High-p_T muon Performance in CMS Run 3

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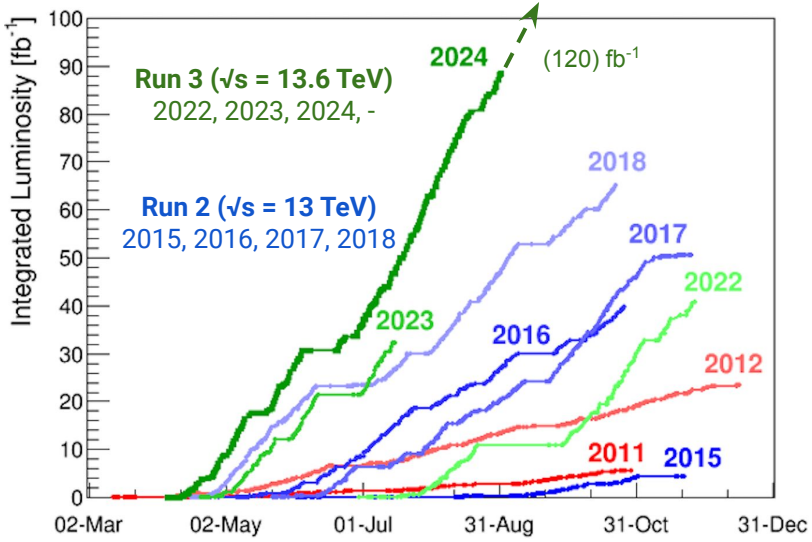
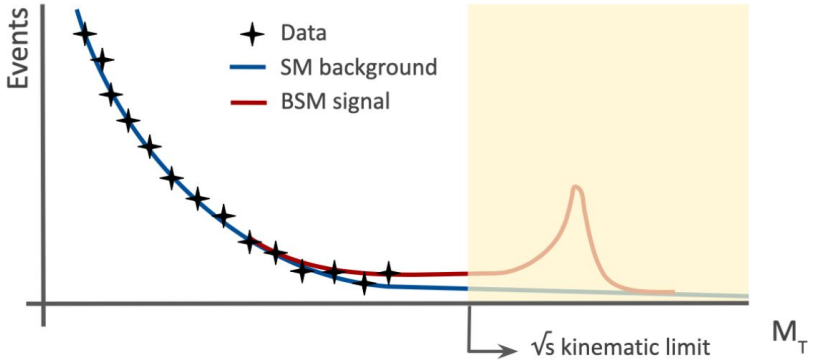
Introduction: Why looking for high-p_T muons?

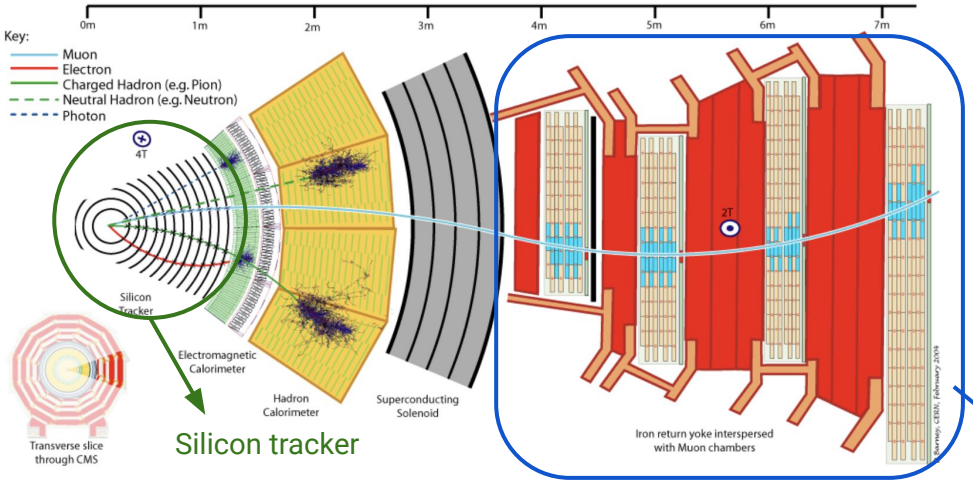
- Currently, LHC Run 3 data taking with **increased energy ($\sqrt{s}$ = 13.6 TeV)** for the pp collisions, so far collected **integrated luminosity L ~ 180 fb^{-1}**, already **surpassing Run 2 statistics** (138 fb^{-1} @ $\sqrt{s}$ = 13 TeV).
- This dataset supposes a good opportunity for different analyses, in particular for **searches in the energy frontier: high mass/p_T region (distribution tails).**
- Why muons? Offer clean and clear sample, ideal to identify signals.



- Precise description of the high-p_T muons needed ⇒ **Talk structure:**
  - **Part I:** High-p_T muon performance in CMS Run 3
  - **Part II:** Some physics results using high-p_T muons



What are high-p_T muons? Characteristics



- Muons in CMS reconstructed combining information from silicon tracker and muon chambers → **Latter very important for high-p_T muons ⇒ Typically p_T > 200 GeV**.
- The muon p_T is measured from the muon track curvature radius:

$$p_T\ [\text{GeV}] = |\ 0.3\ B[\text{T}]\ R[\text{m}]\ |$$

High-pT muons particular features

I. Showering:

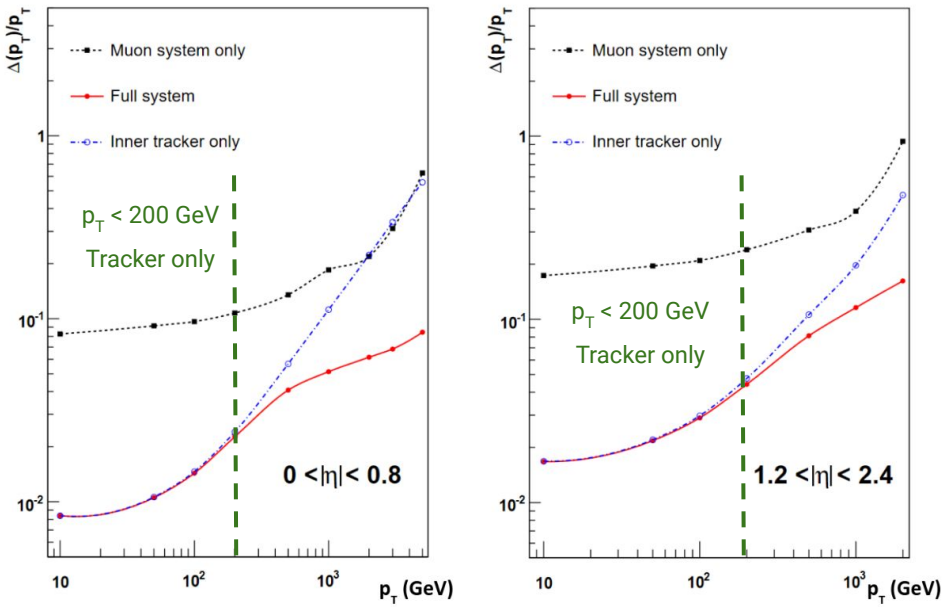
When muon momentum increases, **radiative energy losses become dominant** wrt ionization losses ($E_c^{iron} \approx 300$ GeV). This creates cascades of particles (showers), leading to extra hits in the muon detectors, degrading the performance.

II. Straight Trajectory:

As momentum increases, the trajectory is less affected by the B field ⇒ **Very sensitive to alignment of the sub-detectors.**

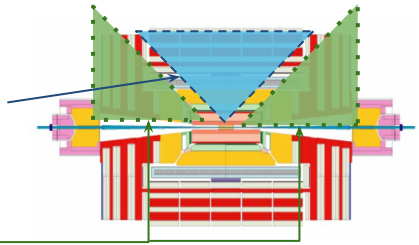
III. Low Statistics

How to measure high-p_T muons?



10.1088/1748-0221/3/08/S08004

High-p_T muon momentum resolution in the CMS barrel (left) & endcaps (right)



- The momentum resolution worsens as the momentum increases ⇒ **Need to incorporate muon system**, improving significantly the performance wrt tracker-only.

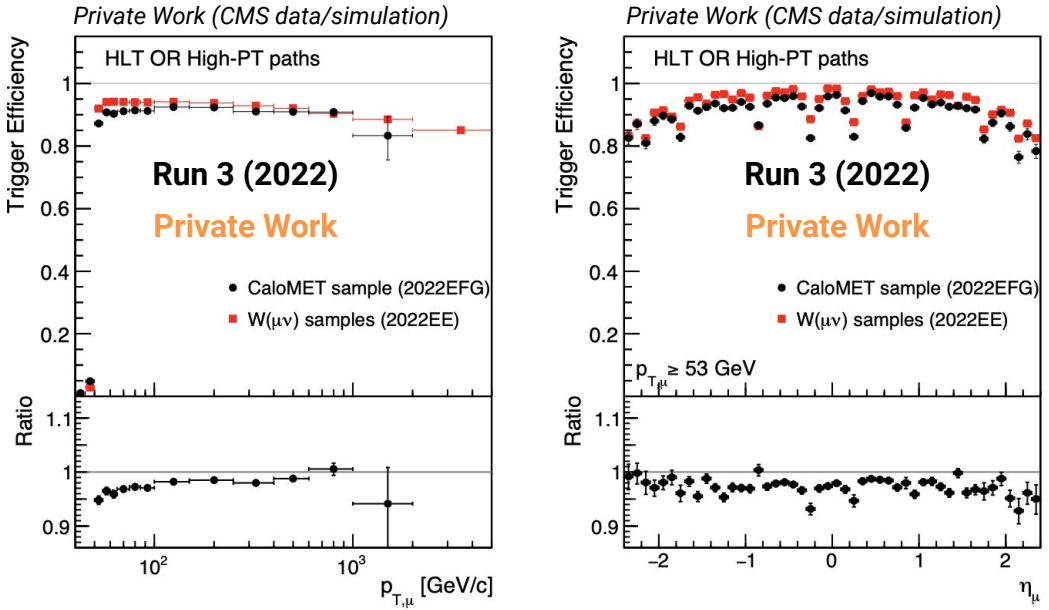
- High-p_T muons are reconstructed using **TuneP algorithm** → Cocktail of different muon track refitters, the one showing the best performance (track fit χ^2 + $\Delta p_T/p_T$) is selected on a muon-by-muon basis.

TuneP

Picky	**DYT**
Good for showers → Ignores chambers (or hits) with high-multiplicity.	Good for energy losses → Eliminates chambers incompatible with extrapolated trajectory
Tracker-plus-first-muon-station	**Tracker-only**

Trigger efficiency for high-p_T muons

- In CMS, the **trigger used for high-p_T muons** selects events with muons having **p_T > 50 GeV** → The efficiency degrades towards higher p_T ⇒ Other paths with higher thresholds and performing different reconstructions allow to recover some inefficiency.



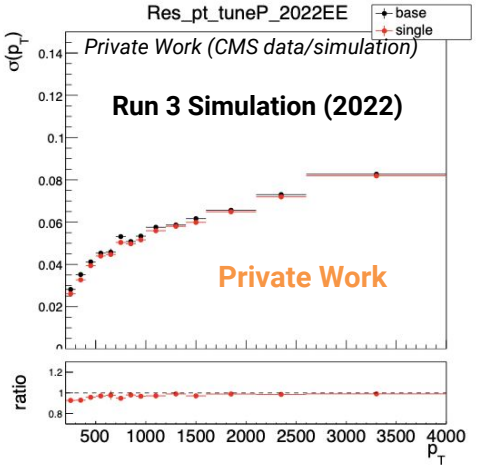
- **How to measure the efficiency**
  - **A. Tag-and-Probe method**
  - **B. <u>Orthogonal dataset</u> (this slide)**

- Efficiencies shown at HLT level (L1 efficiency included). **High efficiency (~90%)**, with slight decrease at high-p_T due to showers, reco difficulties…

- Efficiency vs η reproduce the detector geometry → Lower in the endcaps.

Trigger efficiency vs p_T (left) & pseudorapidity (right), for **data (2022)** and MC simulation. A scale factor (ratio) accounting for the difference is applied to the MC.

Momentum resolution for high-p_T muons

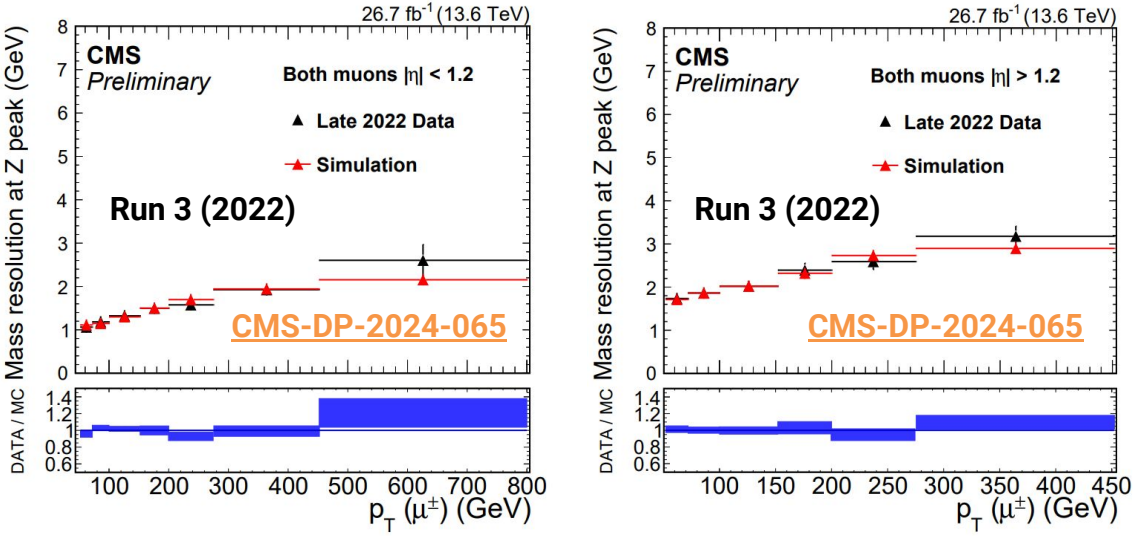


- In **simulation**, since the generated momentum (p^{gen}) is known, the resolution can be measured from the momentum residual:

$$R_{\text{reco-gen}} = \frac{(q/p)^{\text{reco}} - (q/p)^{\text{gen}}}{(q/p)^{\text{gen}}}$$

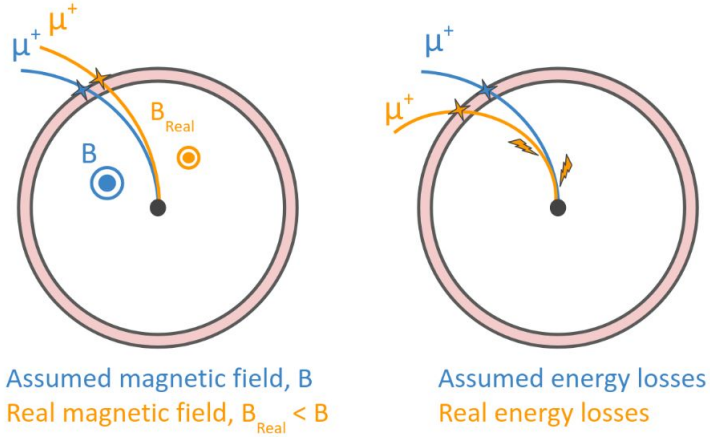
- Resolution is 2% for muons with p_T ~ 200 GeV, increasing up to > 7% above 2 TeV

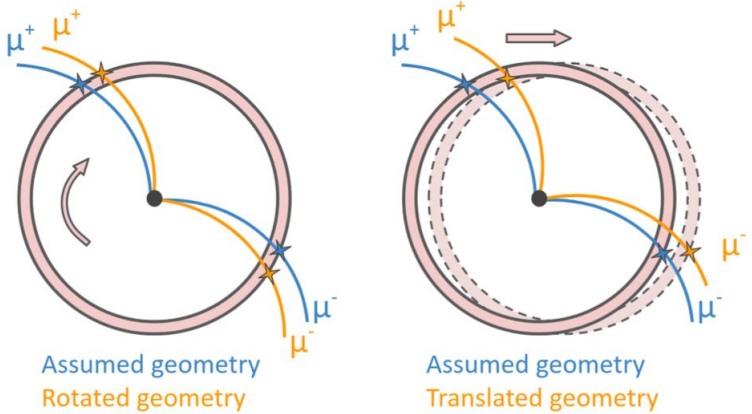
- In **data**, the resolution is measured by fitting the Z mass peak distribution of di-muon events, for different bins of p_T & η
- Sometimes, the resolution in simulation overperforms data one ⇒ Smearing factor applied.



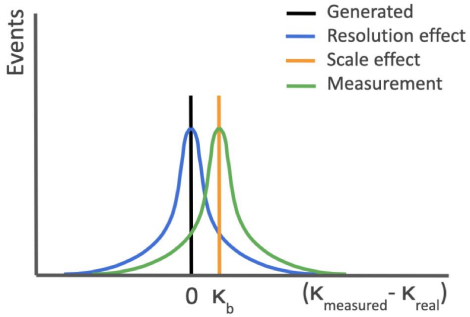
2022 data & MC resolution vs muon p_T, for barrel (left) & endcap (right)

Momentum scale for high-p_T muons





➢ In addition to the resolution effect, high-p_T muons can also suffer from scale effect, observed as a bias (κ_b) in the curvature measurement.



➢ Several effects can introduce a scale bias, in CMS the **detector misalignment** is the most relevant for high-p_T

Two possible cases: rotation of the muon system wrt the tracker affect the same way + and - muons, translated geometry affects differently depending on the charge.

➢ Quantified by the curvature bias (difference between the real and measured curvature), might be different for each detector region (η, Φ):

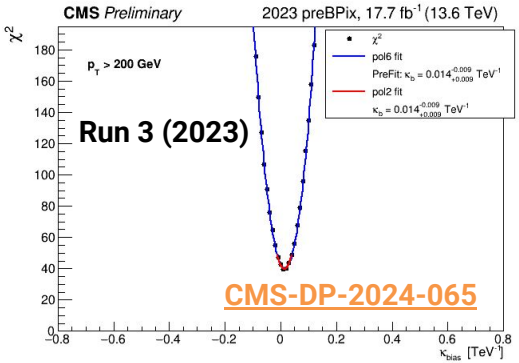
$$\kappa_b(\phi,\eta) = \kappa_{\text{measured}}(\phi,\eta) - \kappa_{\text{real}}(\phi,\eta)$$

Scale measurement: Generalized Endpoint Method

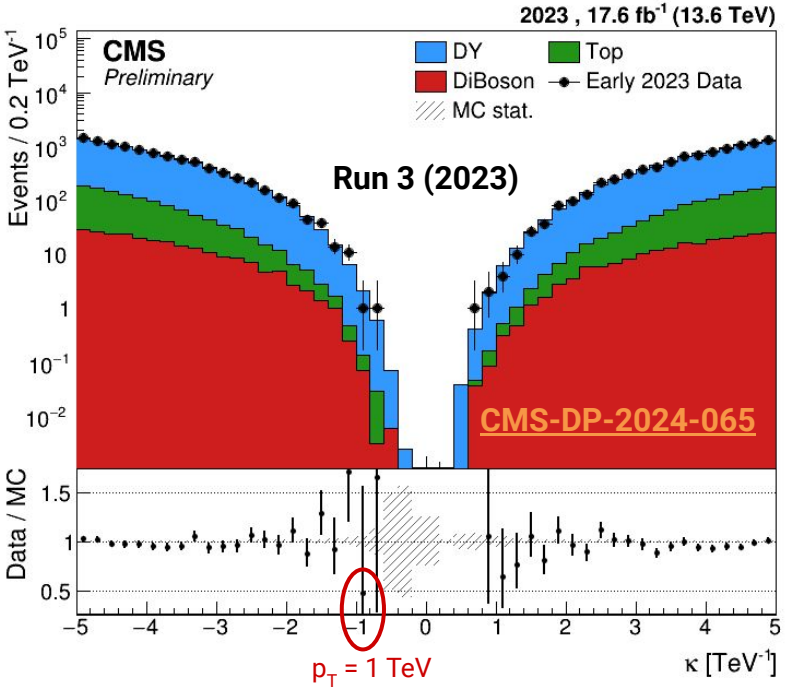
- High-p_T muon scale is measured with the Generalized Endpoint Method (GE) → Based on data vs MC comparison for the curvature ($\kappa = q/p_T$) distribution.
- An additive bias (κ_b) is injected in the simulation, such that the curvature distribution is distorted as:

$$q/p_T \rightarrow q/p_T + \kappa_b$$

- A χ^2 test is performed comparing data vs MC, as a function of the injected bias ⇒ The κ_b value that minimizes it would be the measured scale.



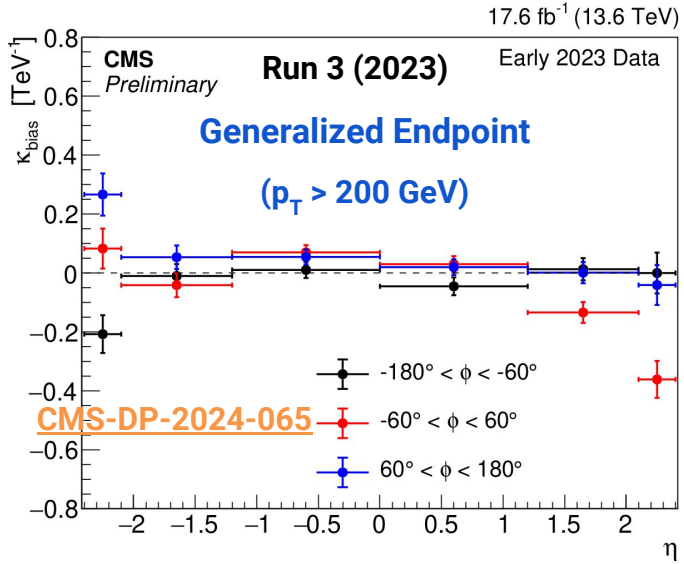
$$\chi^2(\kappa_b) = \sum_{i}^{nbins} \left(n^i_{data} - n^i_{MC}(\kappa_b)\right)^2$$

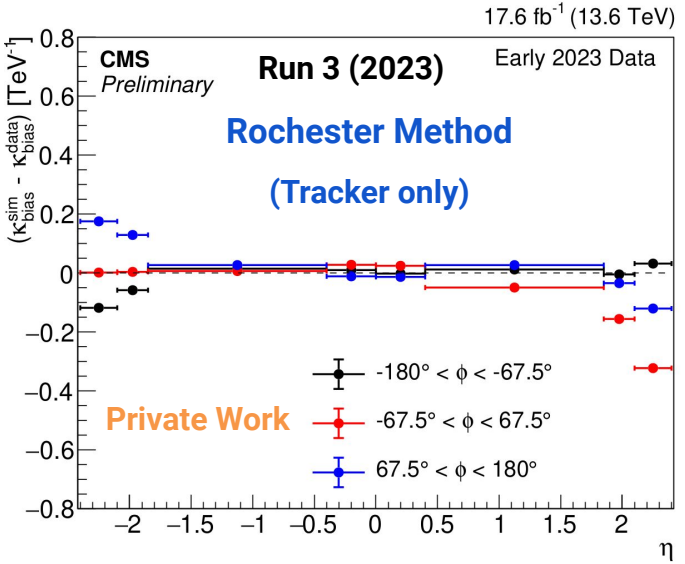


Data/MC comparison for the curvature distribution in 2023. Note that $\kappa = 5$ TeV^{-1} ⇔ $p_T = 200$ GeV

Momentum scale for high-p_T muons: Results

- The scale bias is measured for different η and Φ regions of the detector (left figure, 2023 data)
  - Only forward regions (|η| > 2.1) show significant discrepancies with zero scale bias → Largest measured scale is κ_b = -0.36 TeV^{-1} ⇒ For a 1 TeV muon, real p_T is 735 GeV (only in this region).
- GE results can be compared with the ones obtained for lower p_T (~ 50 GeV), with Rochester method *(right figure)* → **Results are compatible ⇒ Muon system not contributing significantly to the misalignment.**

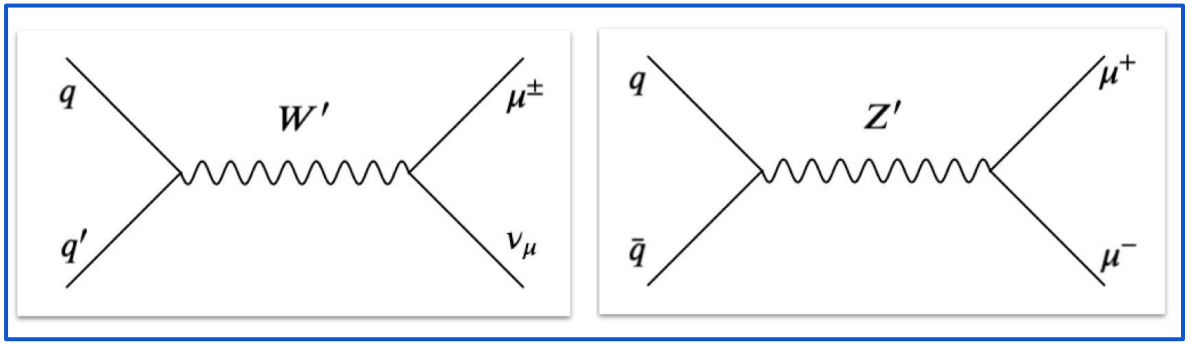




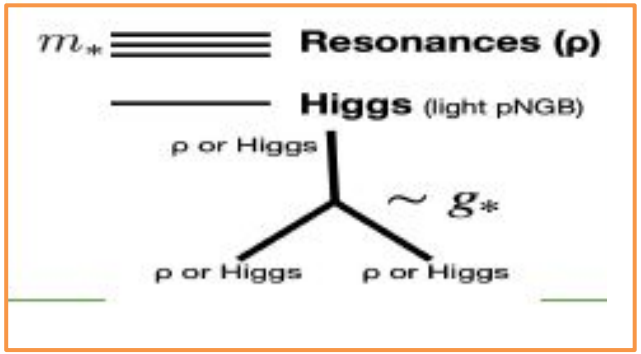
High-p_T muons in physics searches: BSM models

- Several BSM theories predict the existence of massive resonances (O[TeV])
  - One of the simplest model is **the Sequential Standard Model (SSM), predicting existence of additional heavy gauge bosons W' and Z'**, analogous to EWK W and Z bosons.
  - Other BSM models predict the **Higgs boson to be a composite particle**.
- These searches are performed looking at deviations from the SM prediction in the muon p_T or dilepton reconstructed mass distribution tails ⇒ **Correct description of the lepton object is a key aspect.**

SSM W', Z'

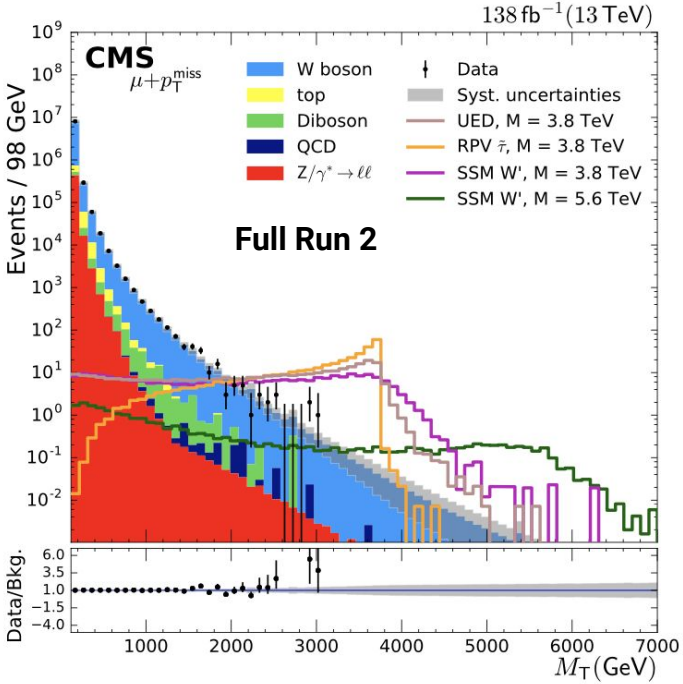


Higgs Compositeness

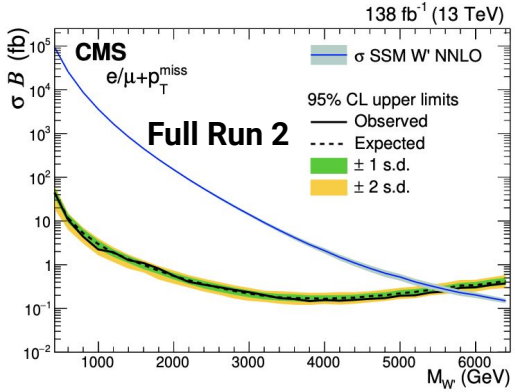


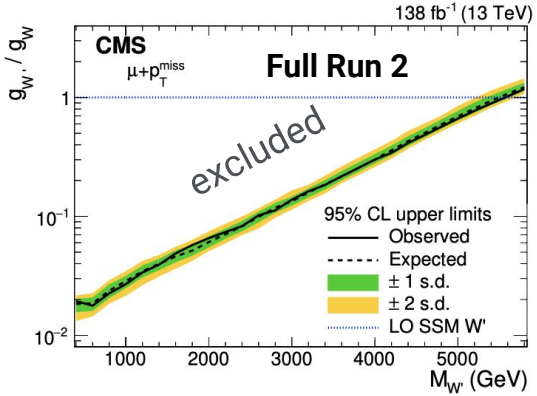
W' analysis

- **Search for a W' resonance** decaying to a lepton (e, μ) plus missing transverse momentum, using as final discriminant the transverse mass (m_T) of the lepton + p_T^{miss} system
  ⇒ **Run 2 published analysis: 10.1007/JHEP07(2022)067 → Run 3 (2022 + 2023 ⇒ L = 60 fb^{-1}) ongoing**



- Limit set on SSM W' σ x B(W' → lν) for electron + muon channel is **$M_{W'}$ > 5.7 TeV** at 95% CL *(left plot)*.
- The case where the coupling is different to that of the SM W ($g_{W'} \neq g_W$) also studied → Area above limit excluded *(right plot)*.





Electroweak oblique parameters

- In the case that the scale of new physics, Λ, is outside the kinematic reach of the LHC **(Λ ≫ √s)**, we can still be sensitive to it by means of the **EWK oblique parameters** S, T, **W, Y** (zero in SM)
  - S, T measured by LEP, dominant at low energies → **LHC sensitive to W and Y, which grow with √s**

- The procedure consists in reweighting the MC simulation, on an event-by-event basis, with a weight given by the ratio of the propagators of the EWK gauge bosons from the effective Lagrangian (incorporating W, Y) wrt the SM one.

Charged current (W)

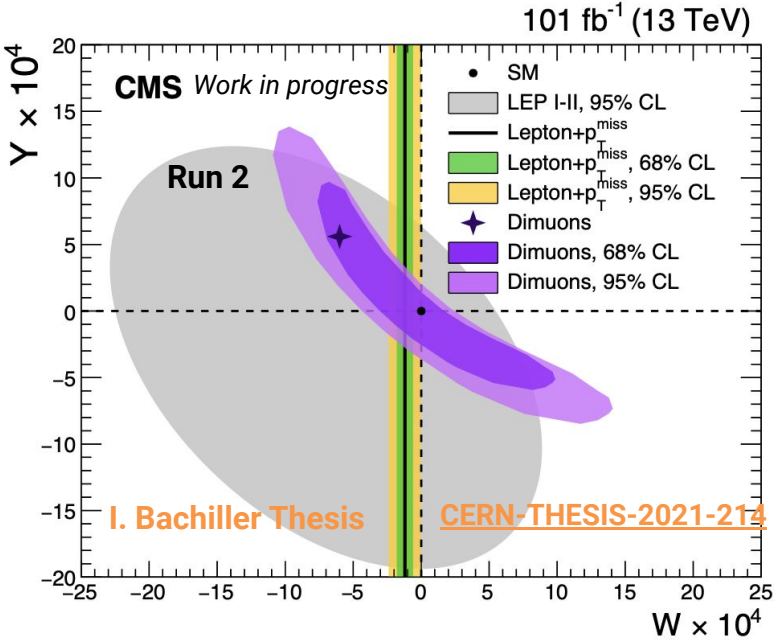
$$\rho_c(q^2|W) = \left(1 - W\,\frac{(q^2 - m_W^2)}{m_W^2}\right)^2$$

- Search in the lepton + p_T^{miss} final state (same as W')
- Only sensitive to W
- Measured with 2017 + 2018 data in e + μ *(black line in the plot)*

Neutral current (W, Y)

$$\text{Weight}(q^2, z, W, Y) = \frac{\left[\frac{d\sigma}{dz}(q^2, z, W, Y)\right]}{\left[\frac{d\sigma^0}{dz}(q^2, z)\right]}$$

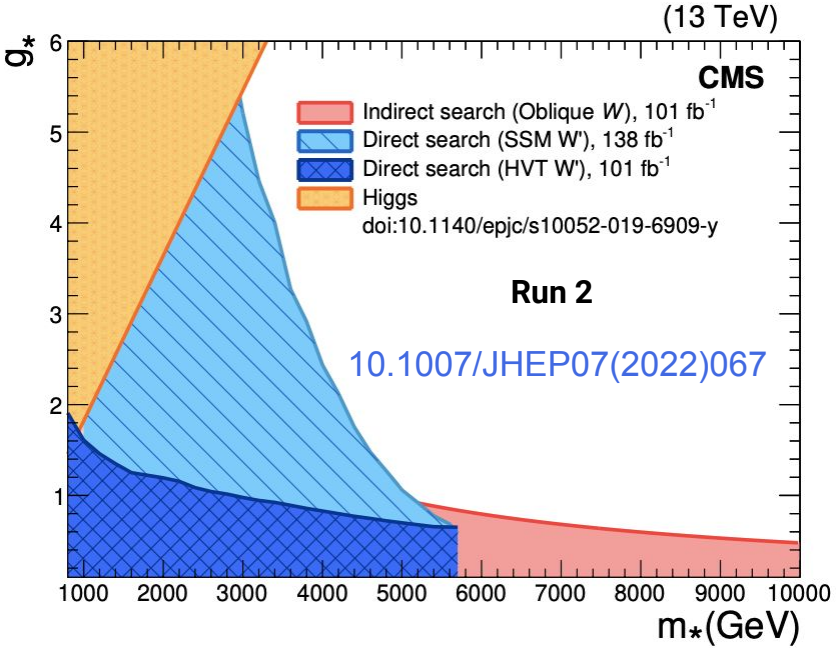
- Search in the charged dilepton final state (same as Z')
- Sensitive to both W and Y
- Measured with 2017 + 2018 data in $\mu^+\mu^-$ *(purple point in the plot)*



Higgs Compositeness

Full Run 2 + Run 3 (2022 + 2023) analysis for e + μ channel ongoing at CIEMAT!

- Some BSM models (SILH) predict the Higgs boson to be a composite particle.
- Two parameters characterize the model: the **mass scale of the new composite resonances, m***, and the **coupling strength of the new interactions, g***.



Two ways of exploring composite sector in l + p_T^{miss}

A. Indirect Search:

New physics scale above LHC access ($\Lambda \gg \sqrt{s}$) → Can use constraints on W parameter to set limits on m* - g*

$$g_*^2 = \frac{g_W^2 M_W^2}{W m_*^2}$$ → **g* < (4770 GeV) / m***

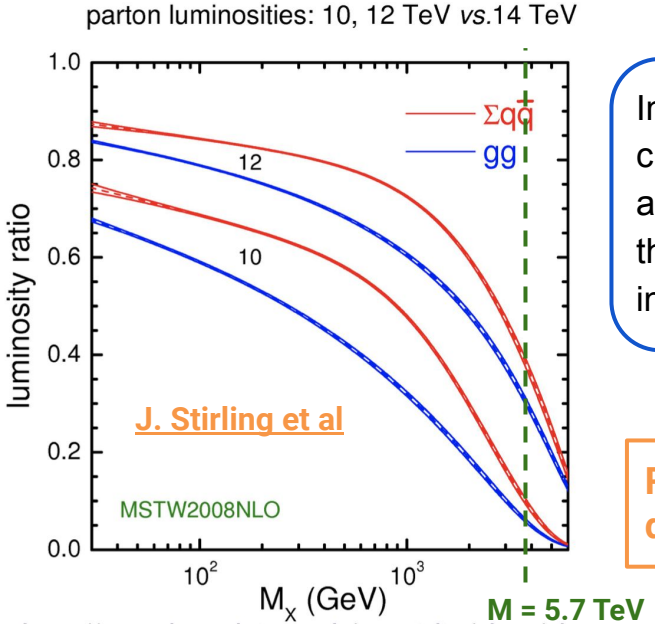
B. Direct Search:

Search for a potential W' resonance, both in the **SSM** and **HVT** (decays to bosons allowed) scenarios, based on the coupling strength ($g_{W'}$) limits

$$g_{W'} = \frac{g_W^2}{g_*}$$

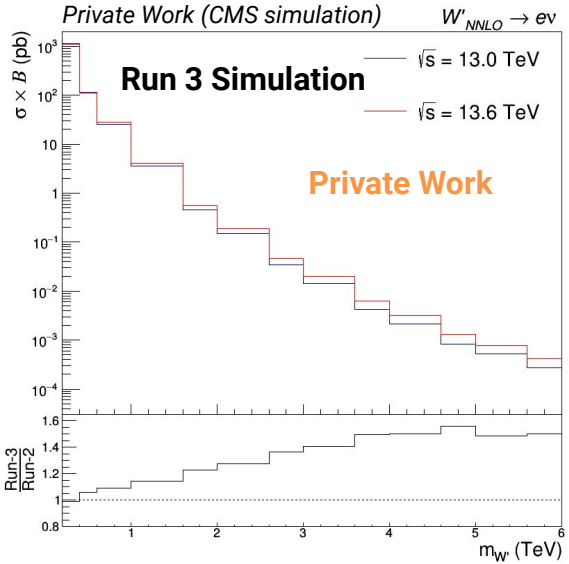
Why keep searching? Sensitivity improvement in Run 3

- In Run 3, the pp collision energy has been increased to √s = 13.6 TeV (from 13 TeV in Run 2)
- The parton luminosity (~cross section) improvement due to the increase of the collision energy (√s) depends on the actual mass of the resonance in question → **The bigger the mass, the larger the improvement is.**



Increase of SSM W' production cross section in Run 3 vs Run 2 as a function of the W' mass. At the highest mass values, the increase is ~ 50%

Run 3 paper with 2022 + 2023 data is ongoing at CIEMAT!



Summary

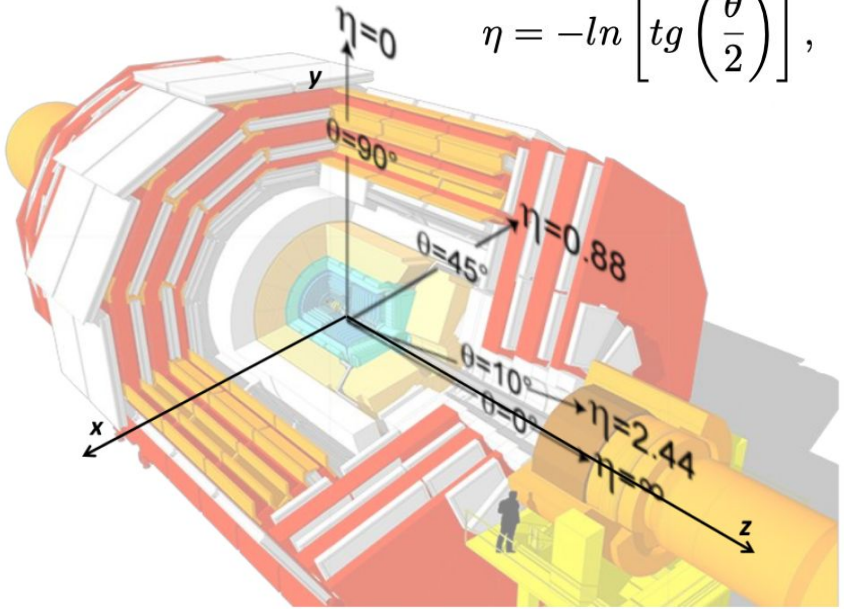
- The Run 3 dataset, with larger statistics (so far 180 fb^{-1}, expected > 300 fb^{-1}) and at higher energy ($\sqrt{s}$ = 13.6 TeV) wrt its precedent Run 2, offers a great opportunity for searches.
- High-p_T muons have particular characteristics (showering, straight trajectory, low statistics), requiring specific algorithms to measure (TuneP) and identify (High-p_T ID) them .
- A precise description is needed → Several performance studies presented in terms of trigger efficiency, momentum resolution and momentum scale with the Generalized Endpoint Method.
- **Physics searches:** High-p_T muons key object for many BSM scenarios
  - W' resonance searches → Run 2 results guide expectations for **Run 3, ongoing (CIEMAT).**
  - EWK oblique parameters measuring SM deviations, interpreted in terms of Higgs compositeness → **Run 3 ongoing (CIEMAT), both l + p_T^{miss} and l^+l^- final states.**
- **Room for improvement:** Increase in collision energy and recorded luminosity improves the expected sensitivity.

BACKUP

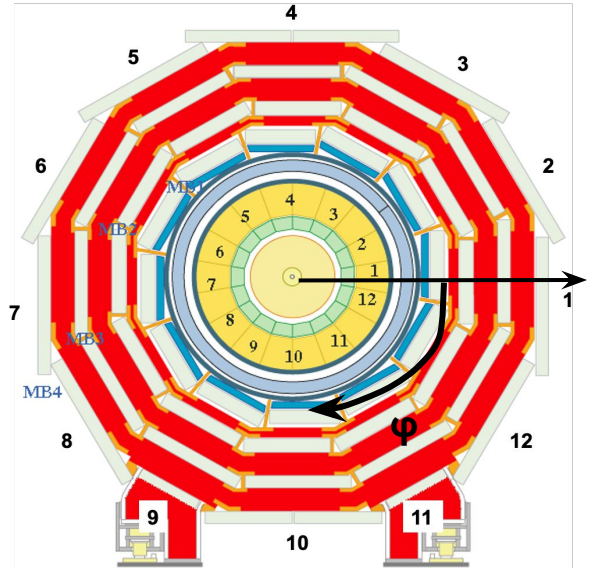
CMS coordinate system

Polar angle θ & pseudorapidity η

$$\eta = -ln\left[tg\left(\frac{\theta}{2}\right)\right],$$



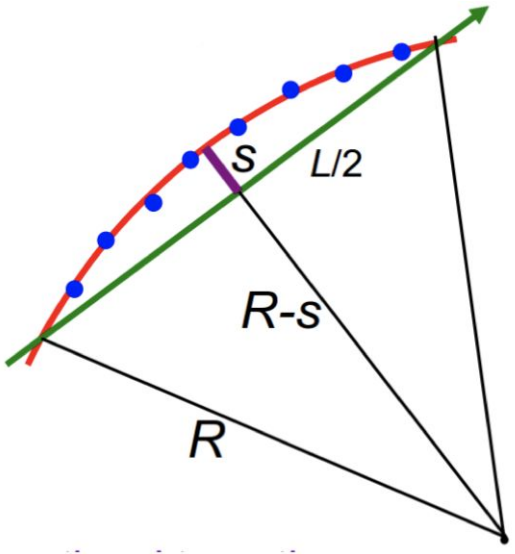
Azimuthal angle φ



Muon p_T measurement from the track

As a first approximation, the measurement of the muon pT depends on the magnetic field B and the radius of curvature R of the track:

$$p_T \text{ [GeV]} = | 0.3 \, B\text{[T]} \, R\text{[m]} |$$



The radius of the track determined indirectly via measurement of experimental observable sagitta, *s* (see figure). The radius of curvature is related to the arc length *L* and sagitta *s* of the track via

$$R \text{ [m]} \approx L^2 \text{ [m]} / 8s \text{ [m]}$$

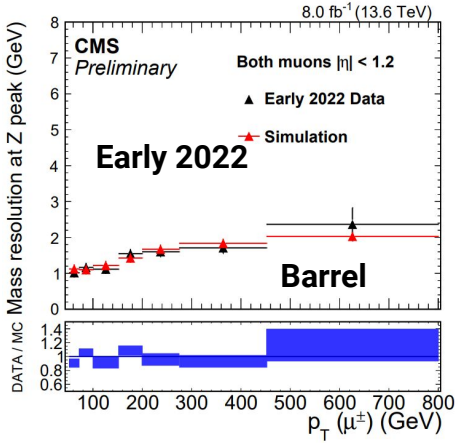
where the approximation is valid for $L/R \ll 1$. Assigning arithmetic signs consistently to *R*, *s*, and the charge *q* (in units of proton charge) yields

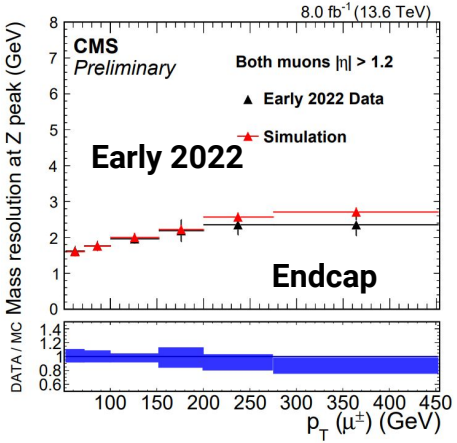
$$s \text{ [m]} \approx (0.3 \, B\text{[T]} \, L\text{[m]} \, 2/8)(q/p_T \text{ [GeV]}) = (0.3 \, BL^2/8) \, \kappa$$

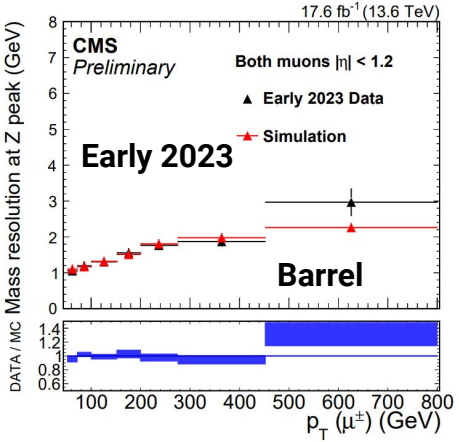
$\kappa = q/p_T$ is the (signed) curvature of the muon track. *s* linearly related to measurement of hit positions in the detector (approximately symmetric uncertainties) ⇒ Uncertainty in κ (rather than p_T) from cumulative effect of hit uncertainties is (approximately) Gaussian ⇒ κ is the more natural variable for use in muon momentum resolution and scale studies

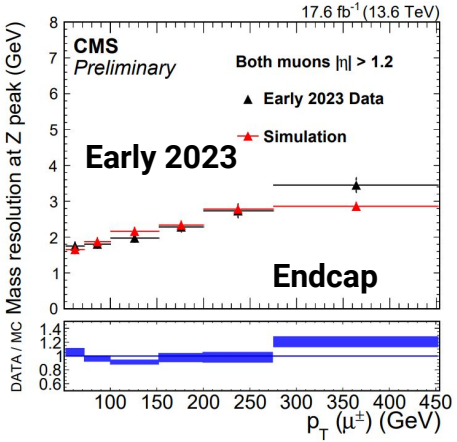
High-p_T muon resolution for 2022 & 2023

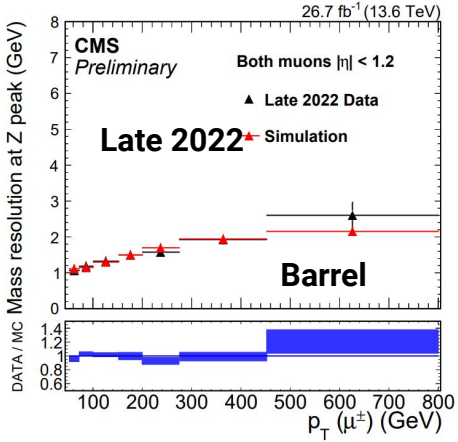
CMS-DP-2024-065

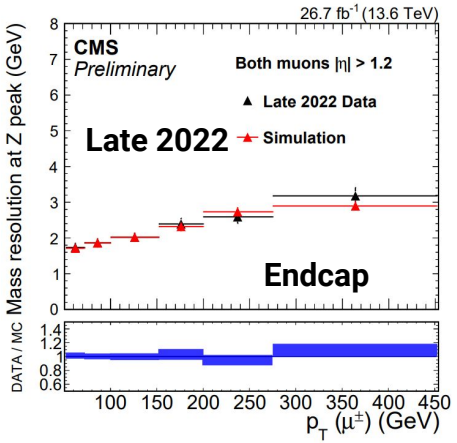


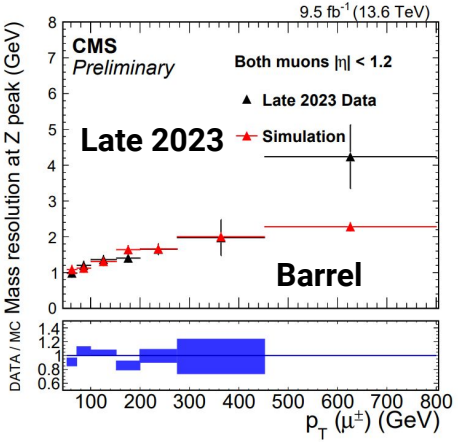


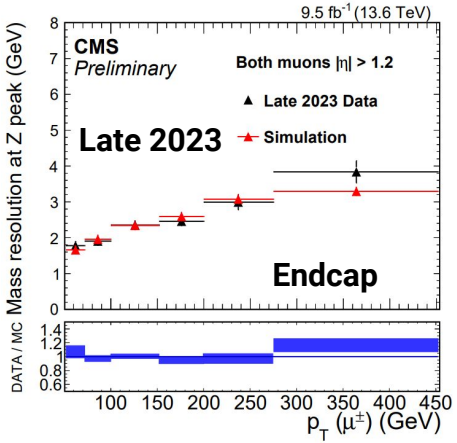












High-p_T muon scale for 2022 & 2023

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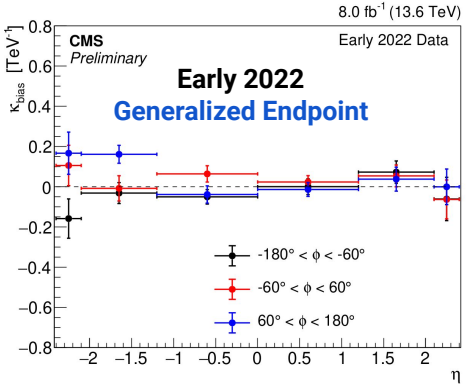

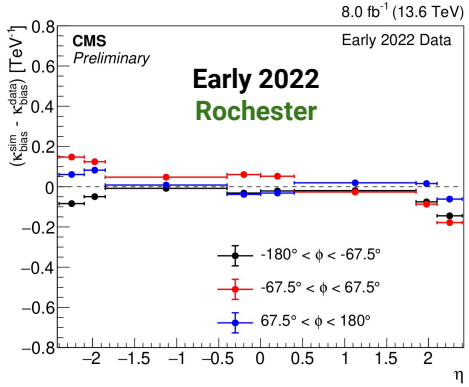

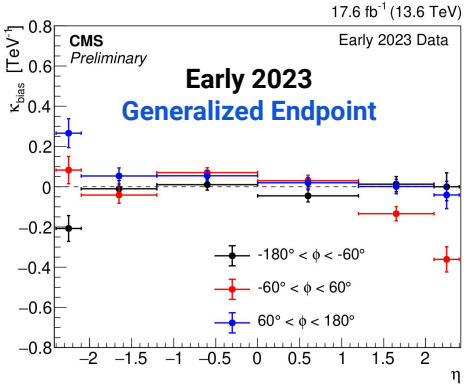

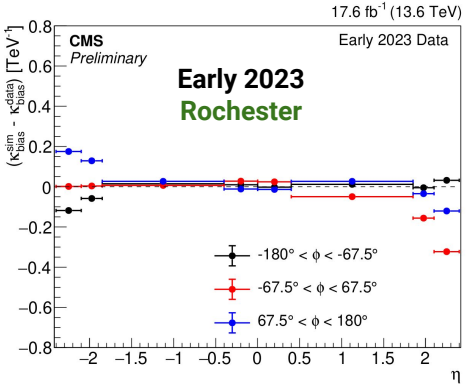

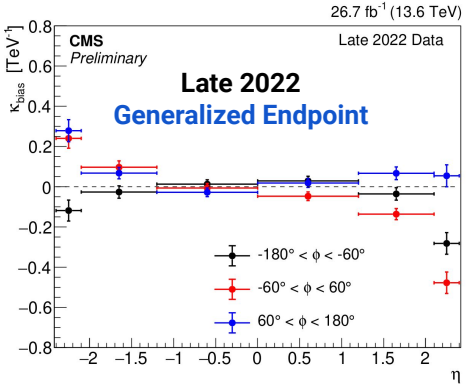

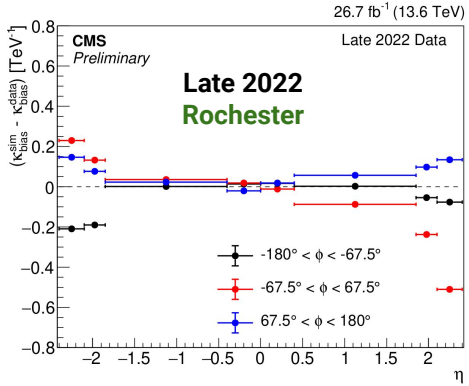

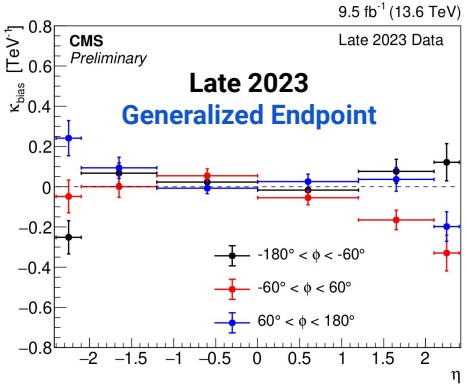

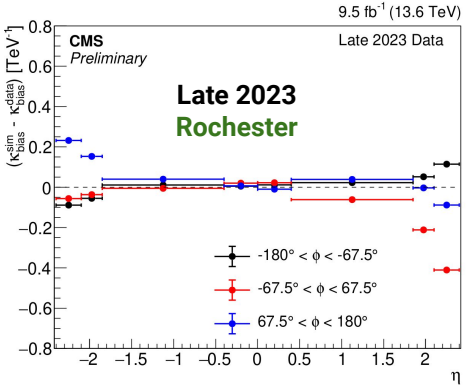

MC reweighting with W and Y oblique parameters (Charged)

In the presence of non-vanishing W and Y parameters, the propagator of the SM charged (W) electroweak gauge bosons should be modified as

$$P_W(q^2,W,Y) = \frac{1+((2t^2-1)W+t^2Y)/(1-t^2)}{q^2-M_W^2} - \frac{W}{M_W^2}$$

In the charged current case, where the measurement of the oblique parameters is done studying the final state containing a charged lepton + a neutrino, the propagator given by the SM is $P_W^{(0)} \equiv 1/(q^2 - M_W^2)$, and the relative deviation wrt the SM prediction would be given by the ratio

$$\left|\frac{P_W}{P_W^{(0)}}\right|^2 = \left(1+\frac{(2t^2-1)W}{1-t^2}+\frac{t^2Y}{1-t^2}-\frac{W(q^2-M_W^2)}{M_W^2}\right)^2$$

This ratio is used to reweight the MC simulation of the SM process $W \rightarrow l\nu$. Now, since current bounds on W and Y are quite stringent ($< 10^{-2}$), the terms that do not depend on q^2 (energy of the collision), are negligible in practice, leading to a weight that is independent of Y

$$\mathrm{Weight}(q^2,W,Y) \xrightarrow[\mathrm{large}\, q^2]{} \left(1-\frac{W q^2}{M_W^2}\right)^2 \equiv \mathrm{Weight}(q^2,W)$$

MC reweighting with W and Y oblique parameters (Neutral)

In the neutral current case, where the measurement of the W and Y oblique parameters is performed in the charged dilepton final state, the reweighting procedure, in this case for the SM Drell-Yan process ($Z/\gamma^* \rightarrow ll$), is done in an analogous way as for the charged current case.

However, here the expression of the differential cross section away from the Z boson resonance peak depends on q^2, as before, but also on $z = \cos\theta$, where θ is the Collins-Soper angle, which is the polar angle of the final state lepton wrt the initial state quark, in the quark-antiquark center-of-mass system. The weight would be

$$\rho_{\mathrm{n}}(q^2, z|W, Y) = \frac{\sum_{\chi_{\mathrm{q}},\chi_\ell} (1+\delta_{\chi_{\mathrm{q}}\chi_\ell} z)^2 \left|(C^0_{\mathrm{SM}}(q^2, z; \chi_{\mathrm{q}}, \chi_\ell) + C^0_{\mathrm{BSM}}(z, \chi_{\mathrm{q}}, \chi_\ell|W, Y)\right|^2}{\sum_{\chi_{\mathrm{q}},\chi_\ell} (1+\delta_{\chi_{\mathrm{q}}\chi_\ell} z)^2 \left|C^0_{\mathrm{SM}}(q^2, z; \chi_{\mathrm{q}}, \chi_\ell)\right|^2}$$

where the δ is +1 if quark (χ_q) and lepton (χ_l) chiralities are equal, and -1 otherwise. The factors $C^0_{\mathrm{SM}}(q^2, z, \chi_q, \chi_l)$ and $C^0_{\mathrm{BSM}}(q^2, z, \chi_q, \chi_l | W, Y)$ are proportional to the SM and BSM amplitudes of the process, respectively.