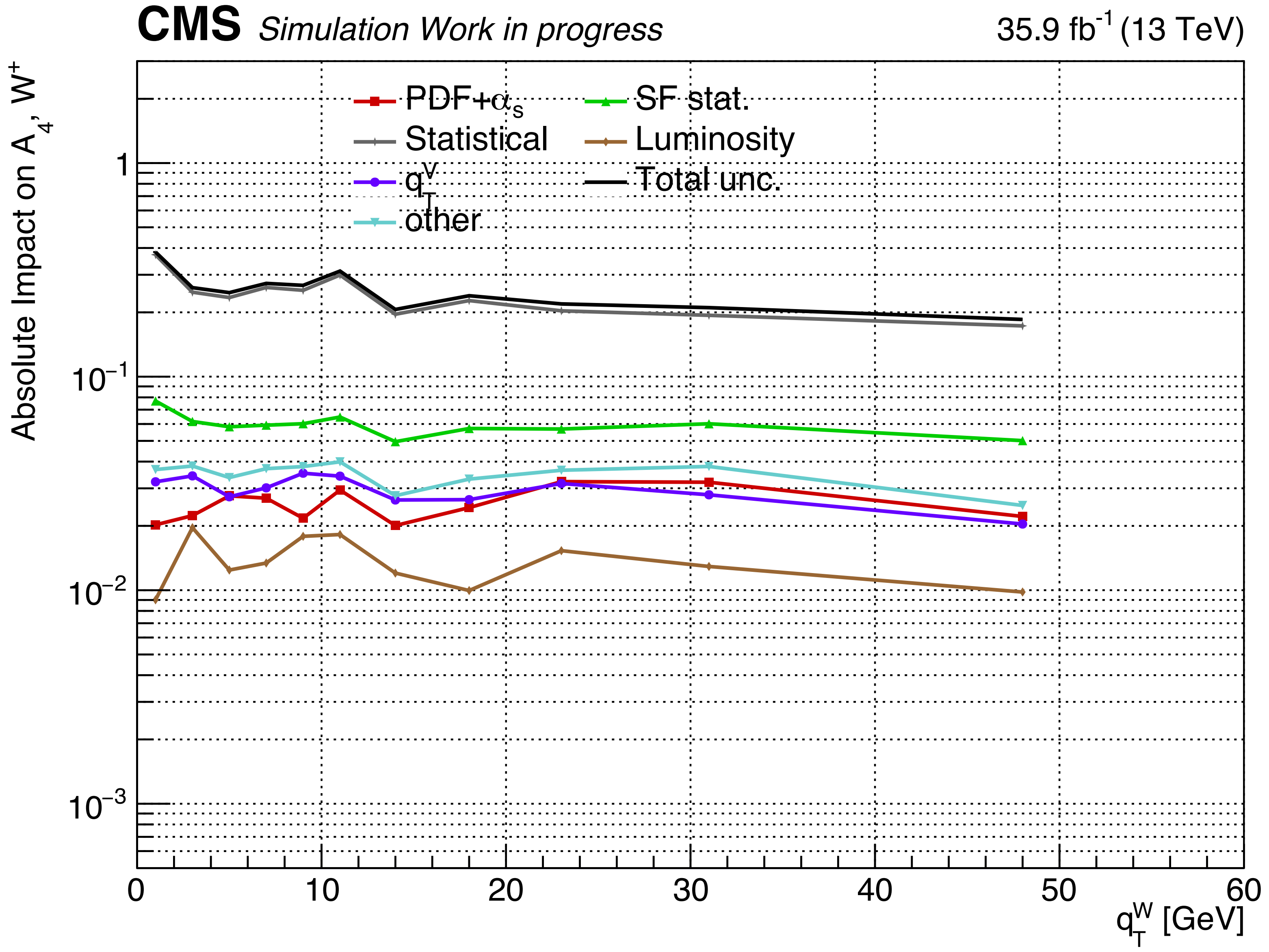
Impact definitions

- $I_{\theta_k}(\mu_p) = \dfrac{V_{p,k}}{\sigma_k},$
- $V_{p,k}$ = covariance matrix of μ_p and θ_k
- $\sigma_k =$ post-fit uncertainty on θ_k
- In the limit of gaussian uncertainty equivalent to shift induced on μ_p as θ_k fixed to $\pm 1 \sigma_k$ and all the others parameters are profiled as usual

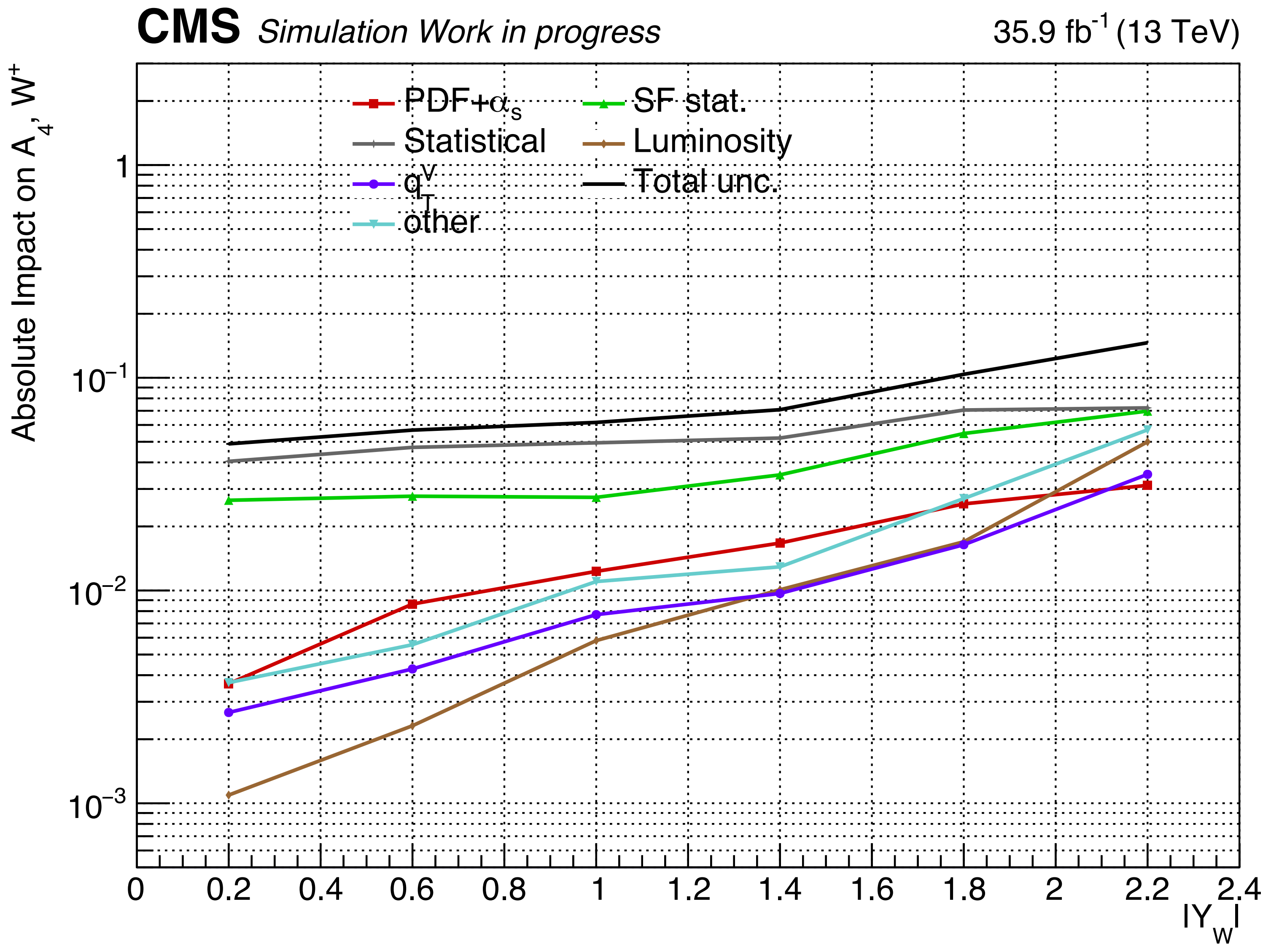
A_4 impacts



CMS Simulation Work in progress
35.9 fb-1 (13 TeV)
Absolute Impact on A4, W+
PDF+αs
SF stat.
Statistical
Luminosity
qTV
Total unc.
other
fine binning: qTW 0→ 60 GeV

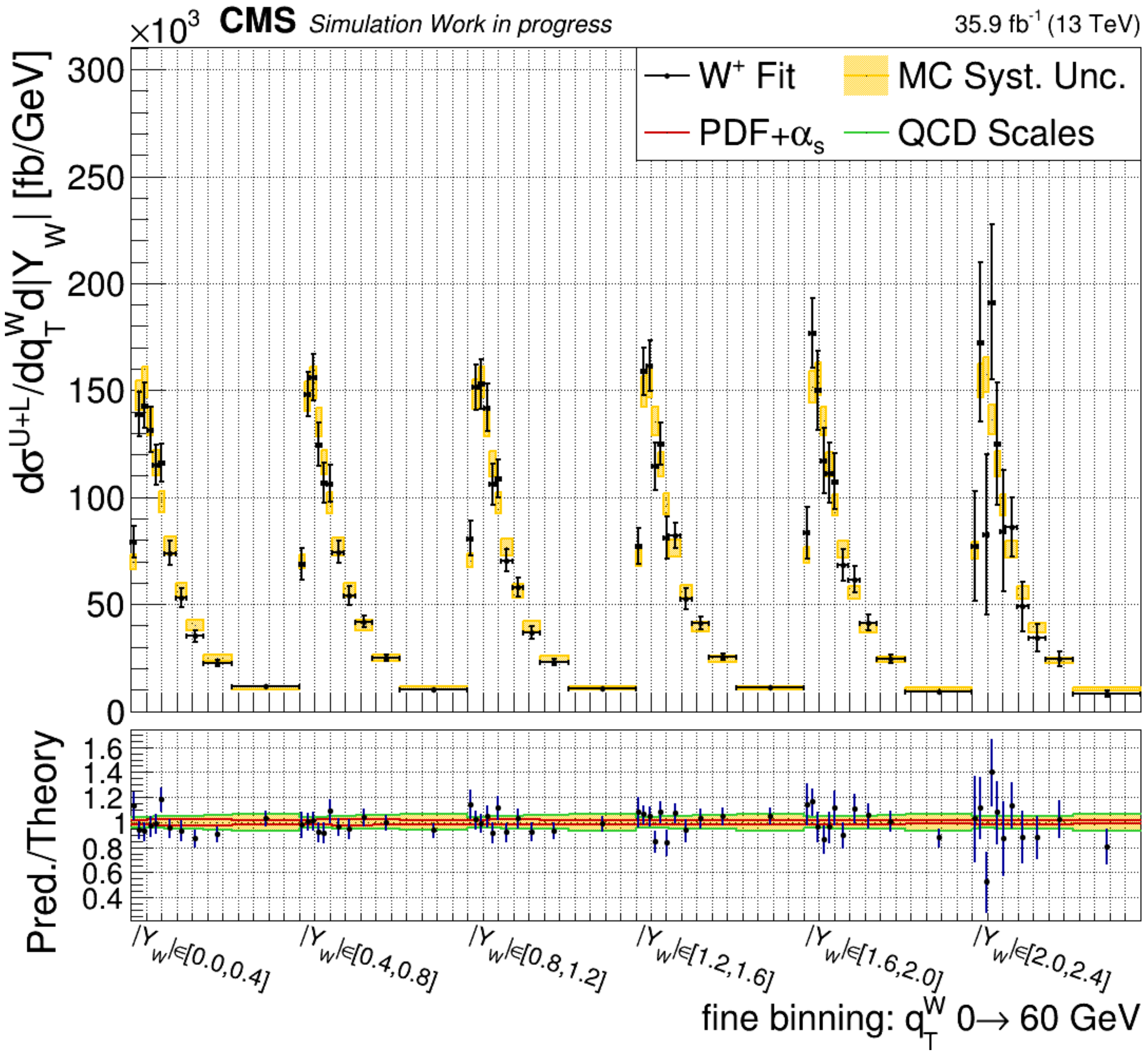


CMS Simulation Work in progress
35.9 fb-1 (13 TeV)
Absolute Impact on A4, W+
PDF+αs
SF stat.
Statistical
Luminosity
qTV
Total unc.
other
qTW [GeV]



CMS Simulation Work in progress
35.9 fb-1 (13 TeV)
Absolute Impact on A4, W+
PDF+αs
SF stat.
Statistical
Luminosity
qTV
Total unc.
other
|YW|

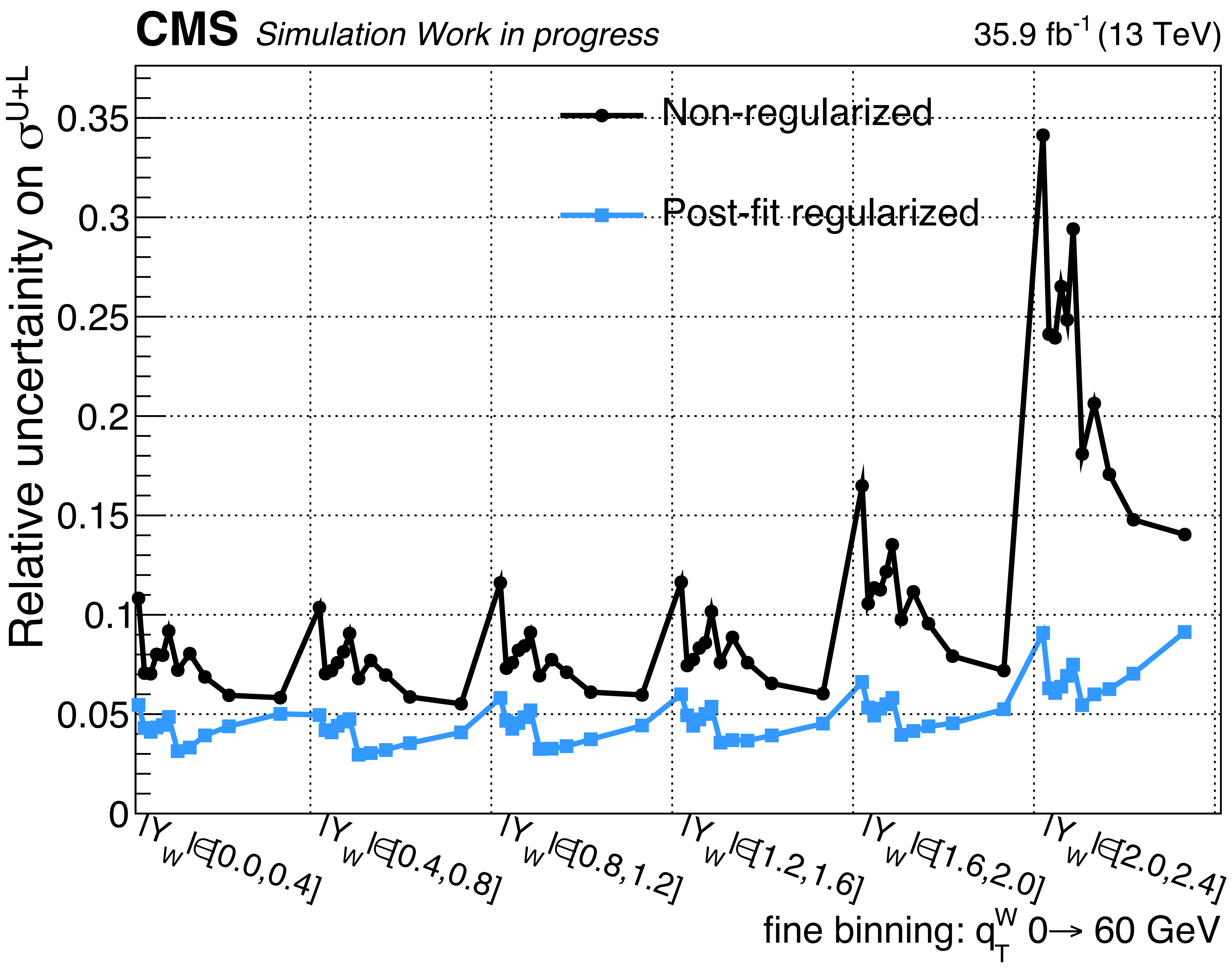
Fit - unrolled toy result σ^{U+L}

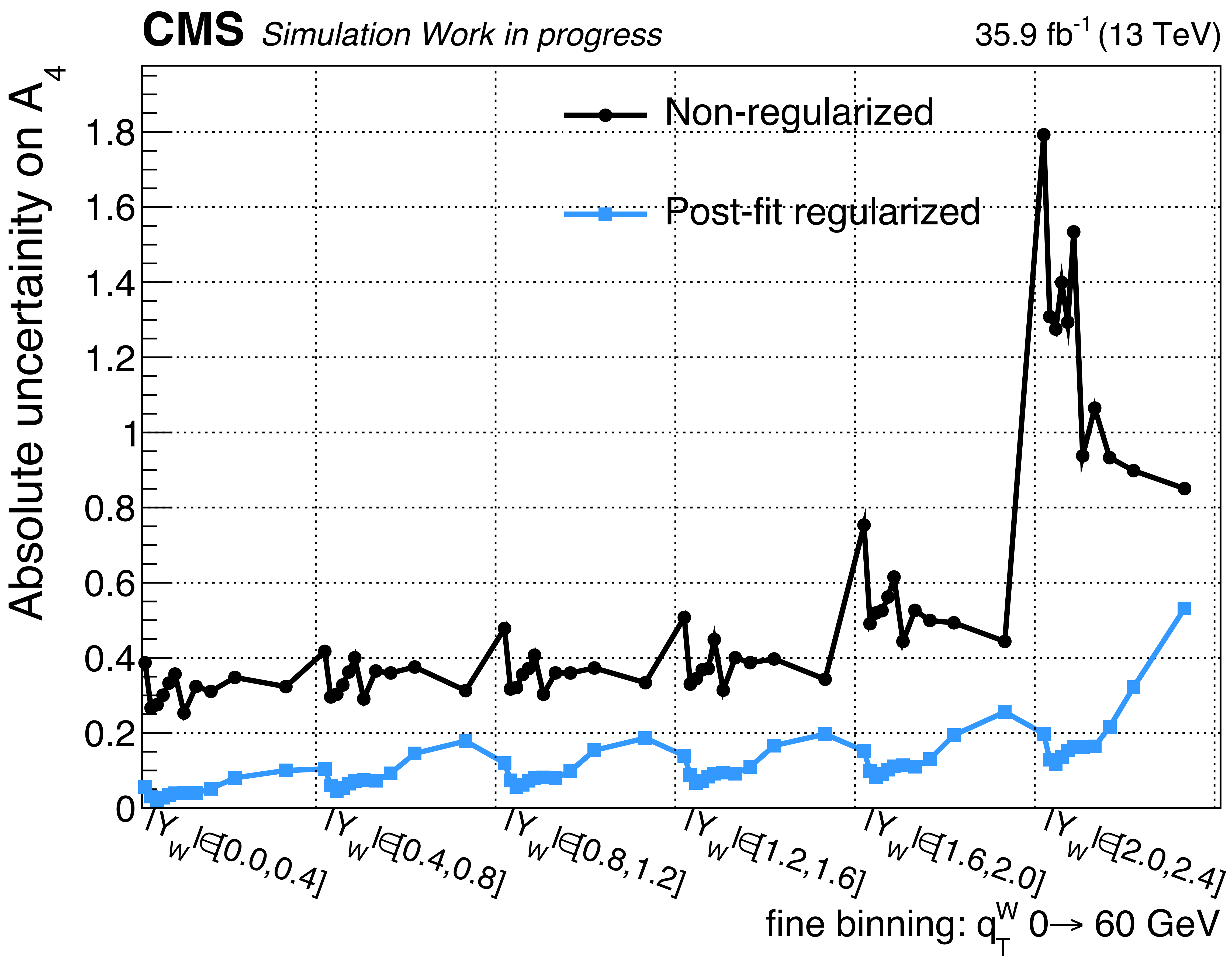


Fit - Regularization preliminary results

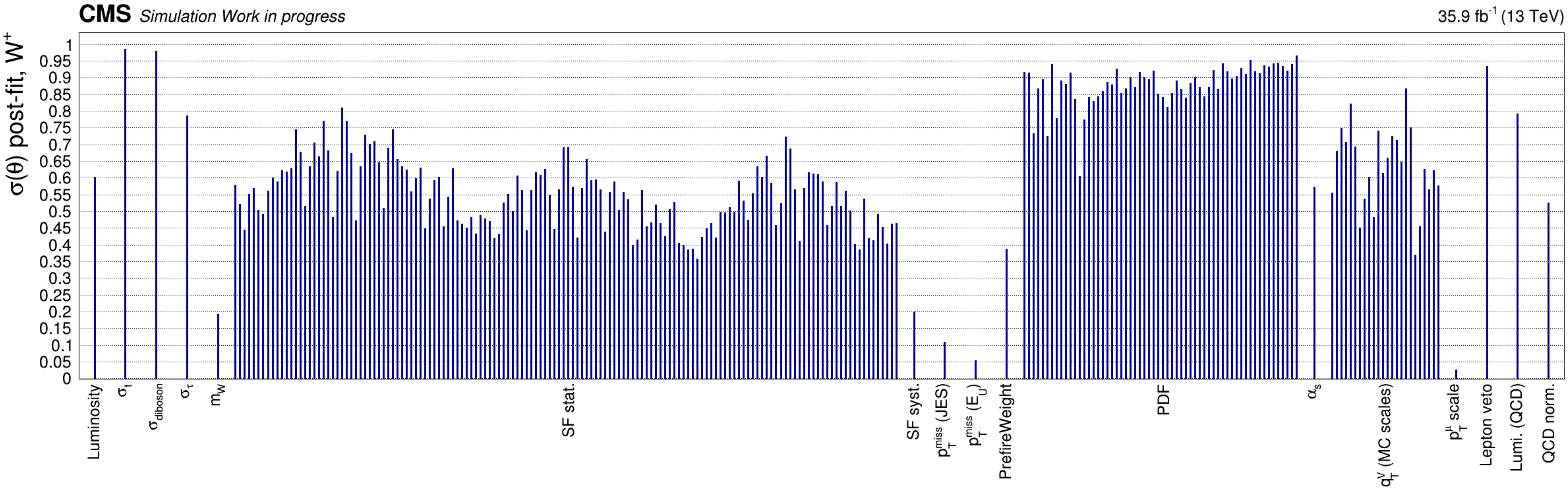
- small bias (<0.02 on A_i or <0.4% on σ^{U+L})
- reduction of uncertainties of factor 2-3

Regularization uncertainty reduction



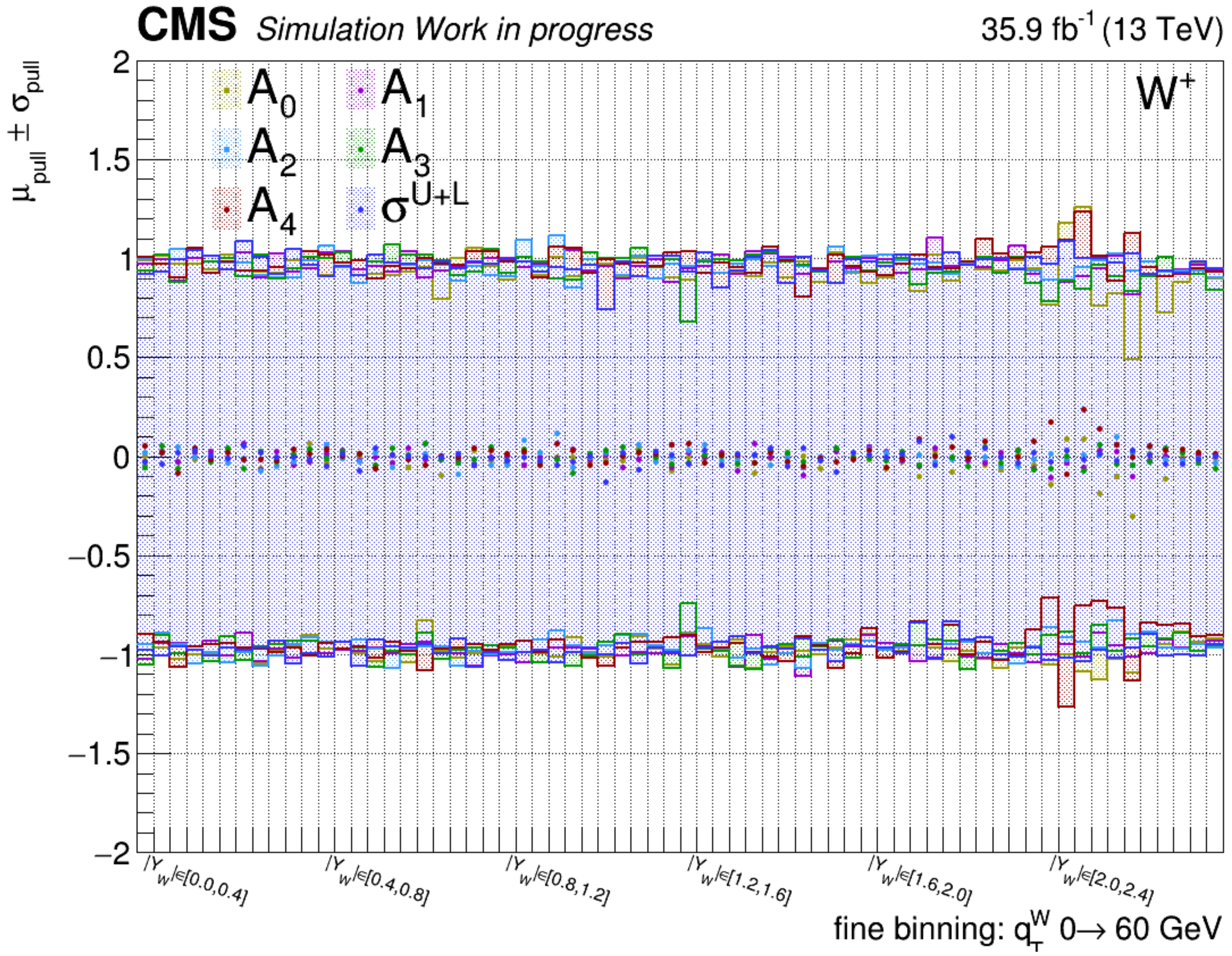


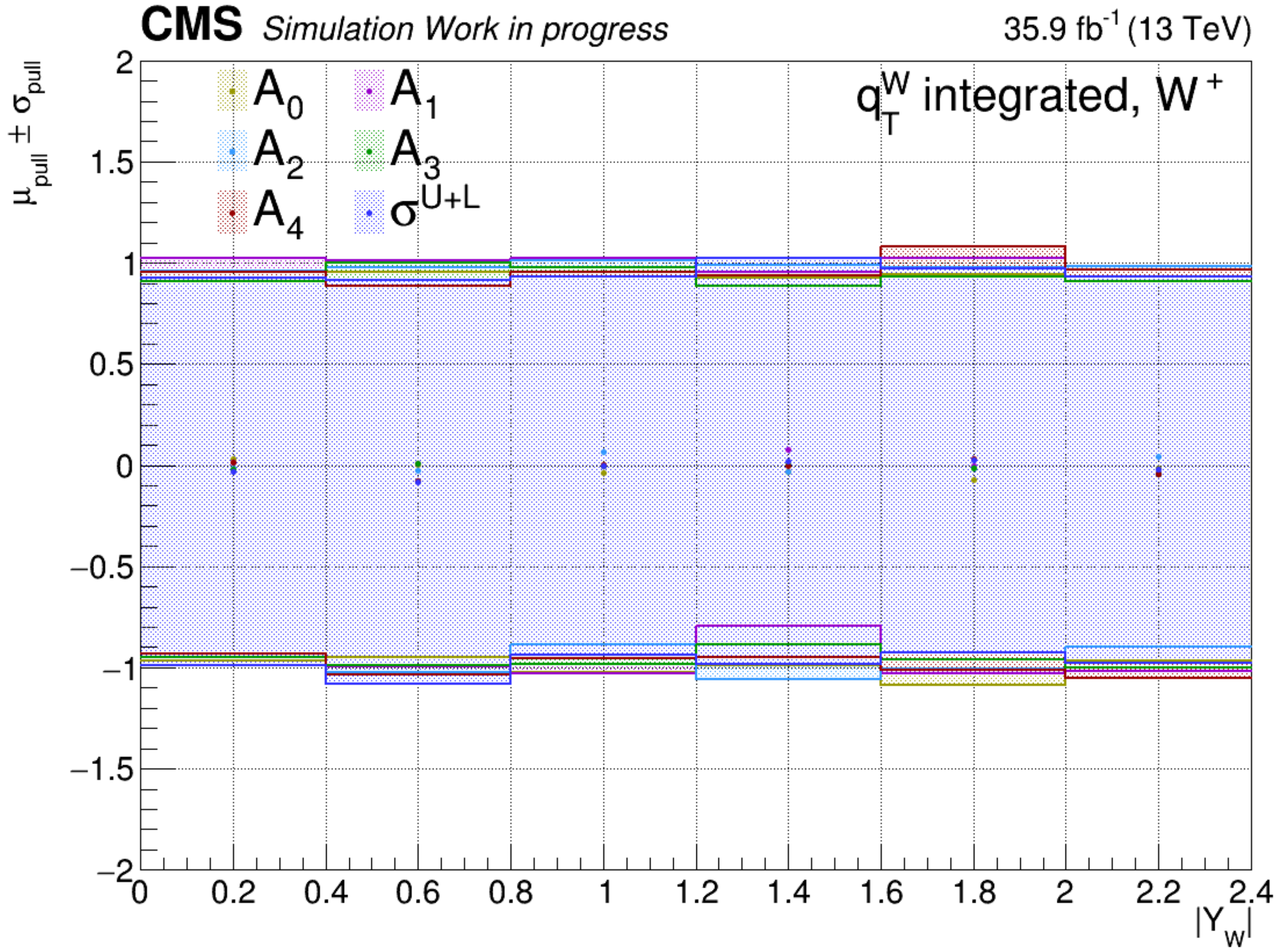
Fit - Nuisance parameter post fit uncertainty

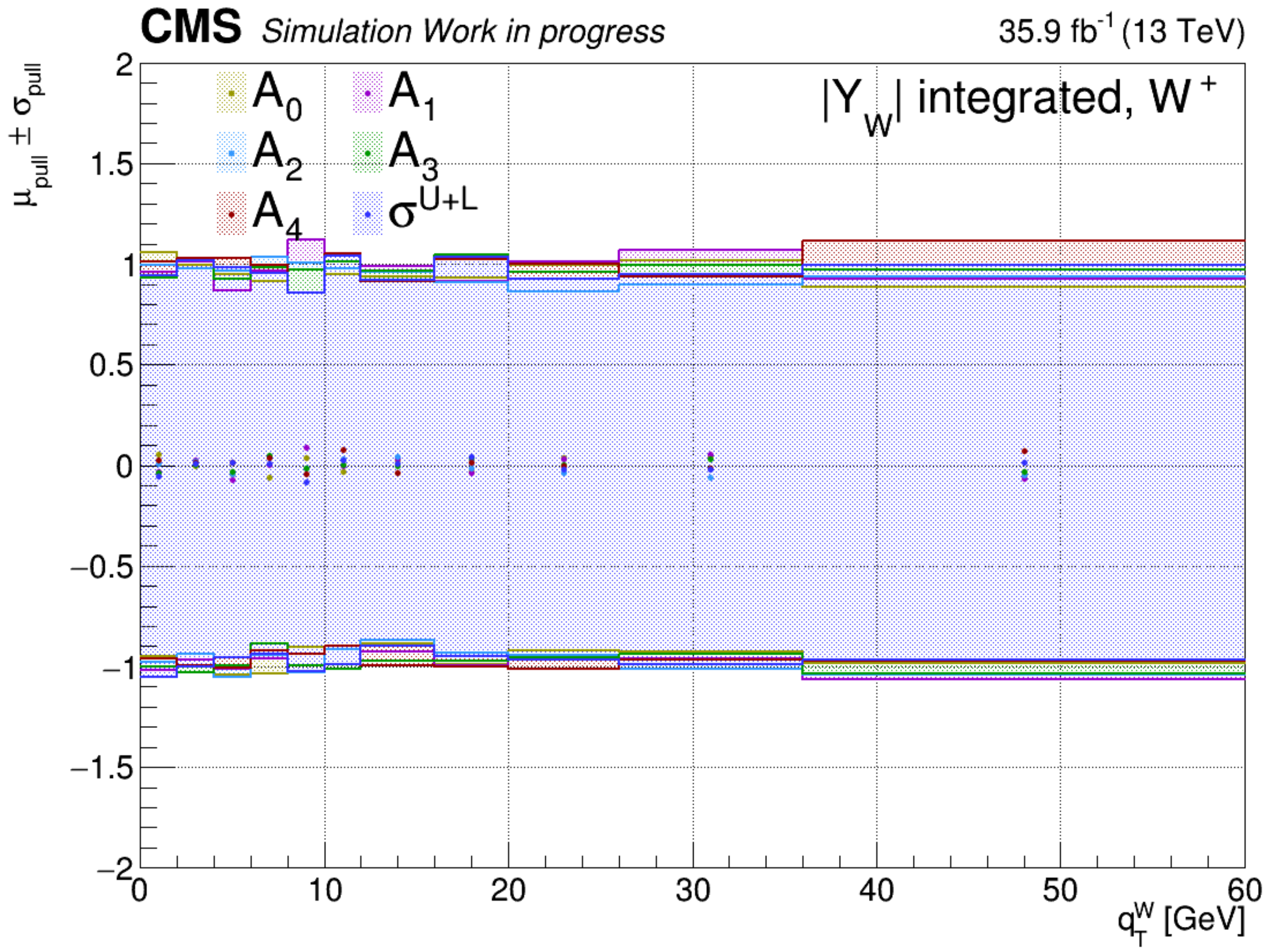


- PDF constraint compatible with SMP-18-012
- MET constraint due to large variation (%) of yield and fully-correlated nuisance on $\eta \times p_T$ plane
- p_T^μ scale constraint due to simplified description
- Luminosity constrained by Z and low-acceptance channels
- m_W constraint reveals the measurement power

Fit - 1k toys pulls





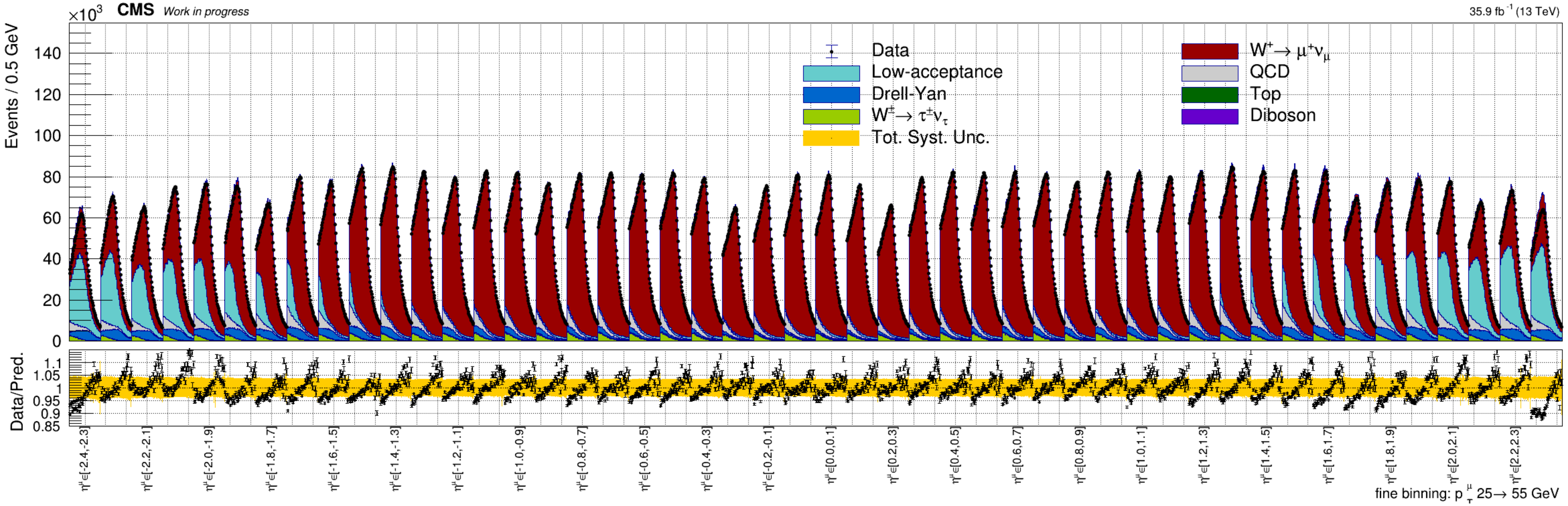


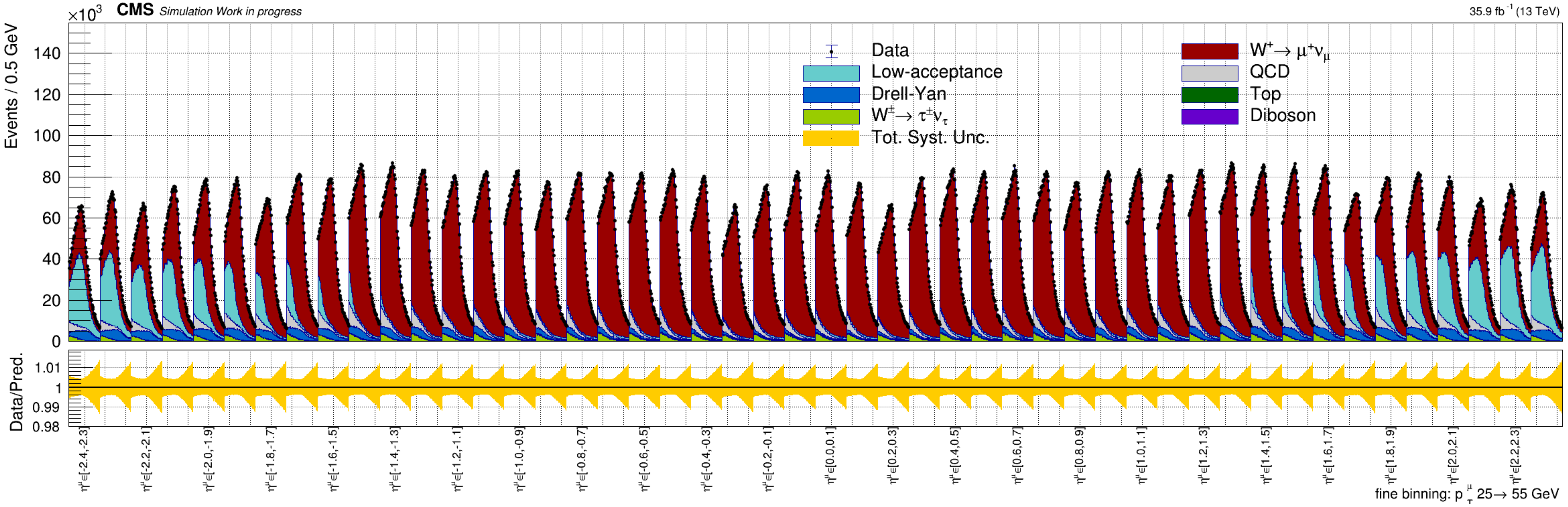
$$\text{pull} = \frac{X_{\text{pred}} - X_{\text{exp}}}{\sigma_X^{\text{pred}}}$$

—> mean 0 and RMS 1 observed —> No relevant bias and robust uncertainties

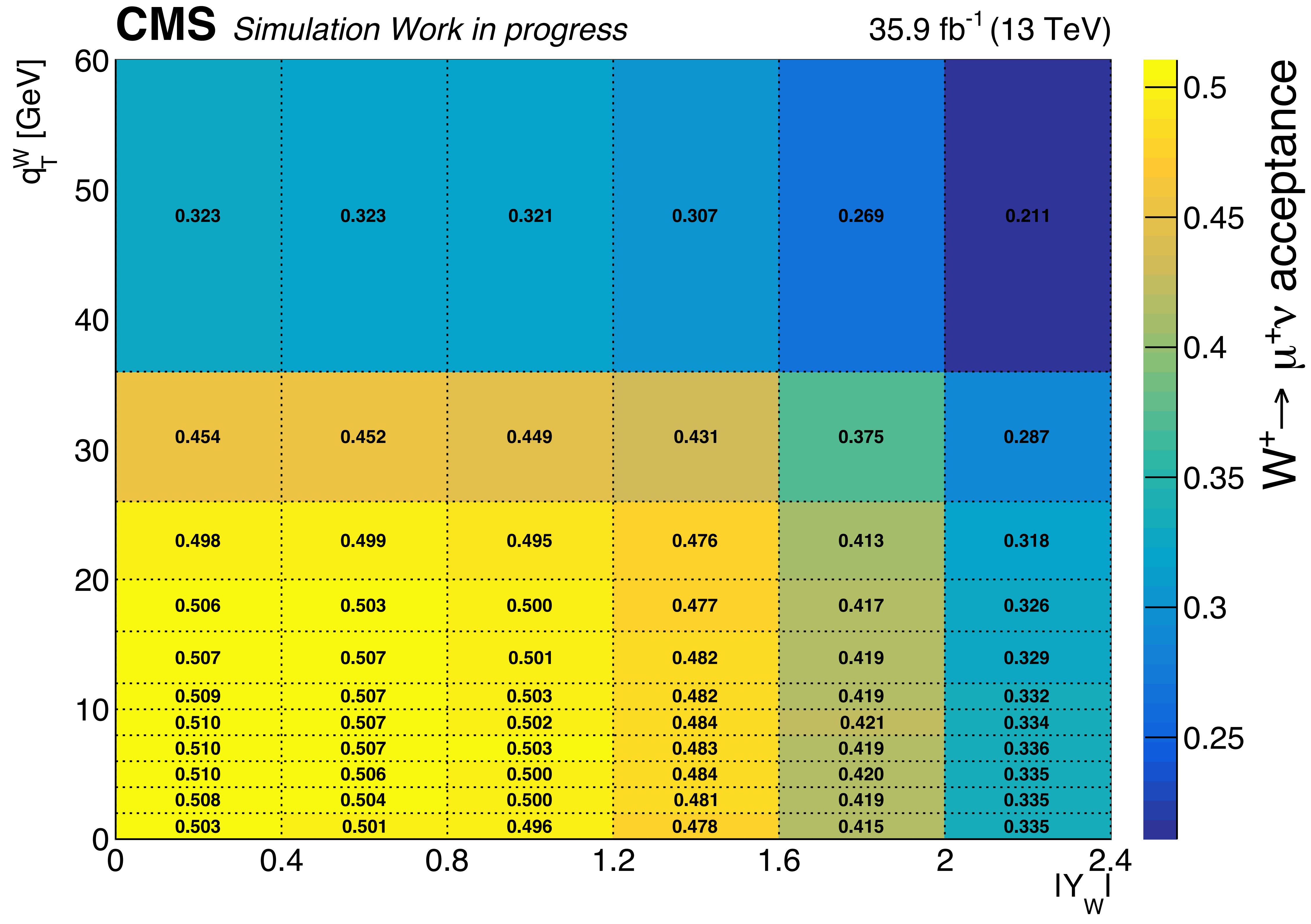
Fit - Prefit vs Postfit uncertainty

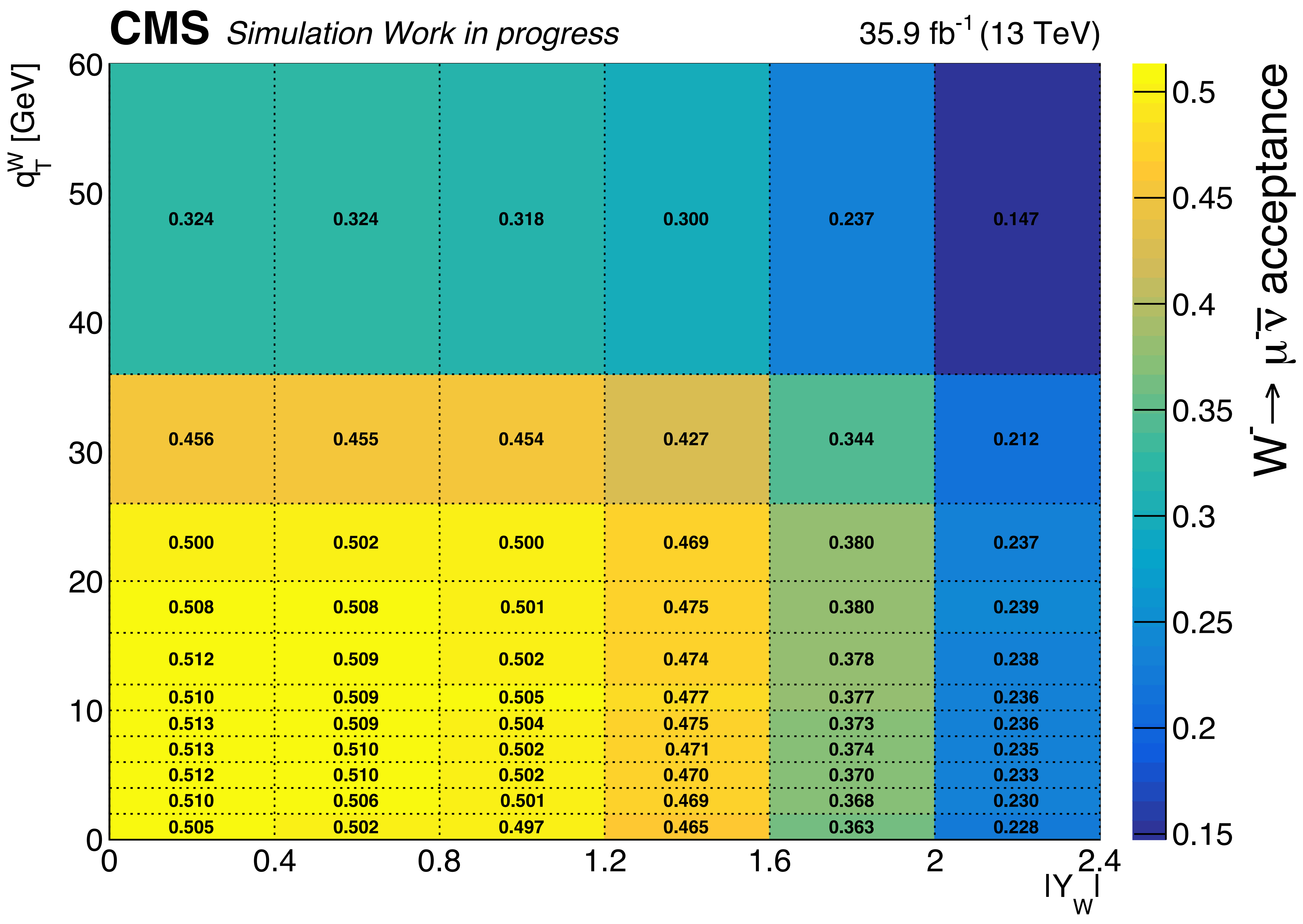
- Asimov Fit
- Real data (prefit)
- Fake data (postfit)





Signal acceptance

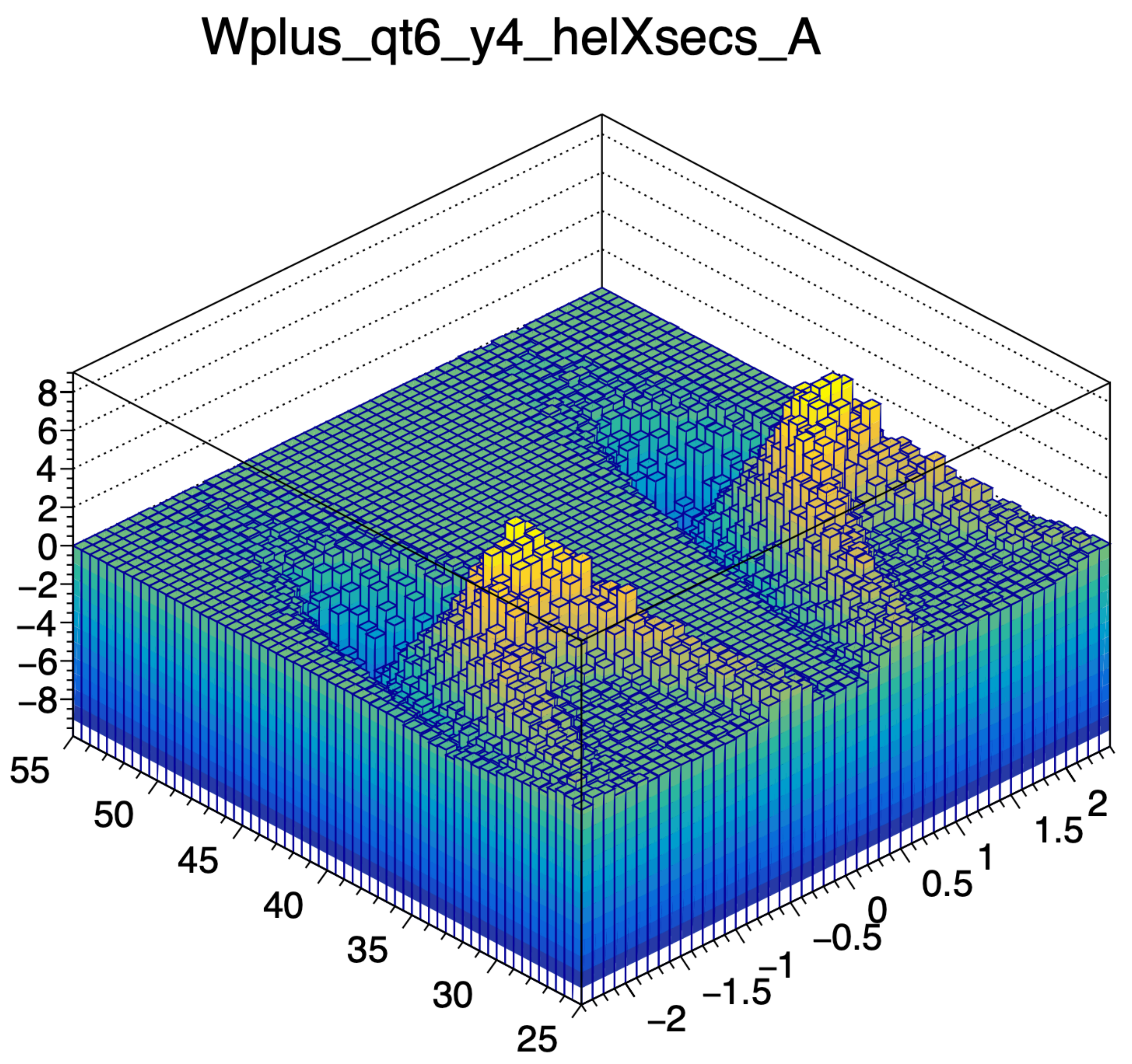


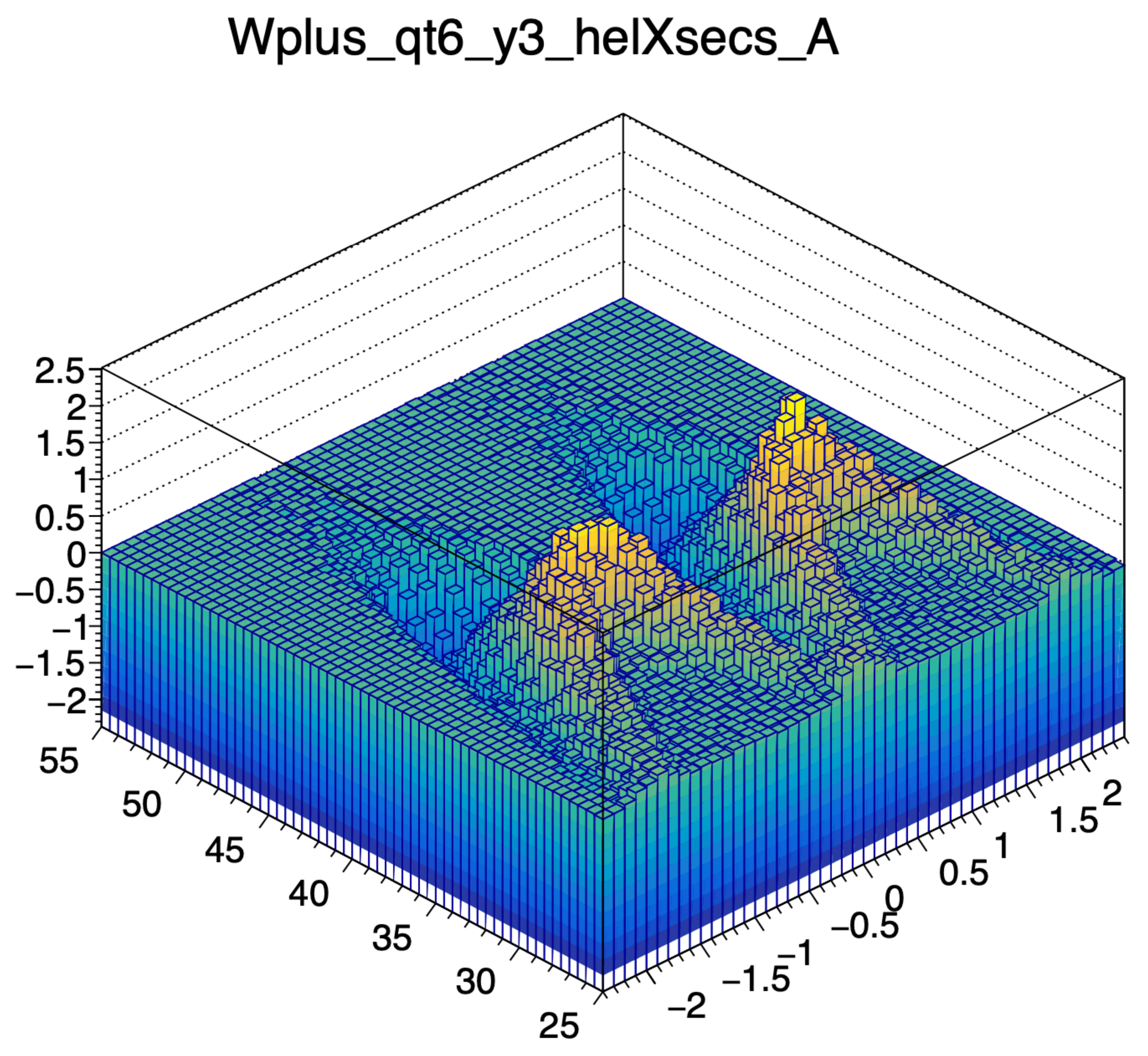


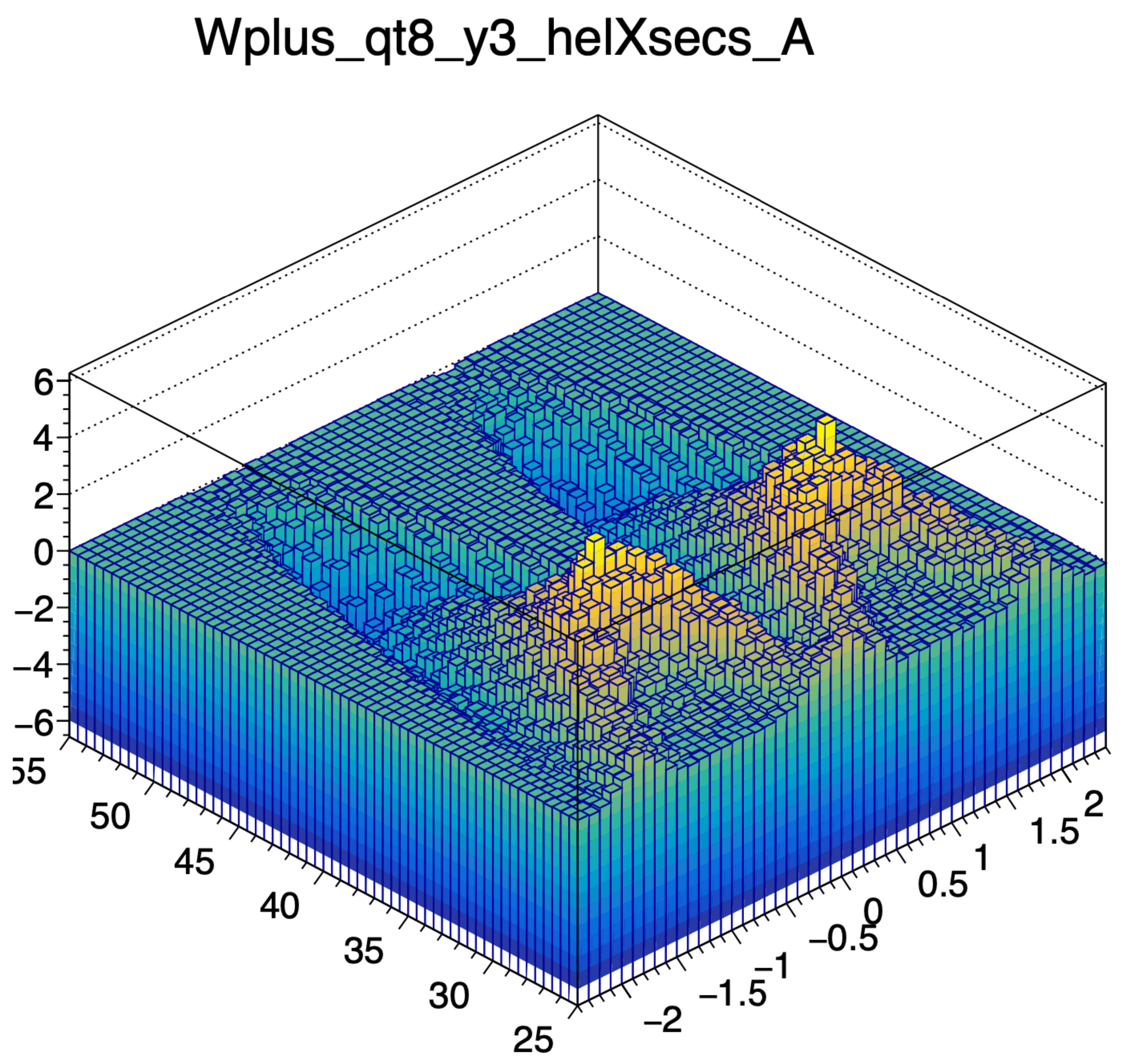
acceptance = sum of signal templates/gen. level W yield

A_3 overlap e correlation scheme

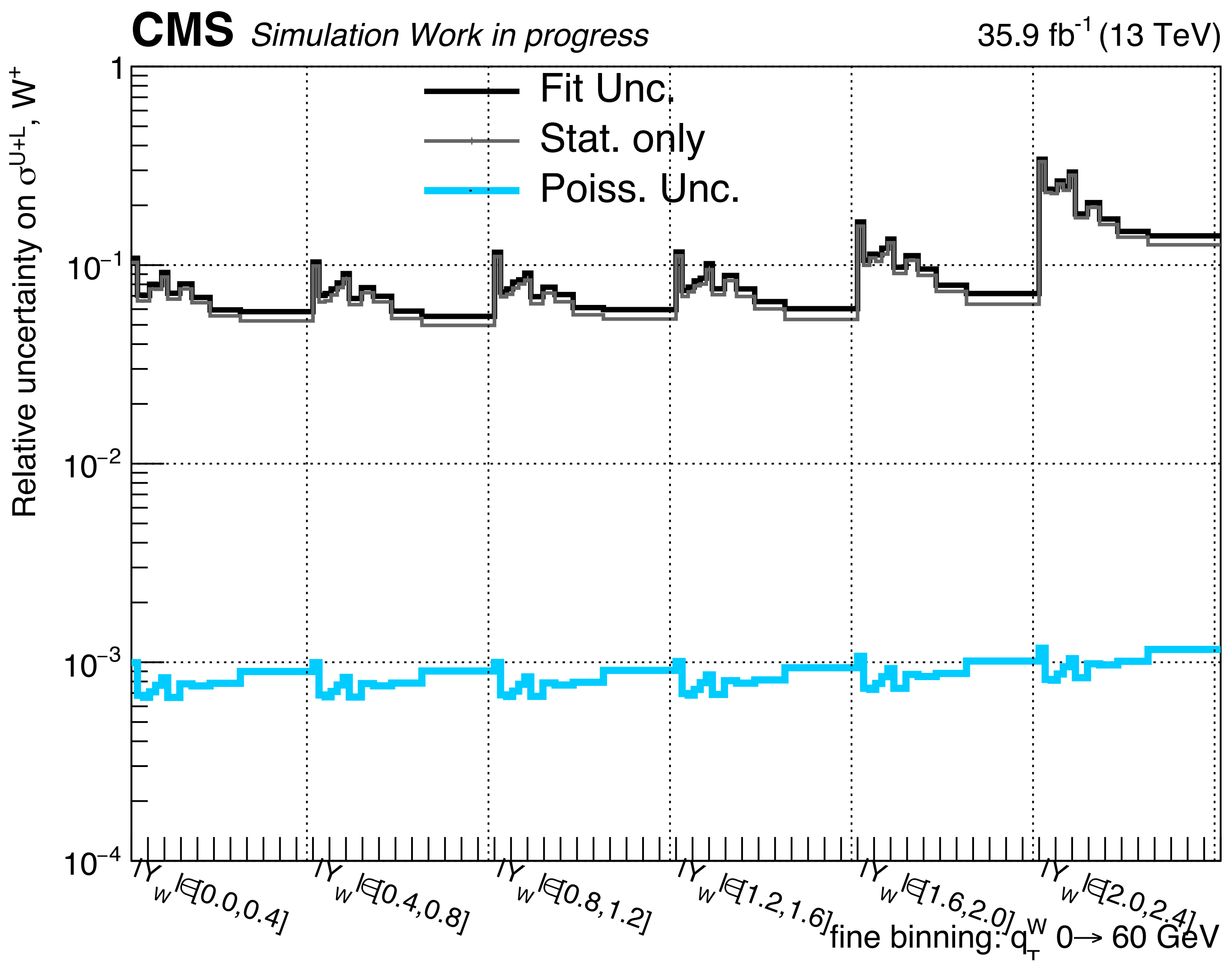
- Single maximum —> almost complete overlap —> strong anti-correlation

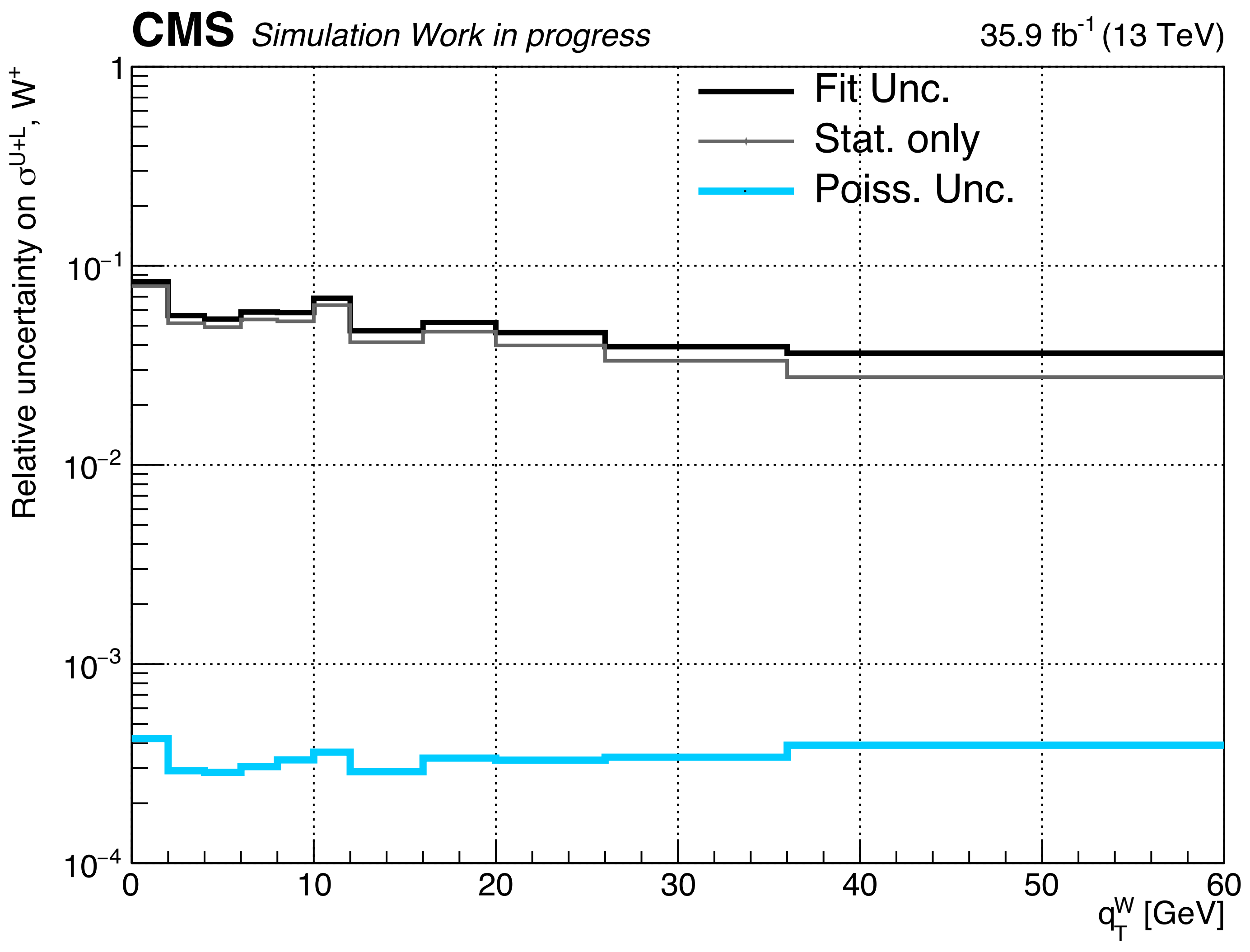


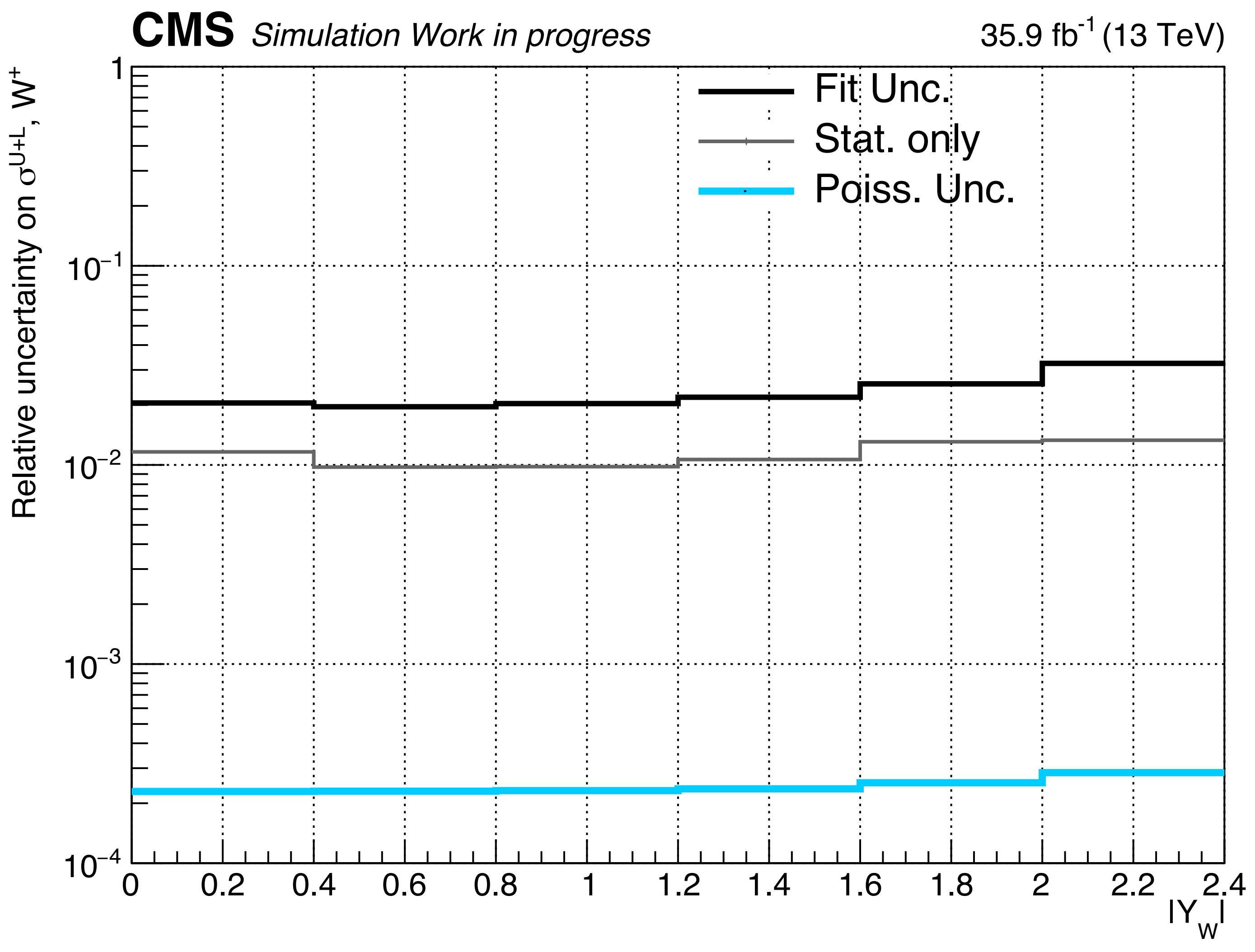




Poisson error comparison

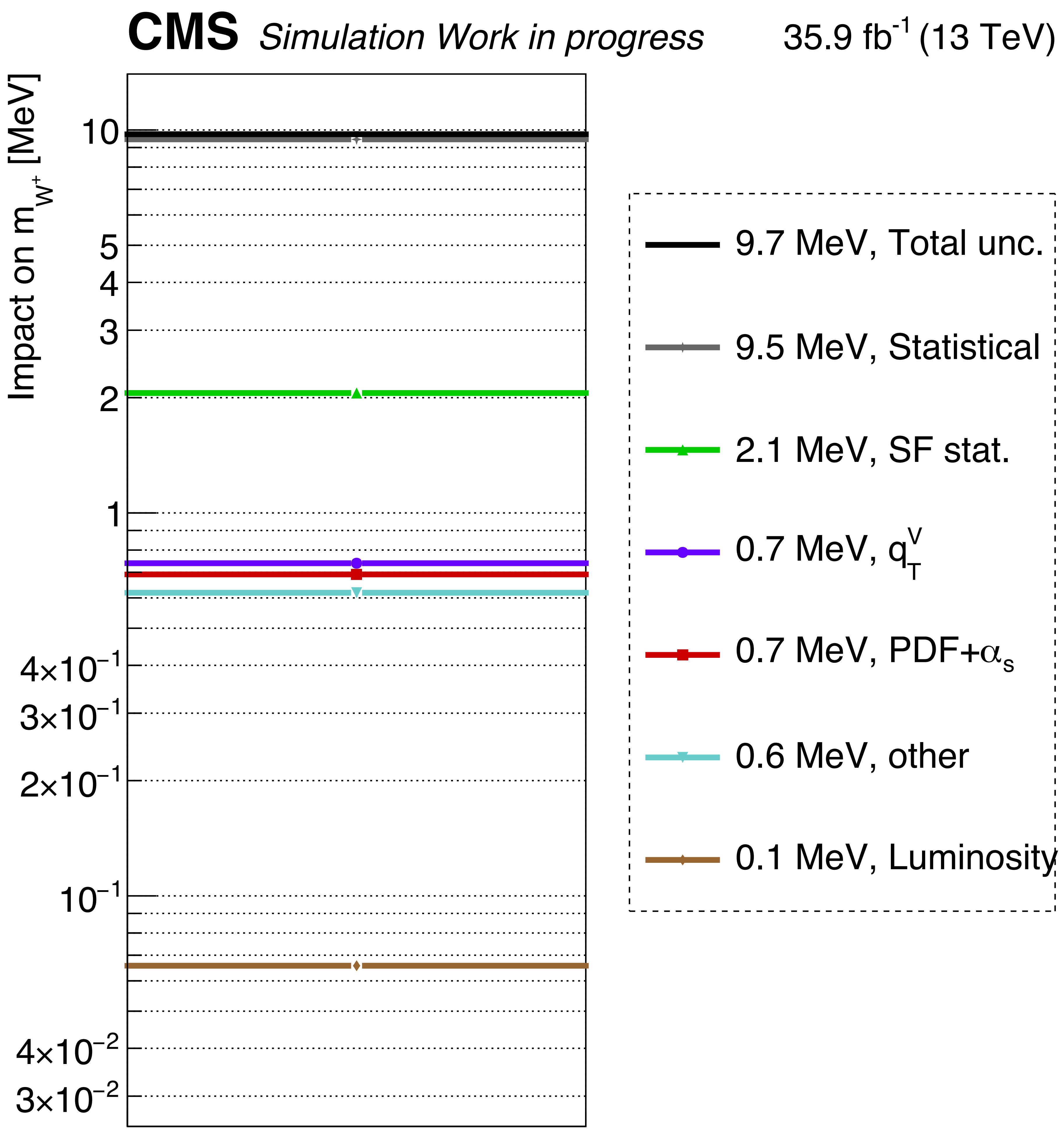


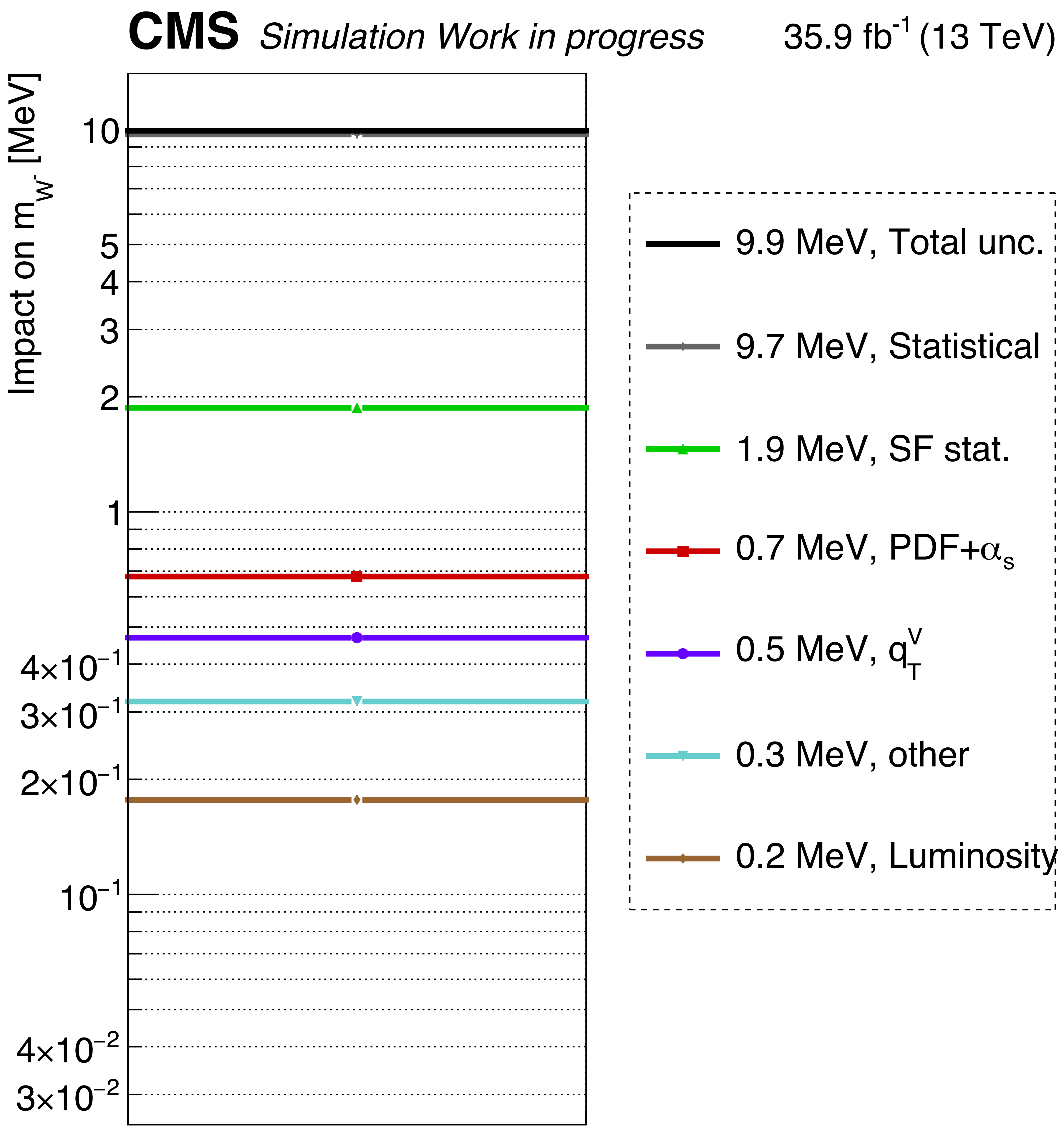




$$\mathrm{BW}(m; M, \Gamma) = \frac{1}{(m^2 - M^2)^2 + M^2\Gamma^2} \quad \text{the weights are: } w_{m_W^\pm} \equiv \frac{\mathrm{BW}(m; M \pm \Delta M, \Gamma)}{\mathrm{BW}(m; M, \Gamma)},$$

W mass uncertainty





Regularization optimization

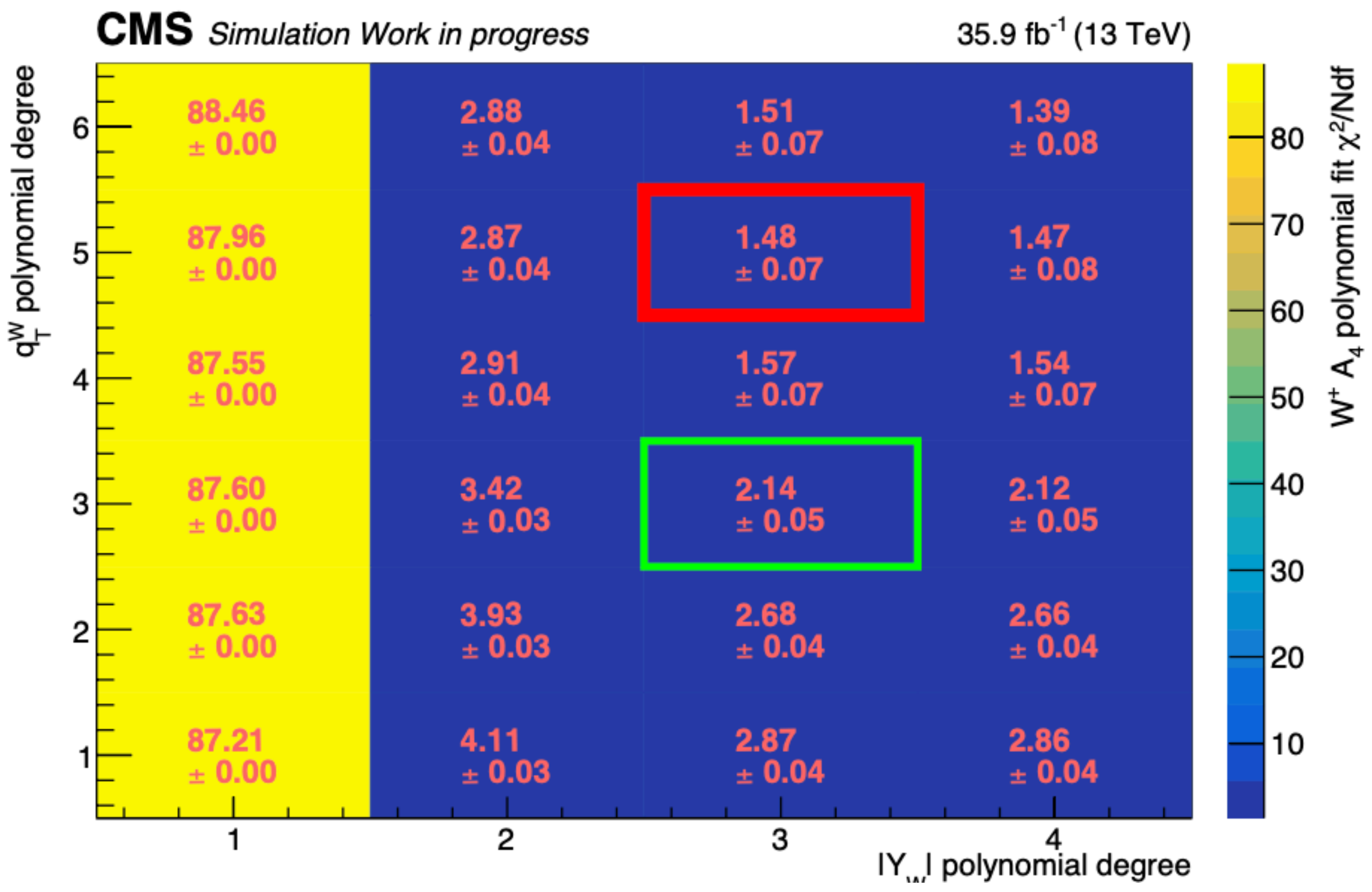
- Tested all the possible polynomial parametrization
- Optimal: most simple model whose χ^2 will not significantly improved increasing the complexity
- used the F-test: test statistic $F = \frac{(\chi_p^2 - \chi_q^2)/(q-p)}{\chi_q^2/(n-q)}$.
-

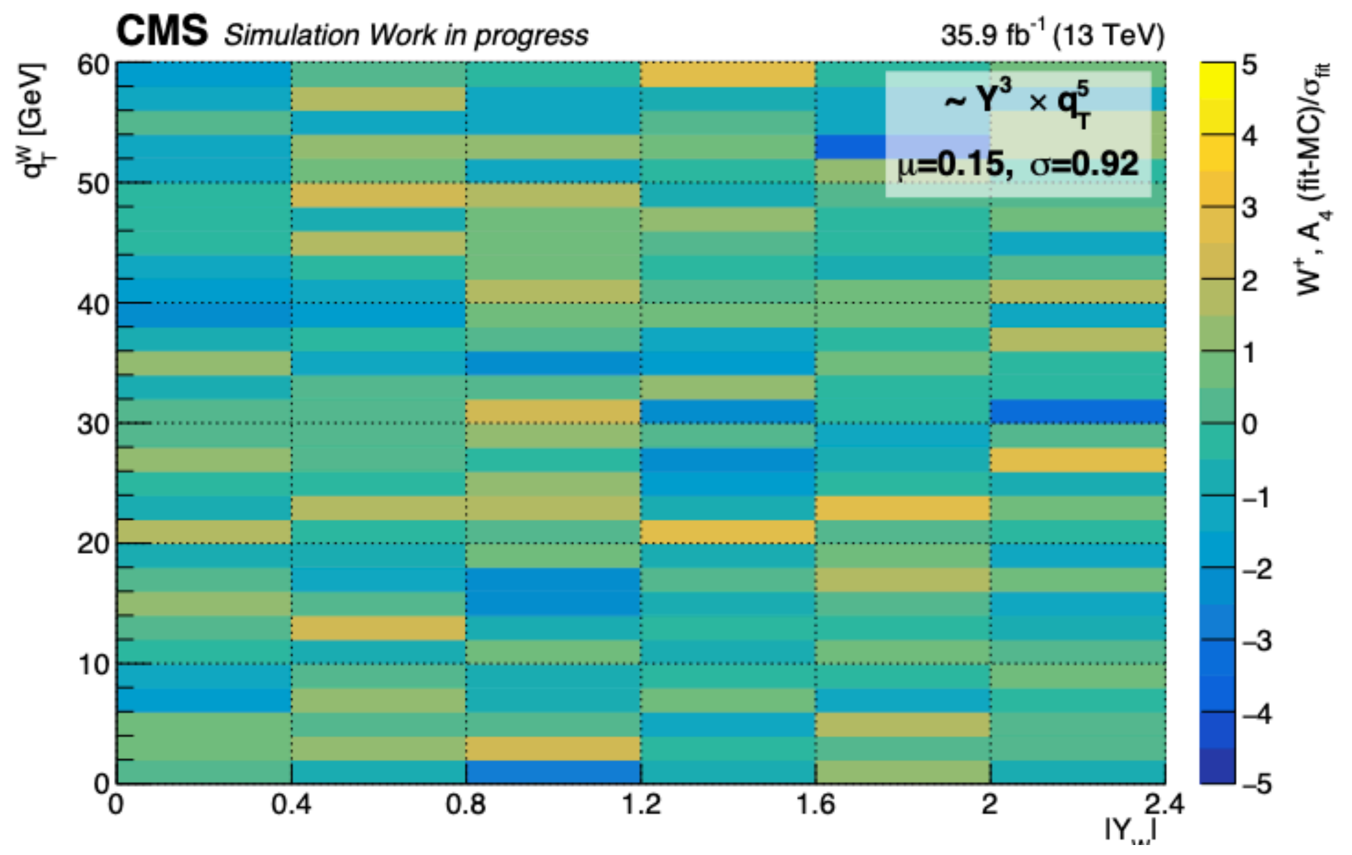
	W^+		W^-	
	max $\|Y_W\|$ deg.	max q_T^W deg.	max $\|Y_W\|$ deg.	max q_T^W deg.
A_0	2	3	2	4
A_1	2	5	2	5
A_2	1	4	1	3
A_3	2	4	2	4
A_4	3	5	3	4

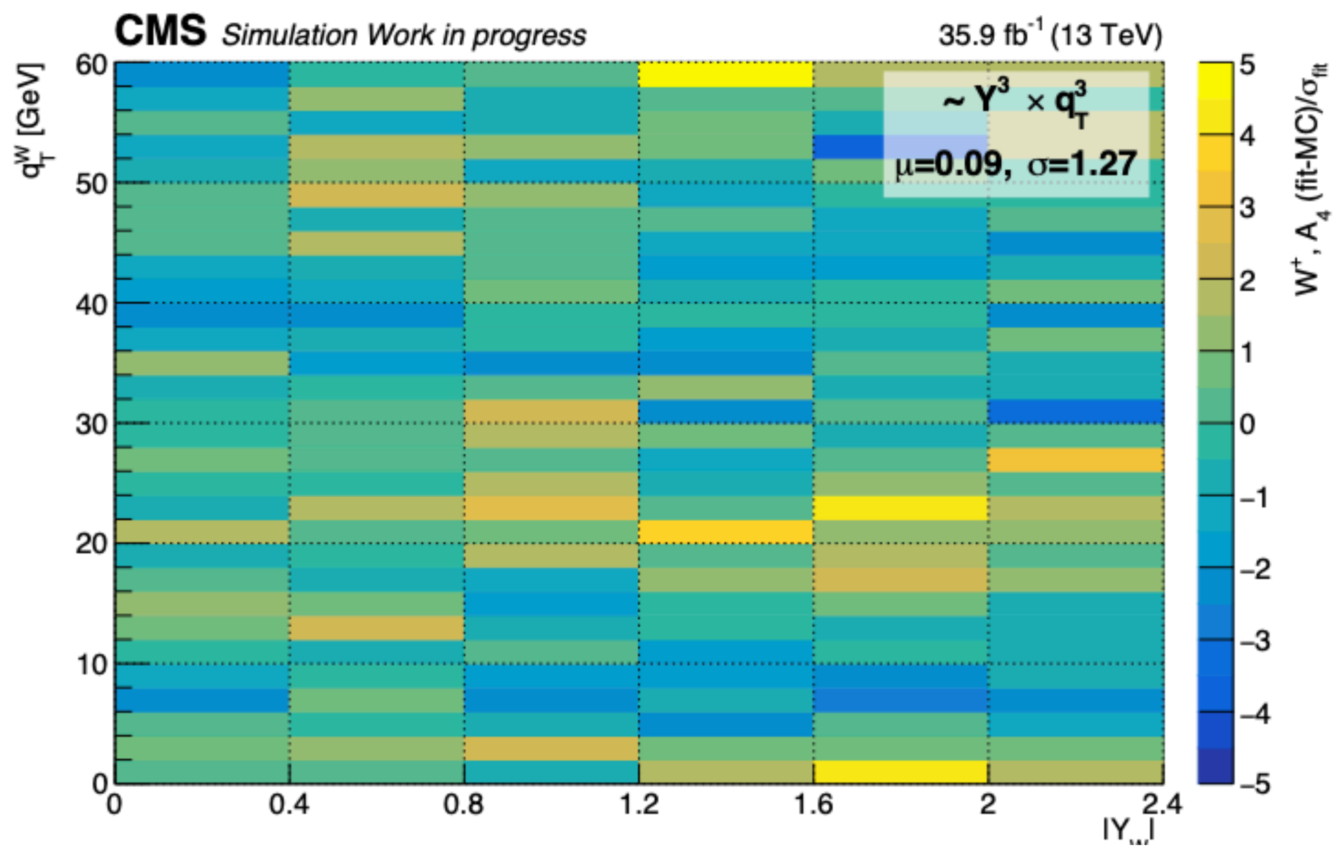
- residuals very similar to the one used in the fit of the post-fit regul.

Regularization optimization residuals

- A4 as example:

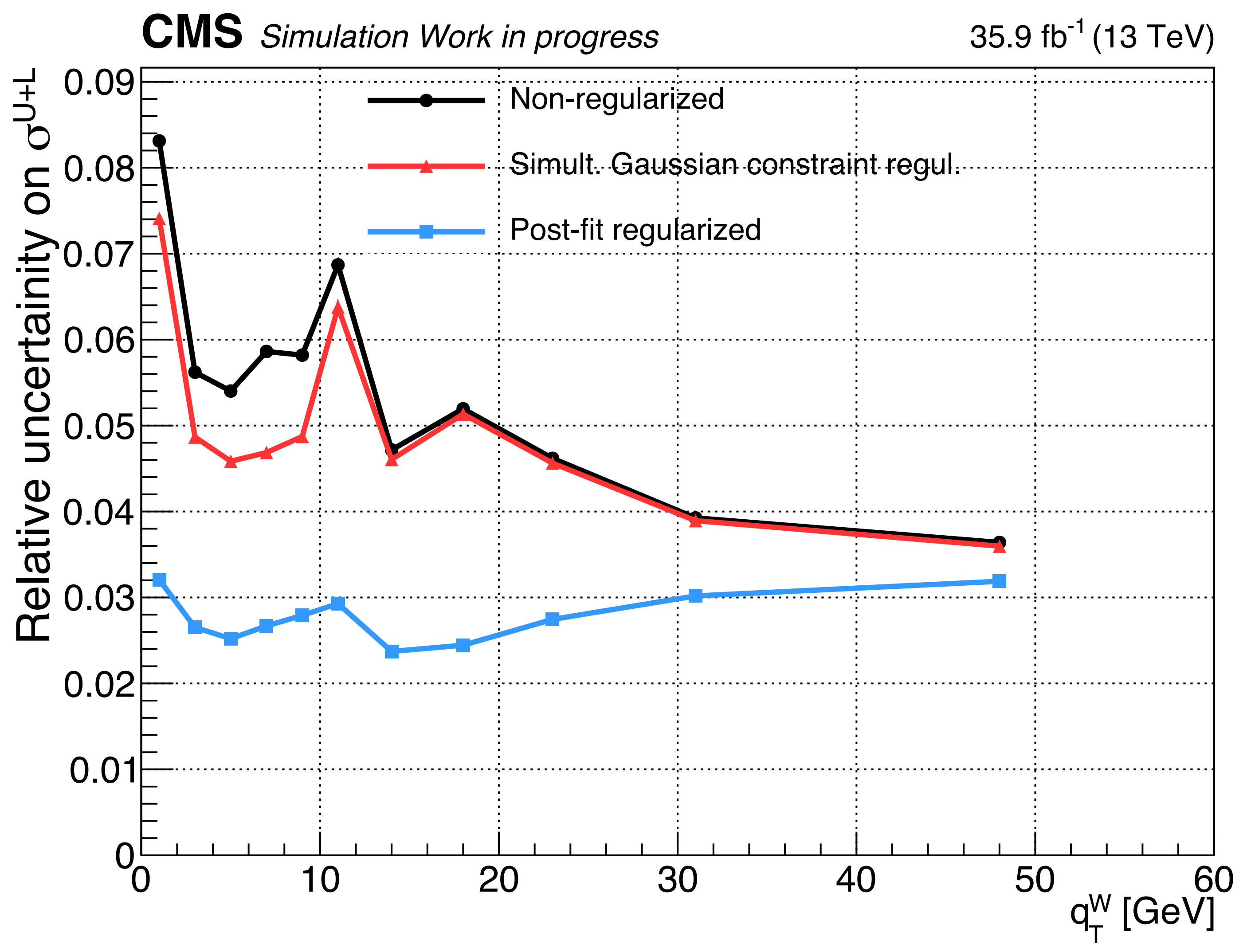


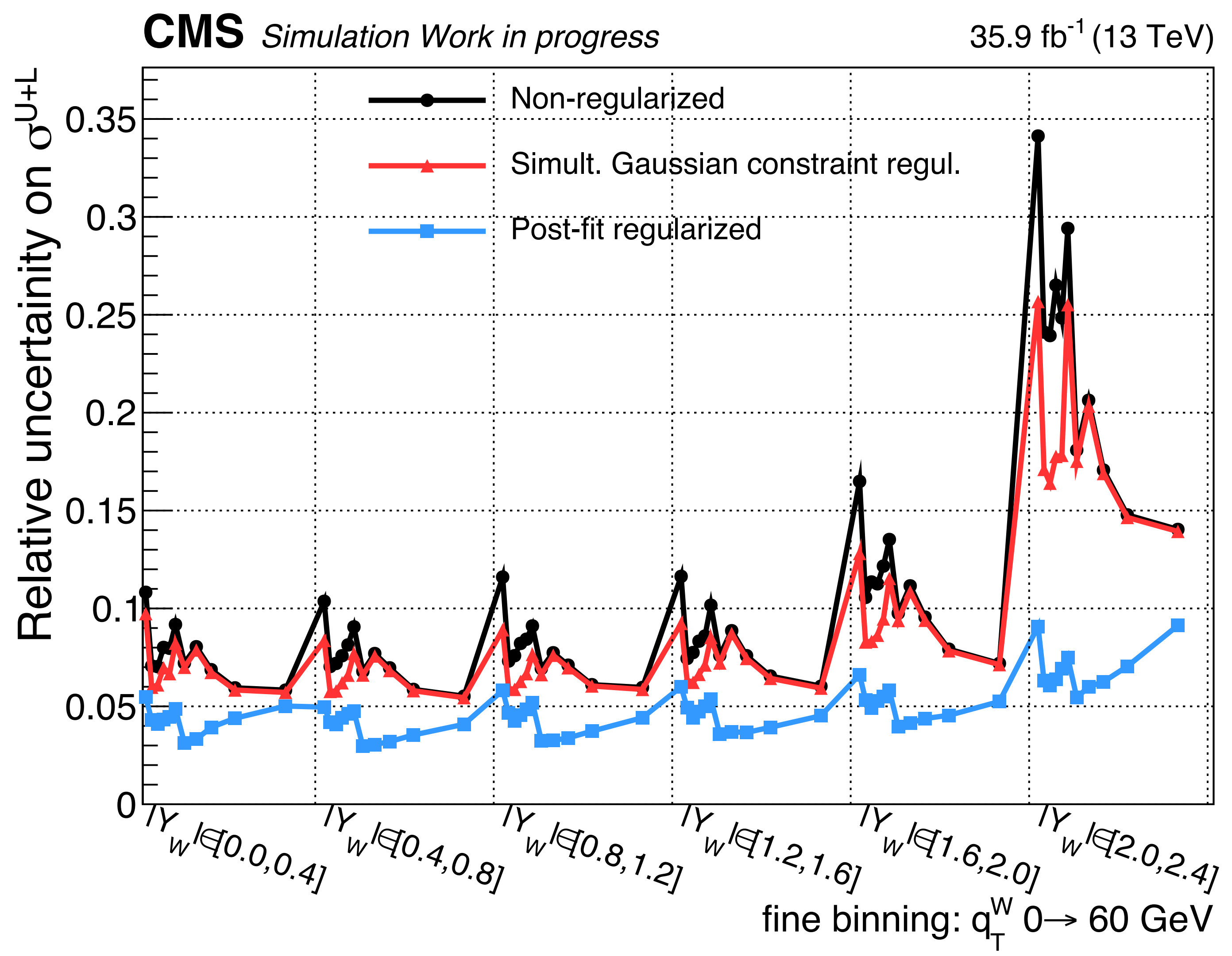




Simultaneous Gaussian Contraint

- Regularize simultaneously to the template fit
- add to the likelihood: $L_\tau = \tau \sum_{i=0}^{4} \sum_{j=0}^{n_Y \times n_{q_T}} c_{i,j}^2 K_{i,j}$ (K=0—>constrained, K=1 —>free)
- τ=power of the constraint
- With $\tau = 100$:





Ongoing analysis differences

- NanoAOD V8
- UL MC 2016
- New efficiency SF
- No Z reweight

- Different QCD bkg estimation method
- implement new muon scale calibration
- combined charges in the fit
- regularization and/or conditioning

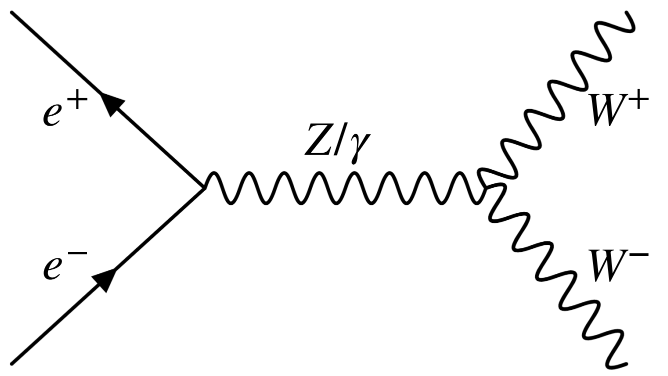
Extra - PDF uncertainty constraint

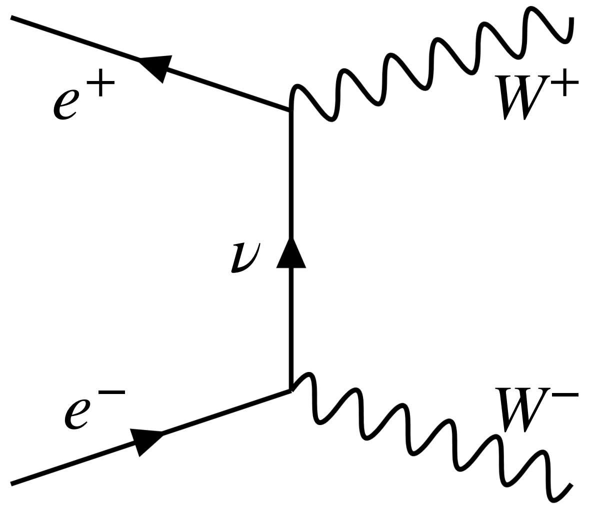
- The measurement of W properties can be used to estimated the constraint given to PDF uncertainty on m_W in a “traditional” measurement (i.e. using p_T^μ spectrum)
- template fit repeated fixing all the POI —> equivalent to assume external knowledge of q_T^W, Y_W, A_i and fitted only m_W
- **Prefit PDF uncertainty** (estimated fixing the nuisance to prefit value)**: 12.75 MeV**
- **Postfit PDF uncertainty = 2.99 MeV**

Outlook

- The W production properties can be measured with extremely low systematics (1-5 % level)
- The statistical uncertainty can be tackled implementing a regularization of A_i
  - more refined approach (like gaussian constraint on the likelihood) is under development
- a competitive (~10-15 MeV precision) **measurement of m_W with 2016 data sample** should be feasible
- Mandatory missing ingredients in the proof-of-feasibility of this talk:
  - p_T^μ **scale** —> very close to be provided with 10^{-4} precision
  - **FSR uncertainty** —> UL MC will allow its assessment
- Optional under development :
  - Combined fit of W^+ and W^-
  - improved QCD estimation, avoiding q_T^W syst —> ready in the UL MC measurement
  - improve SF precision
  - refine regularization implementation

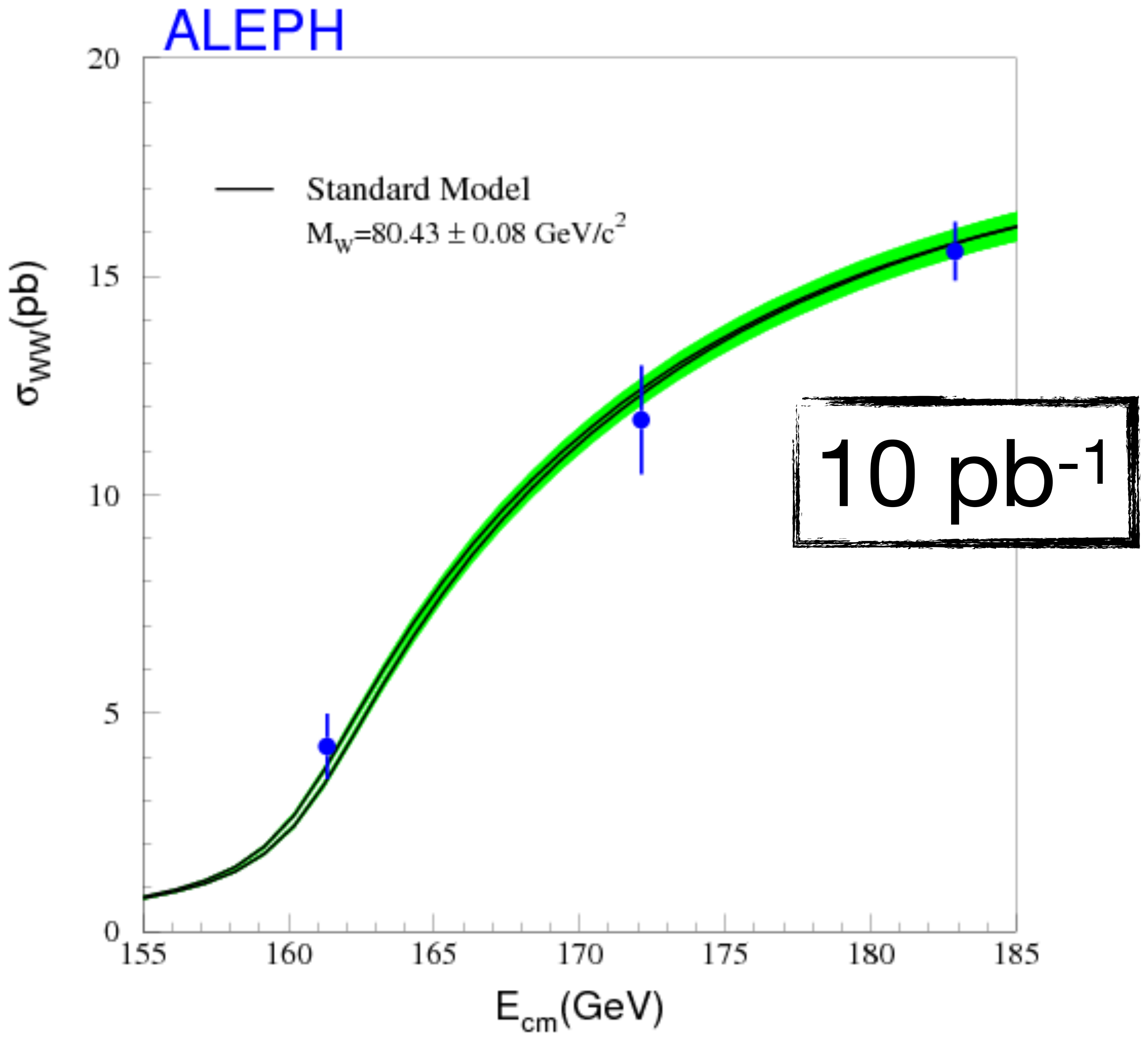
Far future of m_W measurement: FCCee



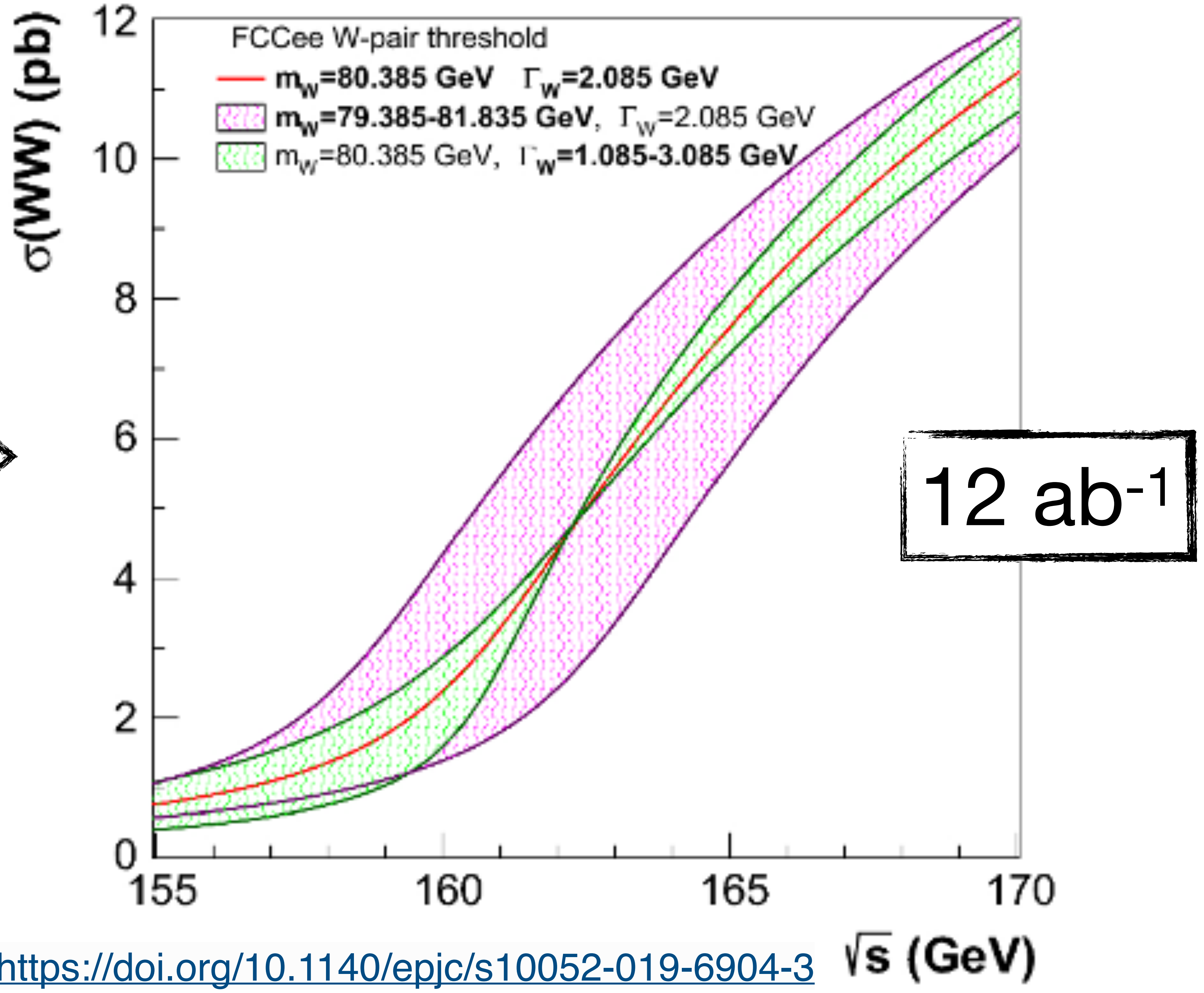


- LEP —>threshold method: $\sigma_{WW} \sim \sqrt{1 - 4m^2/s}$
- 200 MeV uncertainty (mostly stat.) +30 MeV beam energy unc.

- FCC: same approach—> 0.5 MeV precision on m_W
- assumption:
  - $\sigma_{\sqrt{s}} = 0.5$ MeV
  - cross section prediction precision: 10^{-4}
  - acceptance variation knowledge: 10^{-4}
  - background precision 0.1%



https://doi.org/10.1016/S0370-2693(99)00304-4



https://doi.org/10.1140/epjc/s10052-019-6904-3