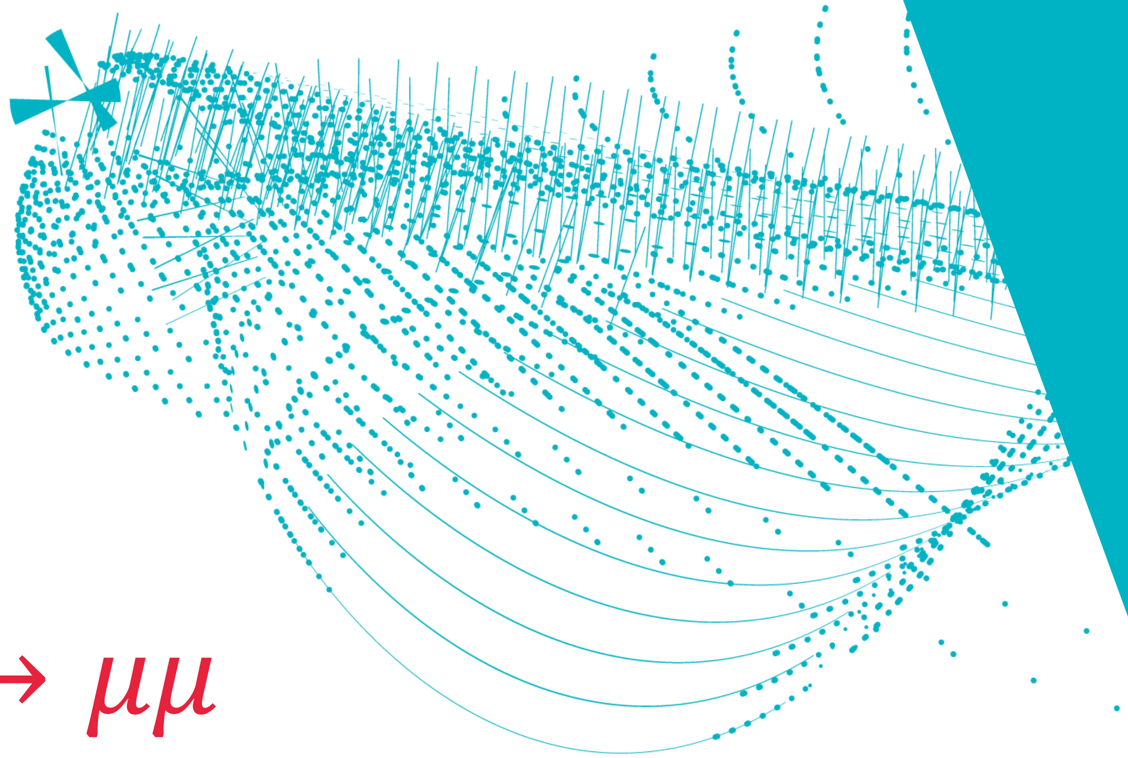
M. BAREL,
P. KLUIT, O. RIEGER, W. VERKERKE



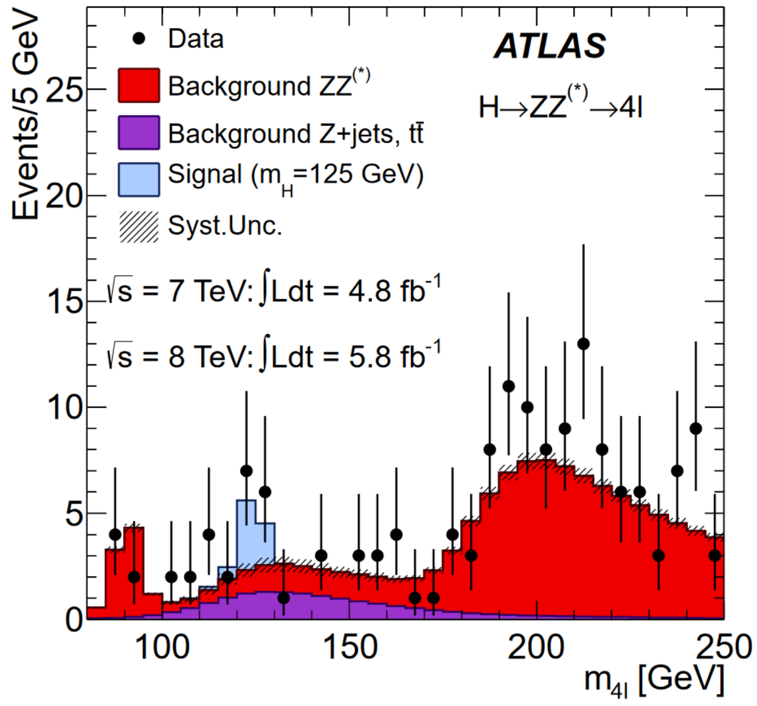
IMPROVING THE $H \rightarrow \mu\mu$ INVARIANT MASS RESOLUTION

NNV Fall Meeting
08-11-2024

Source: ATLAS Higgs Discovery

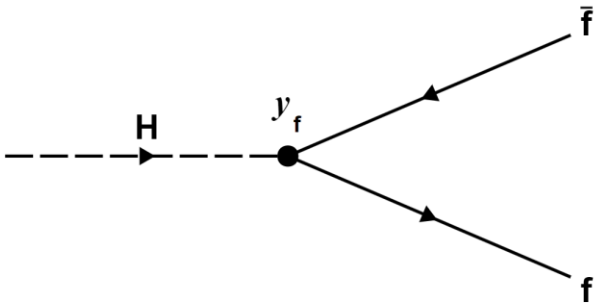
Introduction

Discovery of the Higgs boson (H) in 2012 was a major milestone in the LHC program, and gave evidence for the mechanism[1] that allows for massive gauge bosons in the Standard Model



Particles couple to the Higgs via Yukawa interactions.
Strength of this coupling is proportional to particle mass

$$\frac{y_f}{\sqrt{2}} = \frac{m_f}{v}$$



Where v is a property of the Higgs field

1) As proposed by Brout, Englert, Higgs, Guralnik, Hagen and Kibble in 1964

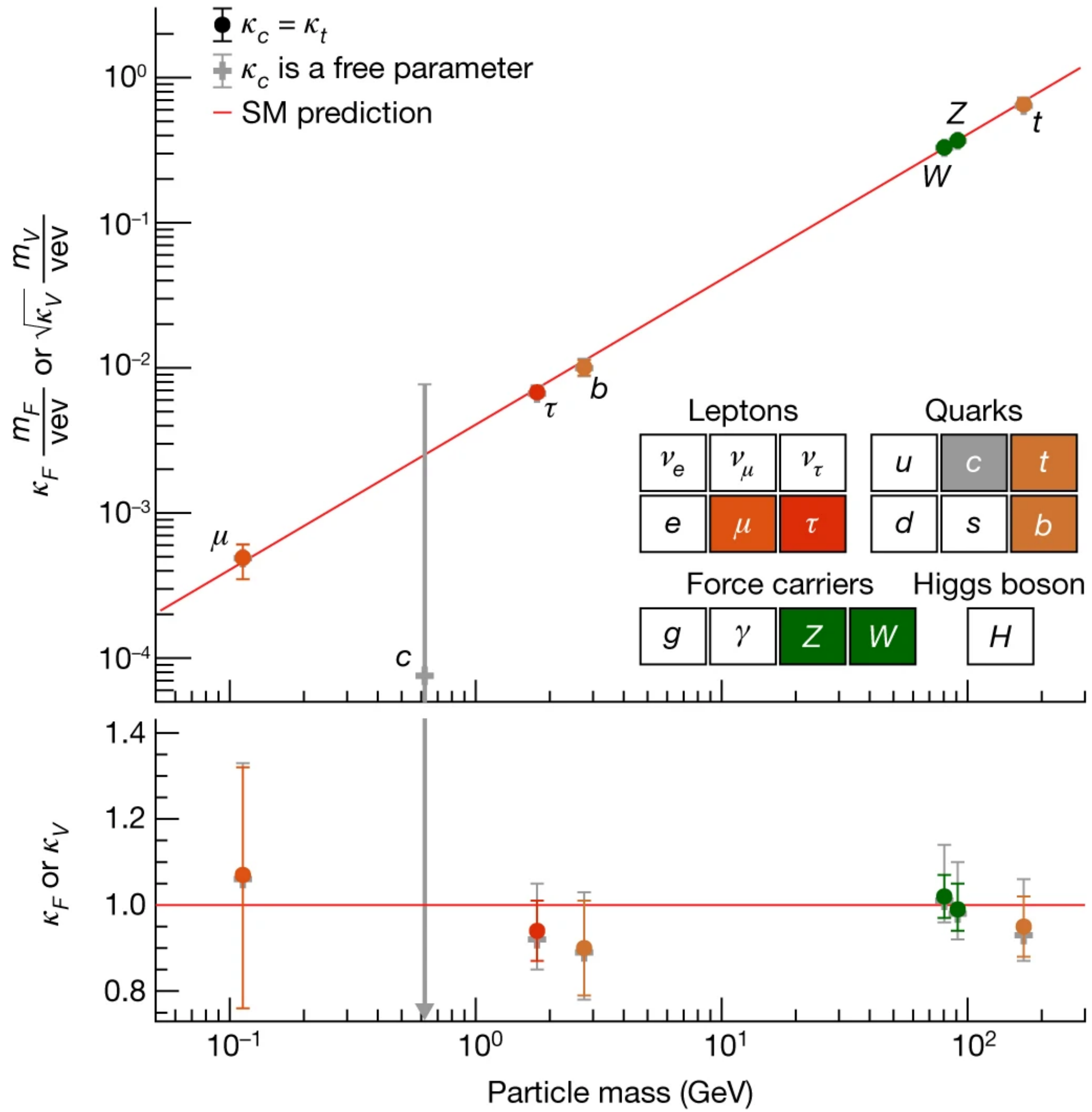
Source: [Nature]

Introduction

Ongoing effort since Higgs discovery to map Yukawa couplings of Higgs to SM particles

Today, couplings to Vector Bosons and 3rd generation fermions have all been measured at $> 5\sigma$

Next step to look at couplings with 2nd generation fermions: c, s and μ



ATLAS EXPERIMENT

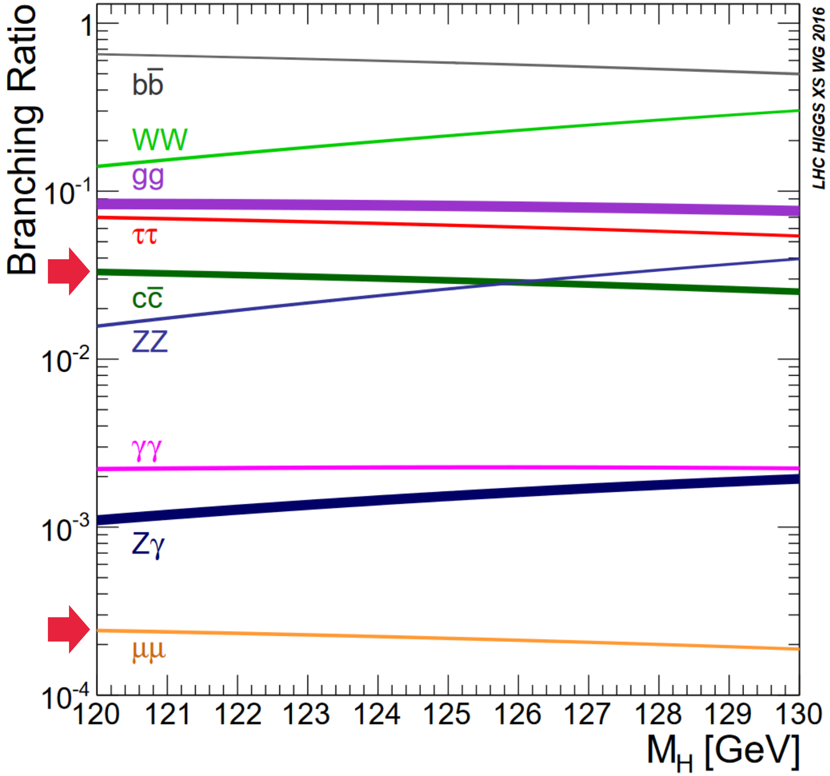
Nikhef

Measuring 2nd generation Yukawa couplings

Couplings to c and s are challenging due to large soft QCD backgrounds in pp collisions and, especially for s, small branching ratios (BRs) of 3% and 0.02%

Compared to c and s, μ decay provides an experimentally very clean signature, despite a BR similar to s

So far, only c and μ couplings have been studied, $H \rightarrow \mu\mu$ is closest to discovery having been measured at 2.0 and 3.0 σ by ATLAS and CMS respectively

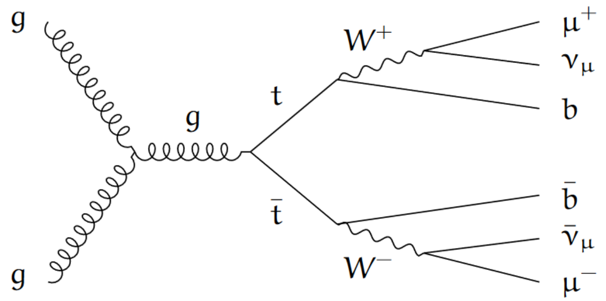


Source: CERN Yellow Report 4

$H \to \mu\mu$: Easy pickings?

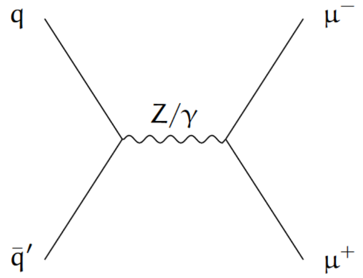
Despite the clean signature and simple decay geometry, still a challenging measurement due to large backgrounds from vector boson and top pair decays

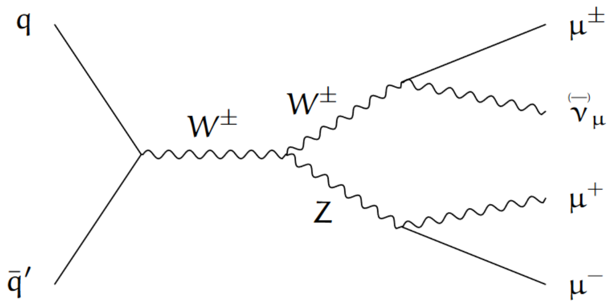
Three main background processes



t – pair production

Drell-Yann ($Z/\gamma^\star$)

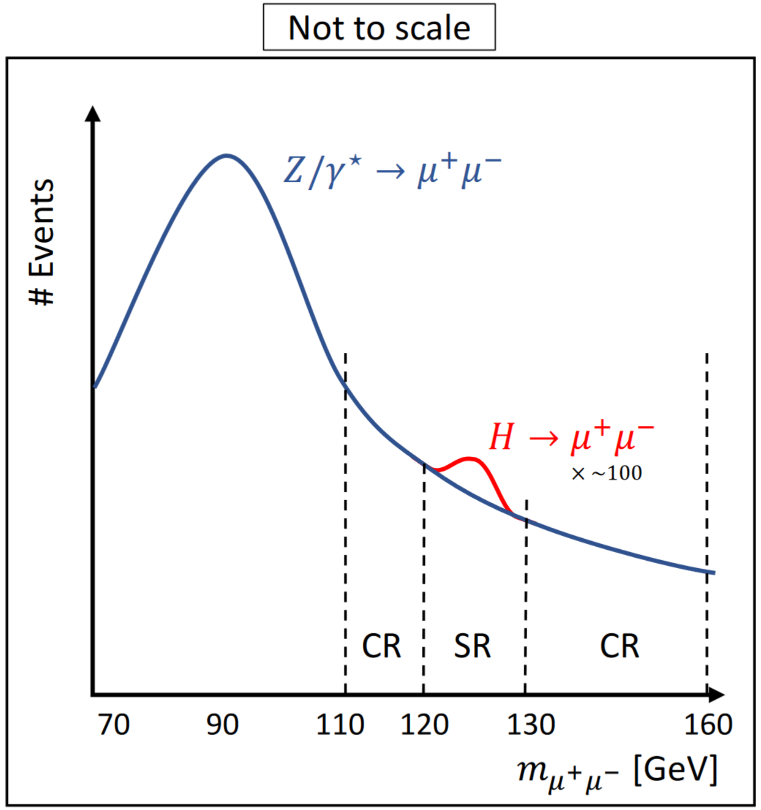




Diboson ($WZ/WW/ZZ$)

Diagram source: [PhD Thesis A. Alfonsi]

Finding the Higgs



Look for a bump on a smoothly falling background in the region $m_{\mu\mu} \in [110 - 160]$ GeV

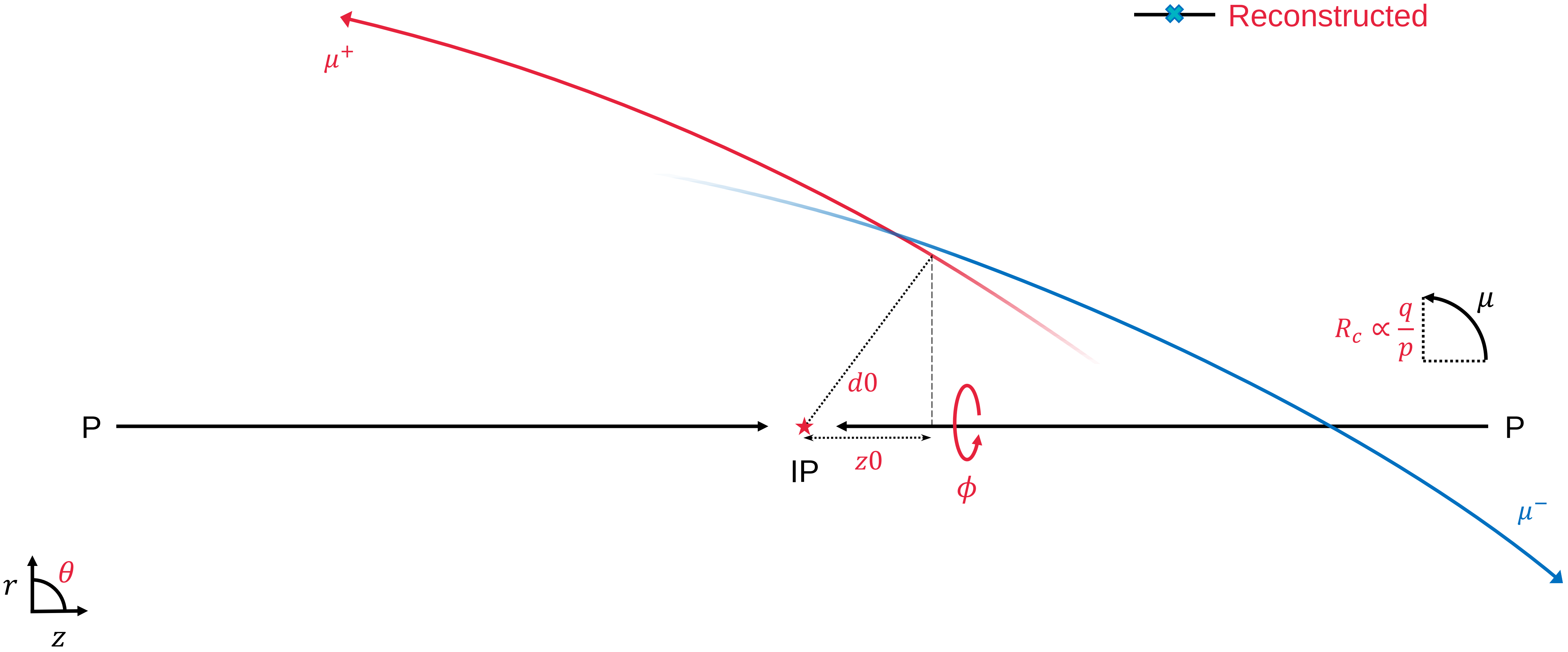
$$\frac{S}{B}_{[SR]} = \frac{\sigma(pp \to H) \cdot BR(H \to \mu\mu)}{\sigma(pp \to Z/\gamma^\star) \cdot BR(Z/\gamma^\star \to \mu\mu)} = \frac{1.17 \times 10^{-2}\, pb}{6.7\, pb} = 0.002$$

Boost sensitivity in order to see anything

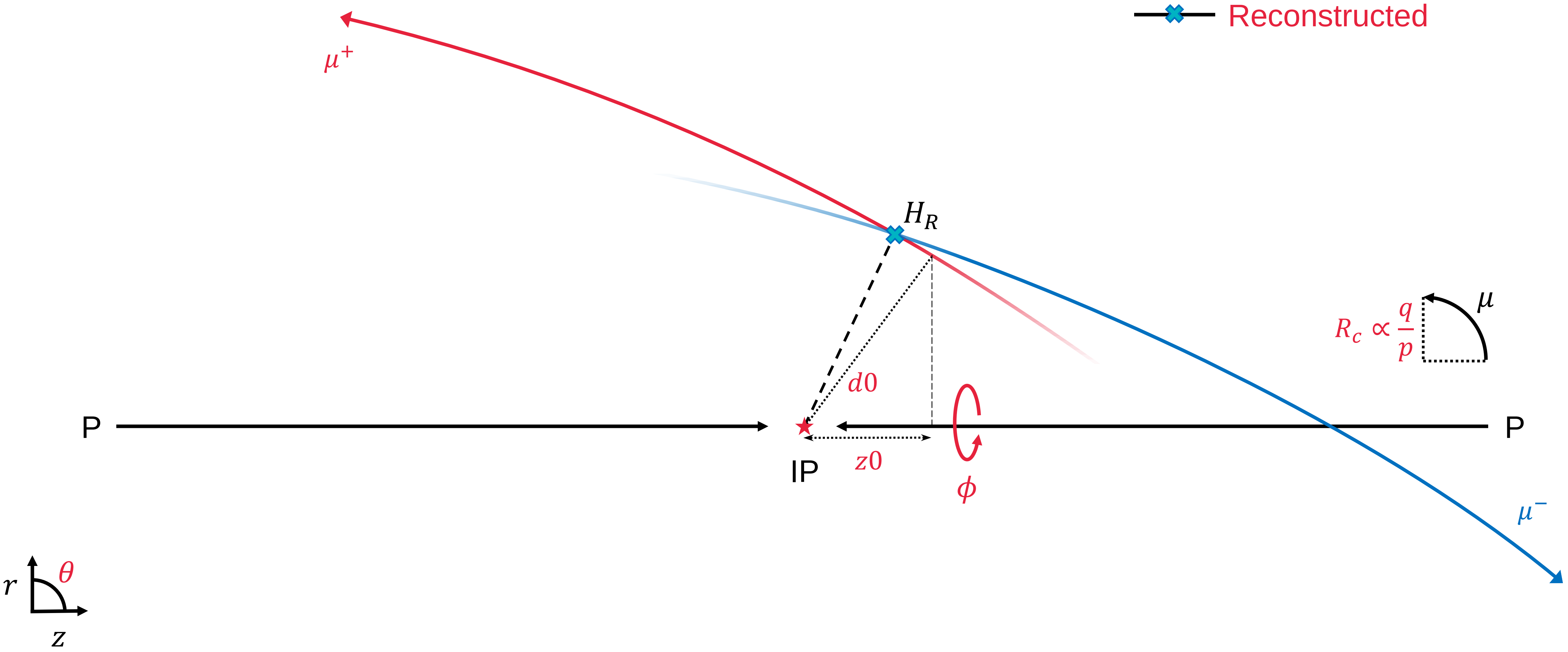
- Reduce B through selections/cuts/ML techniques[2] → Already done
- Increase amount of data → Time
- Improve di-muon invariant mass resolution → This talk

2) A talk on this topic was given earlier today by Karel de Vries

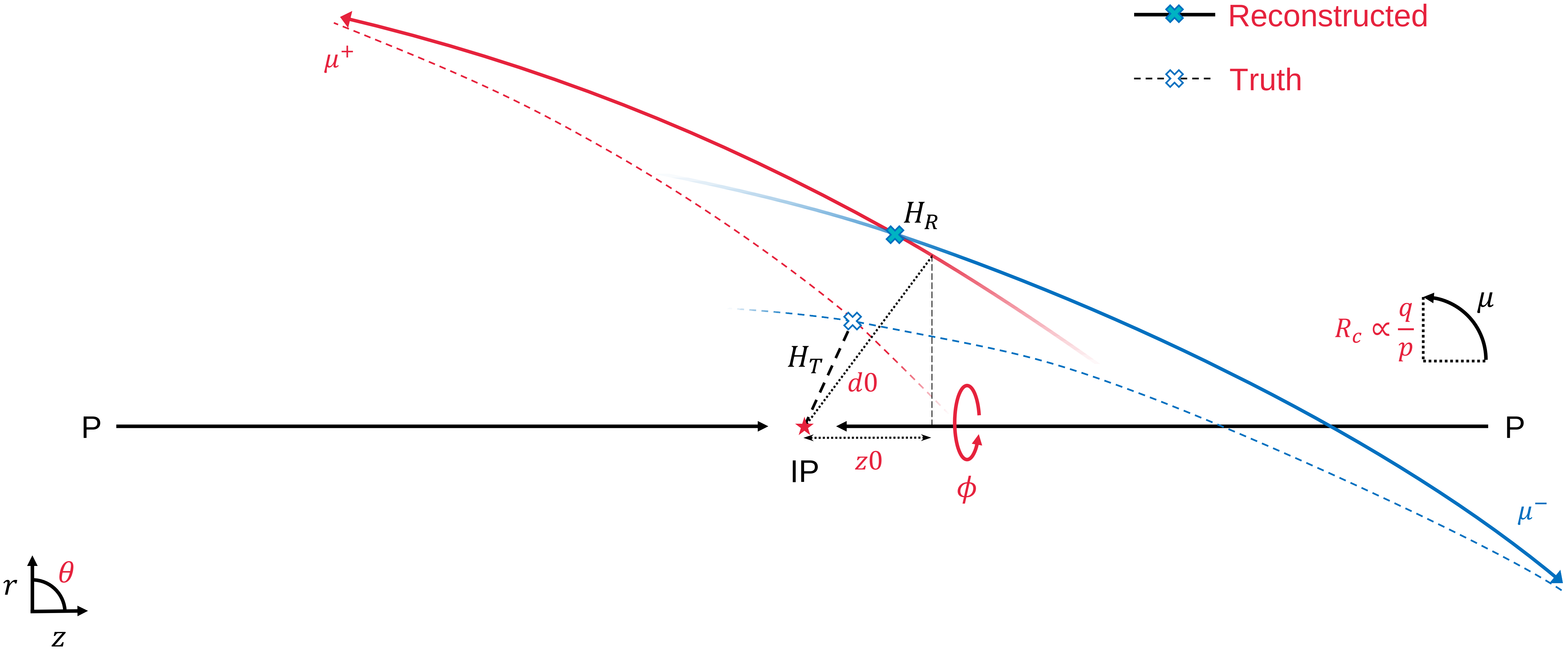
Exploiting $H \rightarrow \mu^+\mu^-$ decay geometry



Exploiting $H \to \mu^+\mu^-$ decay geometry

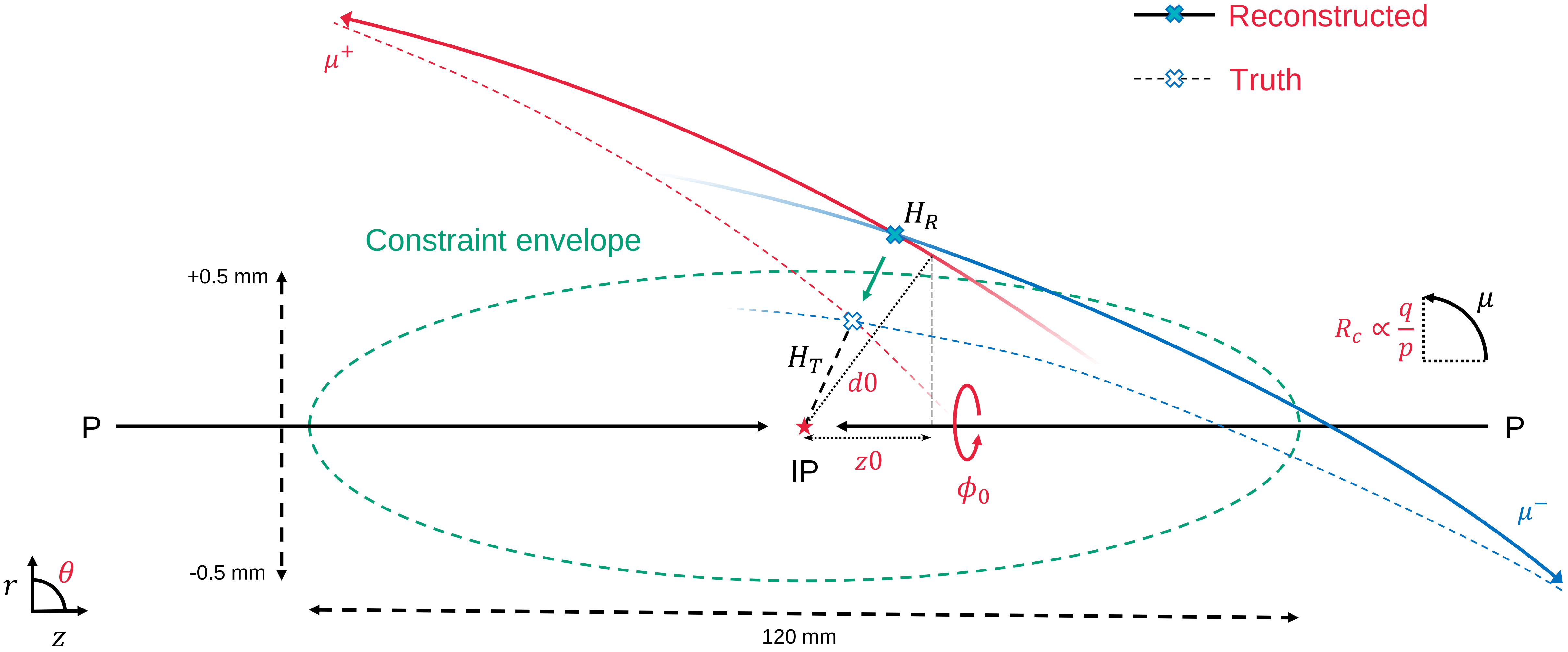


Exploiting $H \to \mu^+\mu^-$ decay geometry

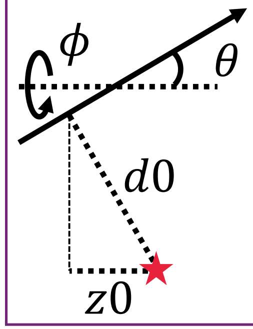


ATLAS EXPERIMENT
Nikhef

Exploiting $H \to \mu^+\mu^-$ decay geometry



Method/Fitting Math



The Higgs decay vertex is fitted using a modified χ^2 fit, adding a constraint term:

$$\chi^2(\boldsymbol{\xi}) = \left(\boldsymbol{u} - \boldsymbol{\mu}(\boldsymbol{\xi})\right)^T C^{-1}\left(\boldsymbol{u} - \boldsymbol{\mu}(\boldsymbol{\xi})\right) + \left(\frac{\Delta x_V}{\sigma_{x,V}}\right)^2 + \left(\frac{\Delta y_V}{\sigma_{y,V}}\right)^2 + \left(\frac{\Delta z_V}{\sigma_{z,V}}\right)^2$$

Where $\sigma_{i,V}$ give the constraint envelope size and $\Delta i_V = i_o - i_V$ the distance between the envelope origin and the fitted vertex position

$$\boldsymbol{u} = \begin{pmatrix} \boldsymbol{P}_1 \\ \boldsymbol{P}_2 \end{pmatrix}, \quad \boldsymbol{\mu}(\boldsymbol{\xi}) = \begin{pmatrix} \boldsymbol{P}'_1 \\ \boldsymbol{P}'_2 \end{pmatrix}.$$

With track parameters $\boldsymbol{P}^{(\prime)}$:

$$\boldsymbol{P_i} = \begin{pmatrix} d0 \\ z0 \\ \phi 0 \\ \theta \\ \frac{q}{p} \end{pmatrix}_{Reco}, \quad \boldsymbol{P}'_{\boldsymbol{i}} = \begin{pmatrix} d0' \\ z0' \\ \phi 0 \\ \theta \\ \frac{q}{p} \end{pmatrix}$$

$d0$ and $z0$ are given by

$$d0_{Reco} = -x_p \sin\phi_0 + y_p \cos(\phi_0)$$
$$z0_{Reco} = z_p - d0\cos(\theta)/\sin(\theta)$$

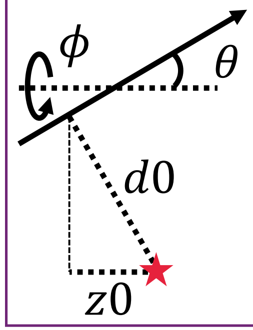
$d0'$ and $z0'$ by

$$d0' = d0_{Reco} - \Delta d0$$
$$z0' = z0_{Reco} - z' + \Delta d0\cos(\theta)/\sin(\theta)$$

With

$$\Delta d0 = -x'\sin(\phi_0) + y'\cos(\phi_0)$$

Method/Fitting Math



Fit is performed by solving

$$\nabla\chi^2(\boldsymbol{\xi}) = 0,$$

using

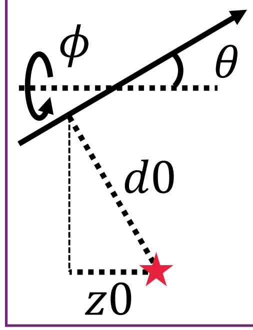
$$\boldsymbol{\xi} = \begin{pmatrix} x' \\ y' \\ z' \\ \widehat{P_1} \\ \widehat{P_2} \end{pmatrix}$$

With reduced track parameters

$$\widehat{P_i} = \begin{pmatrix} \phi 0_i \\ \theta_i \\ \left(\frac{q}{p}\right)_i \end{pmatrix}$$

Since $\boldsymbol{\mu}(\boldsymbol{\xi})$ is non-linear in this case, the fit needs to be performed by iterating

Results



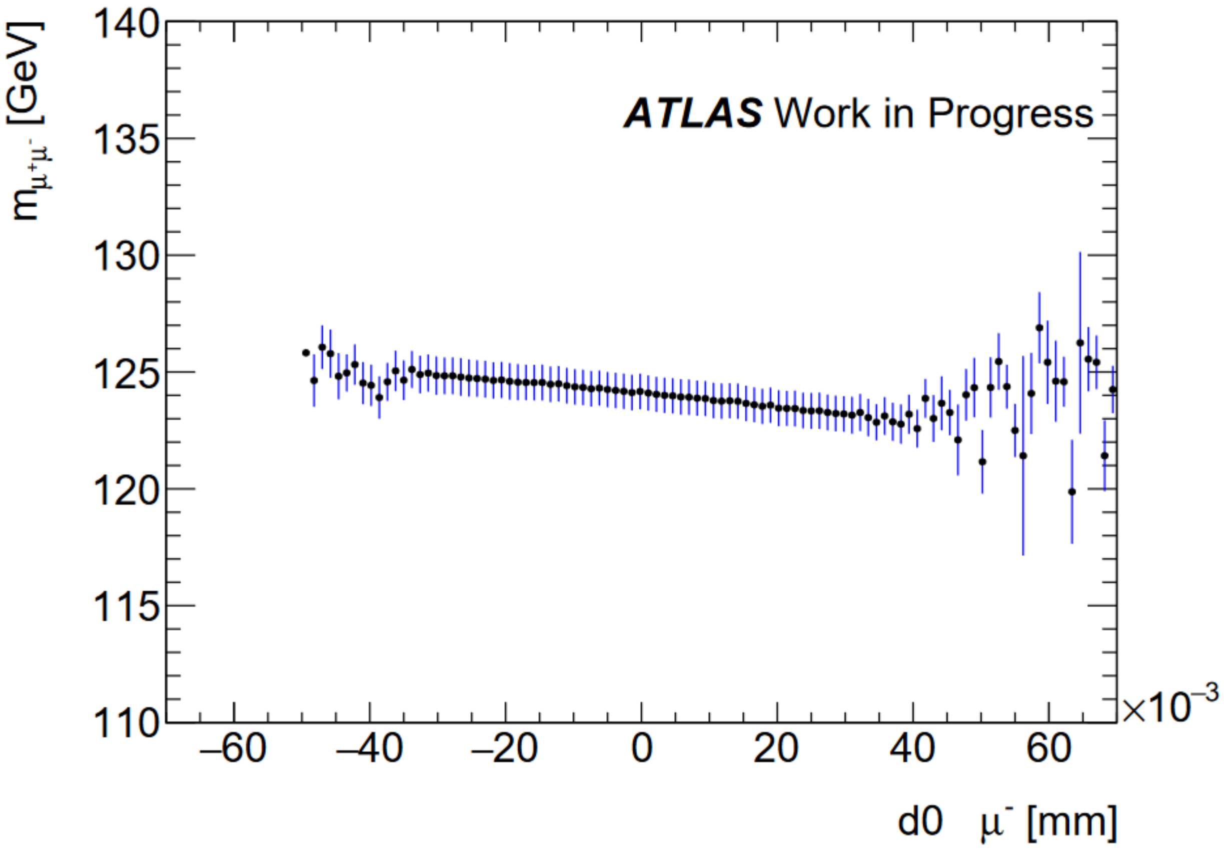
The fit will update the values for d0 and z0 for both muons and through covariance, the other track parameters ϕ, θ and q/p

With these updated track parameters the invariant mass is then recalculated, changing the shape of the distribution

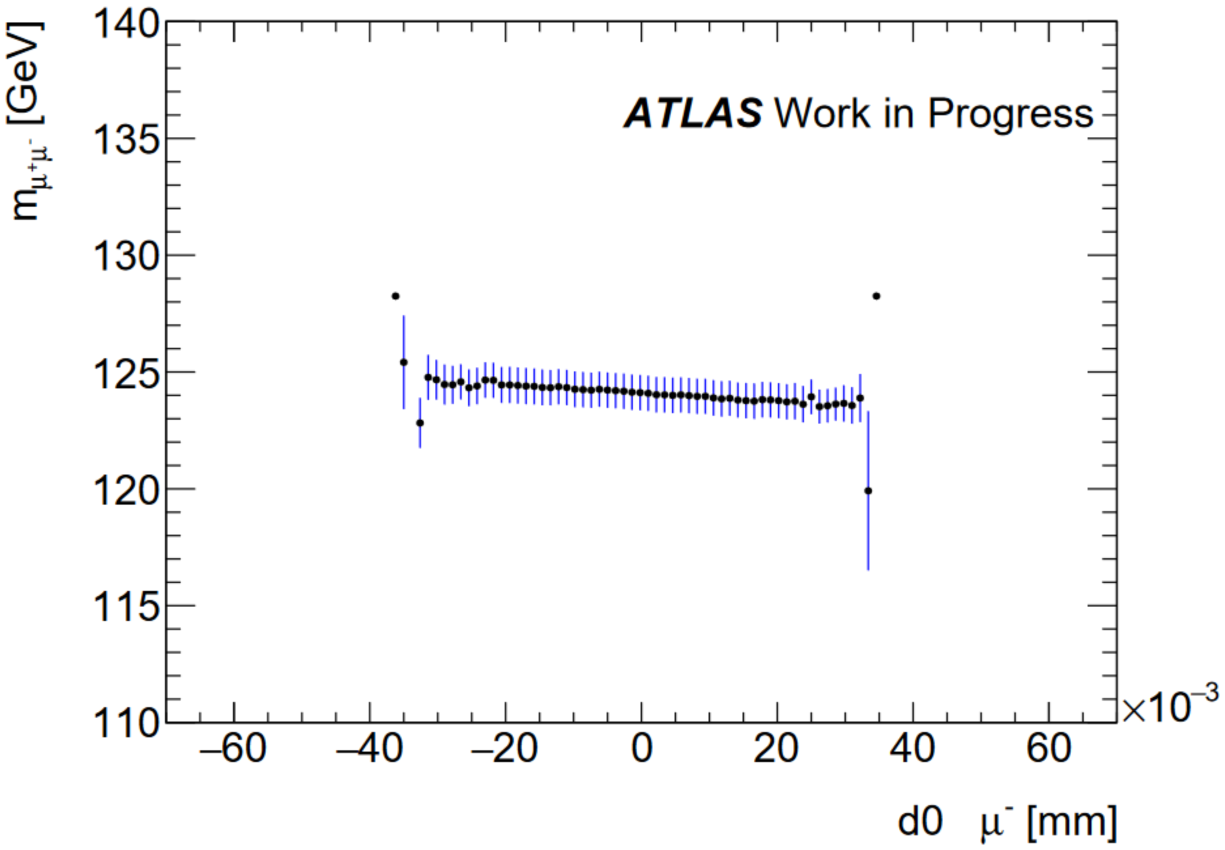
$$m_{\mu^+\mu^-}^2 \approx m_{\mu^+}^2 + \mathrm{m}_{\mu^-}^2$$
$$+2\left[\sqrt{|\vec{p}_t(\mu^+)|^2 + m_{\mu^+}^2} \cdot \sqrt{|\vec{p}_t(\mu^-)|^2 + m_{\mu^-}^2} \cdot \cosh\Delta\eta - \vec{p}_t(\mu^+)\cdot\vec{p}_t(\mu^-)\right]$$

With $\Delta\eta \propto \left|\theta_{\mu^-} - \theta_{\mu^+}\right|$

Results – Updating $d0$

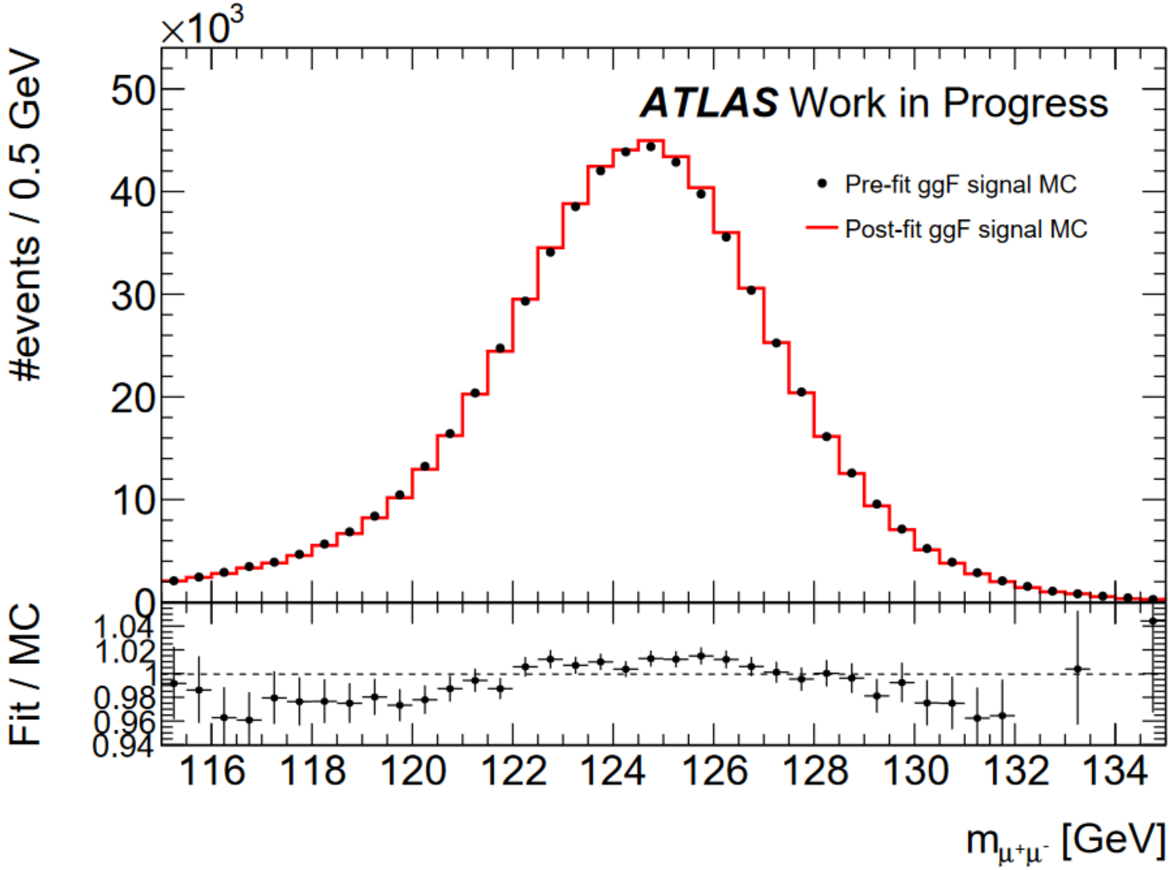


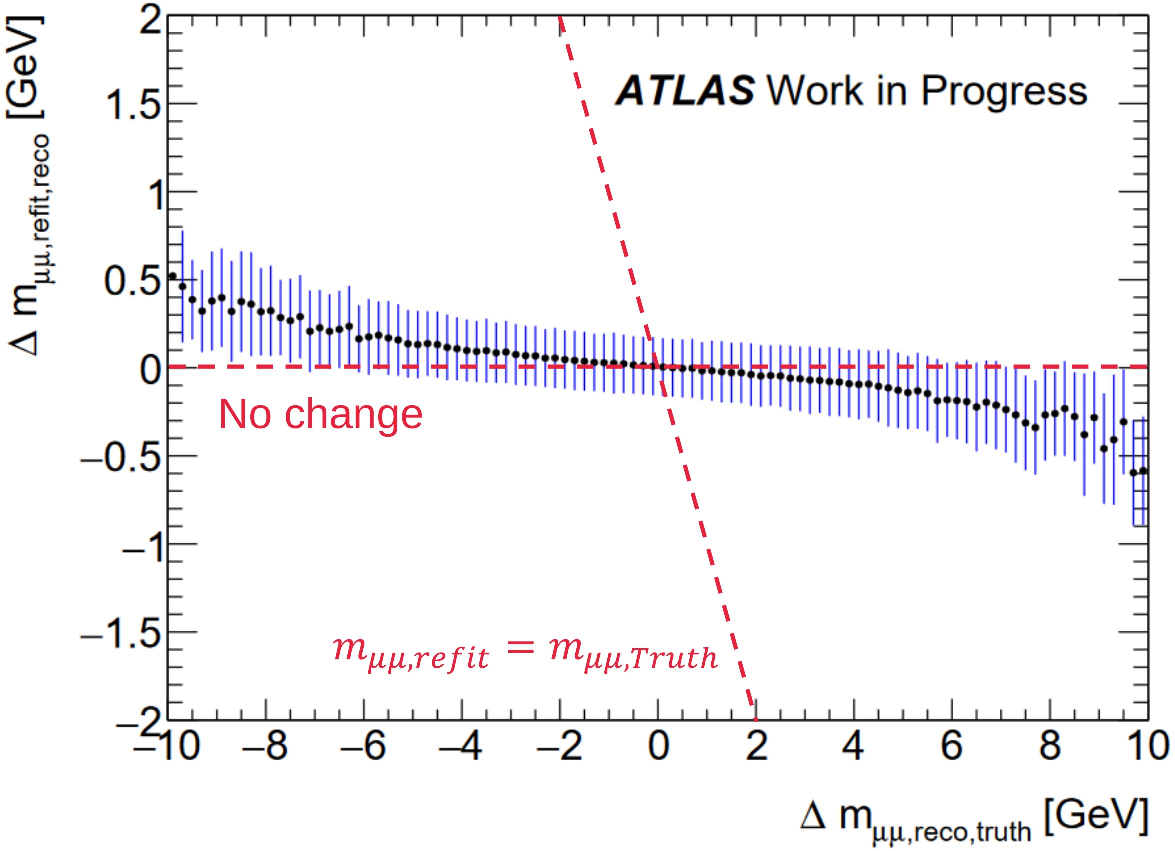
Before the fit there exists a small correlation between $d0$ of μ^- and $m_{\mu\mu}$



After the fit the correlation is reduced and the $d0$ distribution is narrowed

Results – Updating $m_{\mu\mu}$





Event count increases around the Higgs mass and is reduced in the tails, indicating that the peak has narrowed

$m_{\mu\mu}$ is shifted towards the true $m_{\mu\mu}$ value, which is what the fit is designed to do

Results – Counting significance

To quantify the impact of the vertex fit, calculated the counting significance in our signal region

$$Z = \sqrt{2\left((S+B)\ln\left(1+\frac{S}{B}\right)-S\right)}$$

57 fb^{-1} MC ('22+'23)	Signal [120,130] GeV	Background [120,130] GeV	Z	$\frac{Z_{post}-Z_{pre}}{Z_{pre}}$
Pre-fit	375	188995	1.385	-
Post-fit	377	188968	1.402	1.23%
300 fb^{-1} MC (Full R3)				
Pre-fit	1999	1007281	3.197	-
Post-fit	2012	1007134	3.236	1.22%

Closing remarks

I showed a new technique for improving the di-muon invariant mass resolution for the $H \rightarrow \mu^+\mu^-$ analysis by fitting the Higgs decay vertex of the di-muon system

Applying this fit correctly shifts the value of the invariant mass towards that of the true value in simulation, which in the ends results in an improved invariant mass resolution and a ~1% gain in significance

Whilst small, it is only one piece of the puzzle, and combined with all other analysis techniques, it will bring us a little bit closer to discovery at 5σ!

Thank you for your attention!