Electroweak and Top @ LHCb in the Phase II Upgrade

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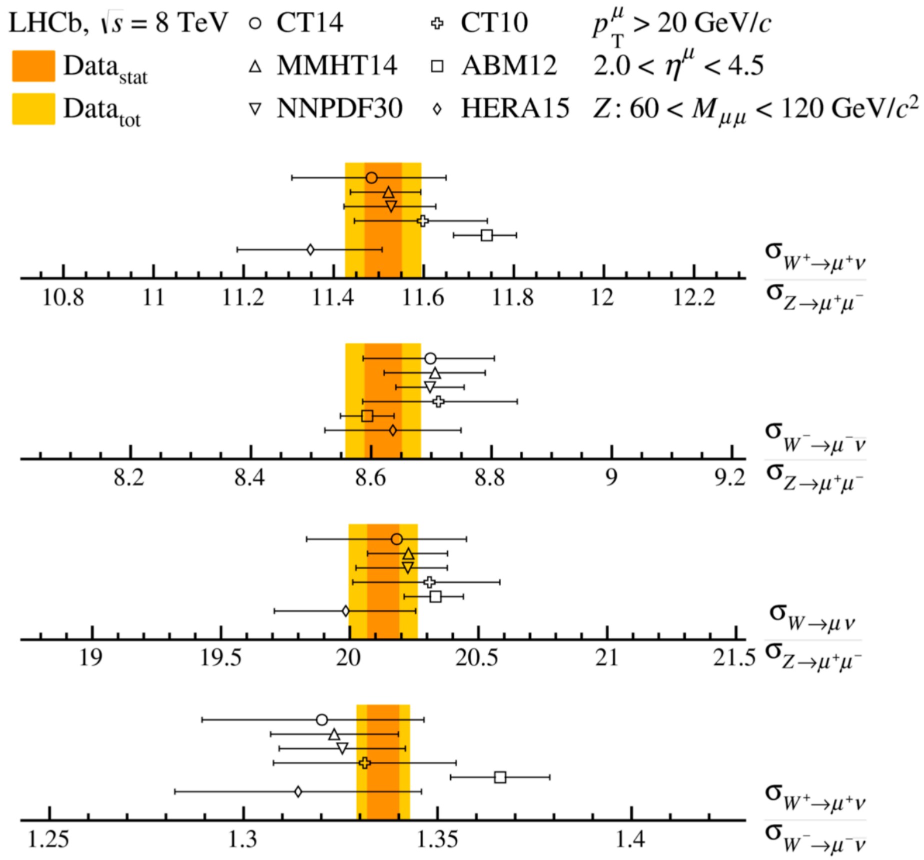
Thanks to many in the LHCb:QEE group for many interesting ideas and discussion!

Introduction

- LHCb is increasingly used as a general purpose detector in the forward region.
- Has all the subdetectors needed to make complementary measurements in "high pT physics" in the forward region.
  - I'll consider what subsytems we rely on currently, and what such future studies will need.
- This talk will address what LHCb can do in high pT Standard Model physics with high lumi (300/fb) in the forward region.
  - What are [some of] the interesting measurements that can be made?
  - Estimates of the LHCb sensitivity?

Introduction

- LHCb high pT measurements so far have been (mainly) probing QCD.
- Differential cross-section measurements and ratios test the our modelling of the hard interaction and hard emission – or of the proton structure (PDFs).
- Most of these measurements dominated by systematic uncertainties by end of run 2 – but often already more precise that theory predictions.



The future EW programme will revolve around a different set of measurements – that test primarily the EW sector of the SM.

Forward top physics measurements will enter realm of precision physics and tests of SM.

Introduction

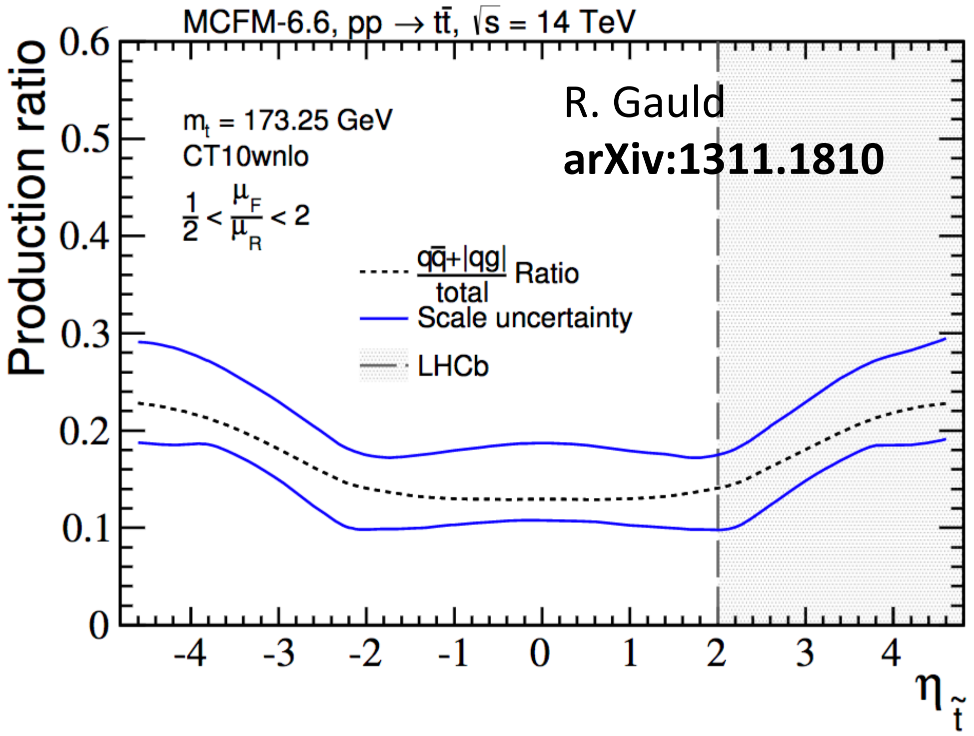
- Will focus on 3 areas:
  1. Top production in the forward region
  2. W mass measurement at LHCb
  3. Weak mixing angle measurement at LHCb

- These measurements require:
  - Excellent lepton reconstruction at high pT.
  - Knowledge of the “rest of the event” - jets, recoil, etc.

- Exemplar (and important) measurements at high pT that will make significant use of different aspects of the LHCb detector.

Top Pair Production @ LHCb

- Why should we care about top @ LHCb?
- Different kinematic regime to ATLAS and CMS.
- LHCb reconstructs up to twice the fraction of qq collisions to ATLAS/CMS.
- Also sensitive to events with a large rapidity gap in top pair system (though only reconstruct one top in this case).

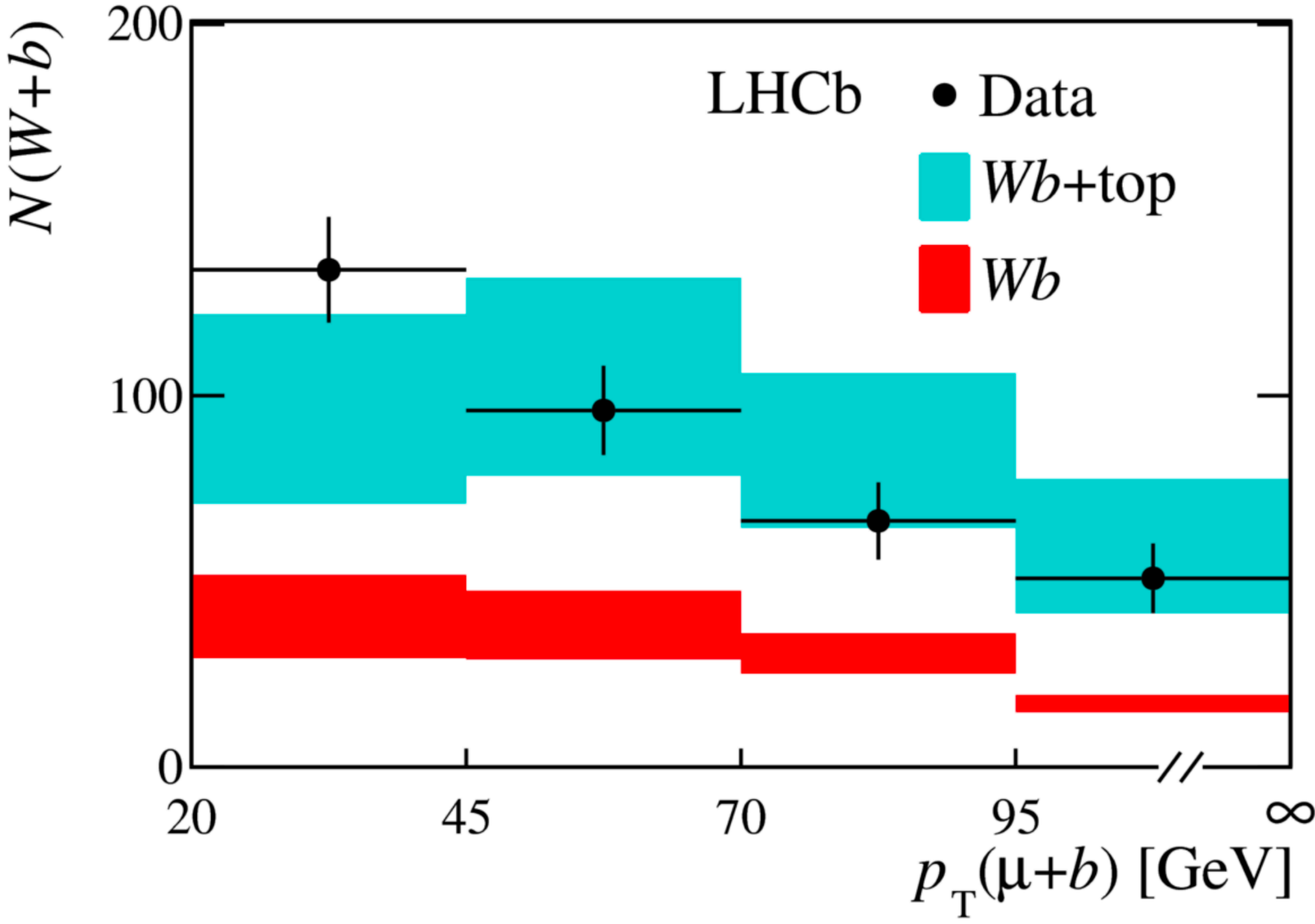


Top @ LHCb

- **Run-1:**

- Measurement of tt, W+bb, W+cc production in pp collisions at sqrt(s) 8 TeV, [Phys. Lett. B767 (2017) 110]
  - Reconstructs μbb and ebb final states.

- First observation of top quark production in the forward region, [Phys. Rev. Lett. 115, 112001 (2015)]
  - Reconstructs μb final state.
  - Includes effects of both single-top and top-pair production

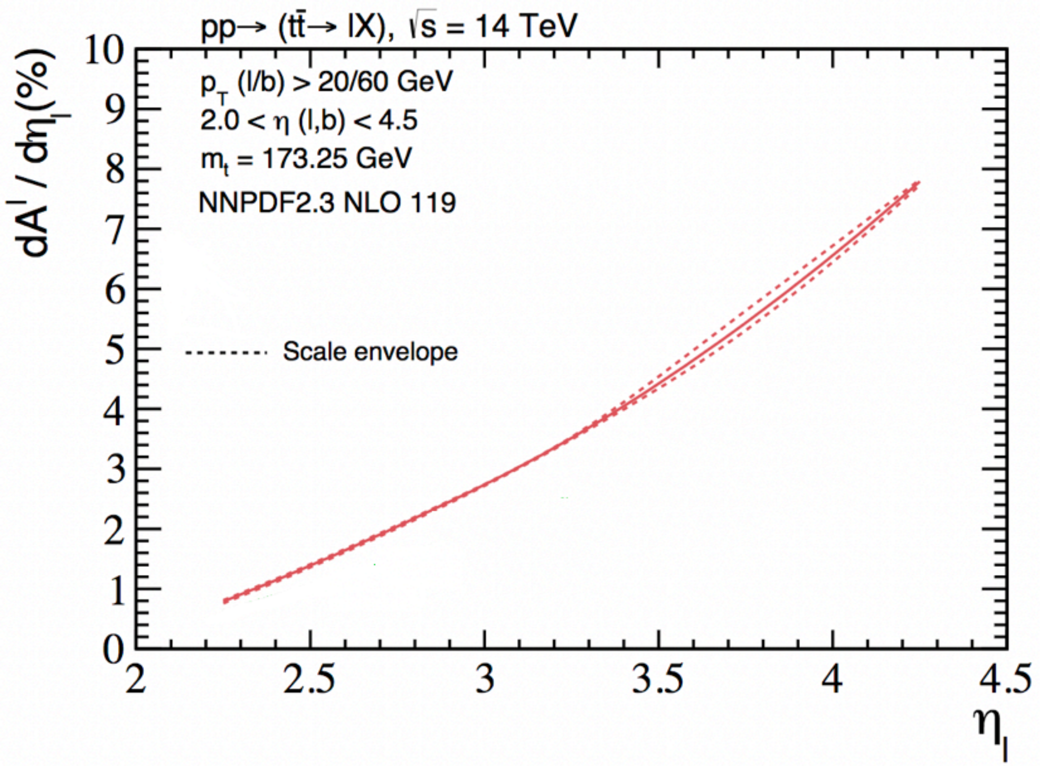


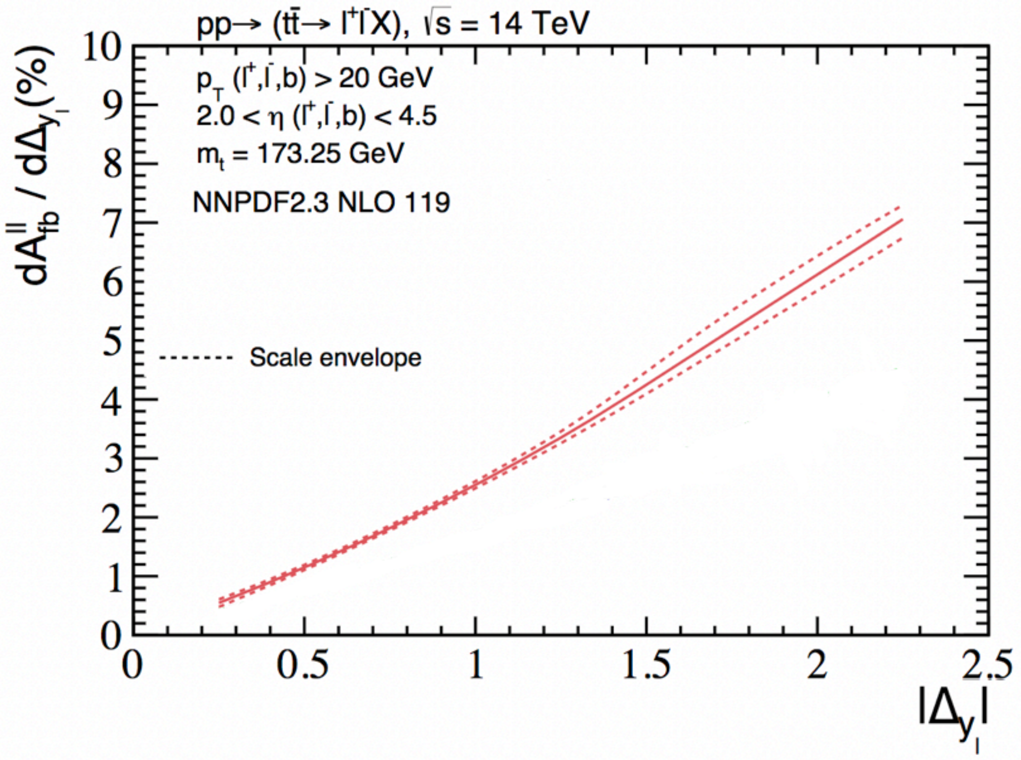
Adapted from: R. Gauld, arxiv:1409.8631

Top Pair Production @ LHCb

$$\frac{dA^l}{d\eta_l} = \left(\frac{d\sigma^{l^+b}/d\eta_l - d\sigma^{l^-b}/d\eta_l}{d\sigma^{l^+b}/d\eta_l + d\sigma^{l^-b}/d\eta_l} \right)$$

$$\frac{dA^{ll}_{fb}}{d\Delta_y} = \frac{\left(d\sigma^{\mu eb}(\Delta_y > 0) - d\sigma^{\mu eb}(\Delta_y < 0)\right)/d\Delta_y}{d\sigma^{\mu eb}/d\Delta_y}$$





Forward region gives non-symmetric initial state – **larger $t\bar{t}$ asymmetries than central region.**
High statistics will allow **precision tests** of top pair physics.

Top Pair Production @ LHCb

- LHCb acceptance contains much larger top asymmetries than central region:
  - Asymmetries in central region are small since gg initial state dominates and is by definition symmetric;
  - And because the pp initial state – even when $q\bar{q}$ induced – is symmetric at low rapidities; the quark is equally likely to come from either direction.
  - This remains true in many new physics models – asymmetries remain close to 0.

- LHCb sensitive to some of these New Physics models which ATLAS/CMS might not see:
  - E.g. t-channel, u-channel exchange of a light mediator.
  - See, for example, Kagan *et al*., PRL 107(2011)082003

Top Pair Production @ LHCb

- What yields can we expect in the future?

Cross-sections for leptons (μ and e) and b-jets in LHCb with significant pT.

LHCb-PUB-2013-009

$d\sigma$(fb)	7 TeV	8 TeV	14 TeV
lb	285 ± 52	504 ± 94	4366 ± 663
lbj	97 ± 21	198 ± 35	2335 ± 323
lbb	32 ± 6	65 ± 12	870 ± 116
$lbbj$	10 ± 2	26 ± 4	487 ± 76
l^+l^-	44 ± 9	79 ± 15	635 ± 109
l^+l^-b	19 ± 4	39 ± 8	417 ± 79

Uncertainties from scale, PDF, and shower model

Note boost by ~10 as acceptance increases at higher collision energies.
Far more than just a lumi boost! Run I cross-sections not indicative of future performance.

Top Pair Production @ LHCb

- Assume a muon reconstruction and identification efficiency of 90%, electron reconstruction and identification efficiency of 70%, b-jet tagging efficiency of 65%.
  - This is roughly current performance; light quark mistag ~0.5%.

Channel	End of Run 2 (5/fb)	End of Run 4 (50/fb)	Future Upgrade 300/fb
lb	11,000	110,000	680,000
lbj	6,000	60,000	360,000
lbb	1,400	14,000	90,000
$lbbj$	800	8,000	50,000
ll	2,000	20,000	120,000
llb	800	8,000	50,000

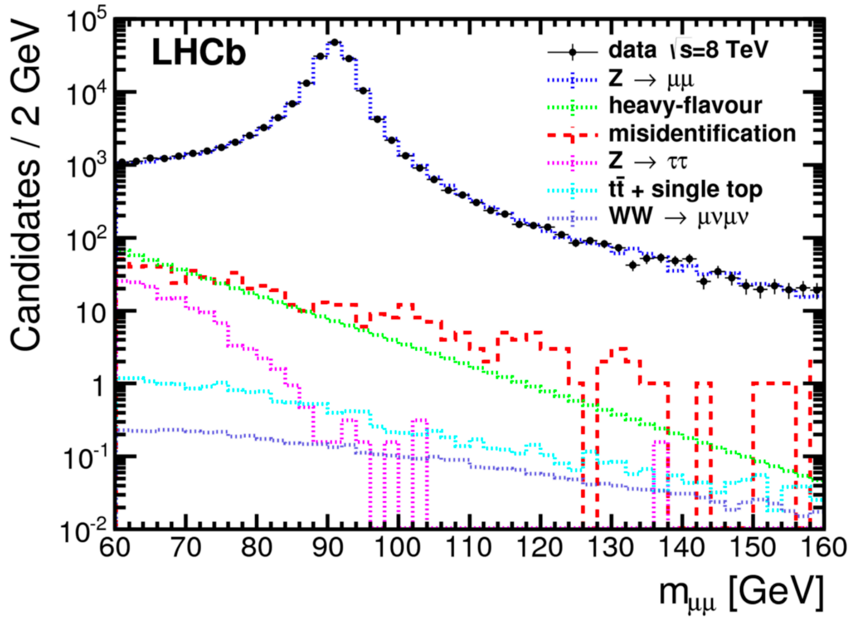
Naïve scalings (and rounded numbers) assume no future gain in performance – even so, LHCb collects significant top!

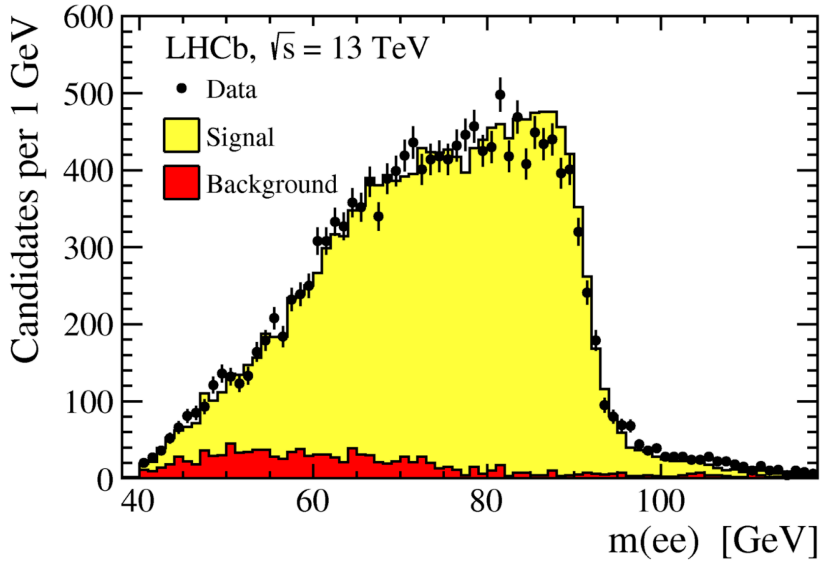
Top Pair Production @ LHCb

- What do we need to reconstruct leptons?
  - Excellent muon and electron reconstruction.
  - Currently use lack of HCAL deposit as key part of electron ID.
    - Need to ensure an ability to identify electrons at high pT while rejecting backgrounds.
  - Current ECAL already has excellent resolution

$$\sigma_E/E = 9.0\%/\sqrt{E/\mathrm{GeV}} \oplus 0.8\% \quad \text{[low ET]}$$

    - …but saturates at higher ET (designed for lower energy flavour physics)





Top Pair Production @ LHCb

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  - Currently use lack of HCAL deposit as key part of electron ID.
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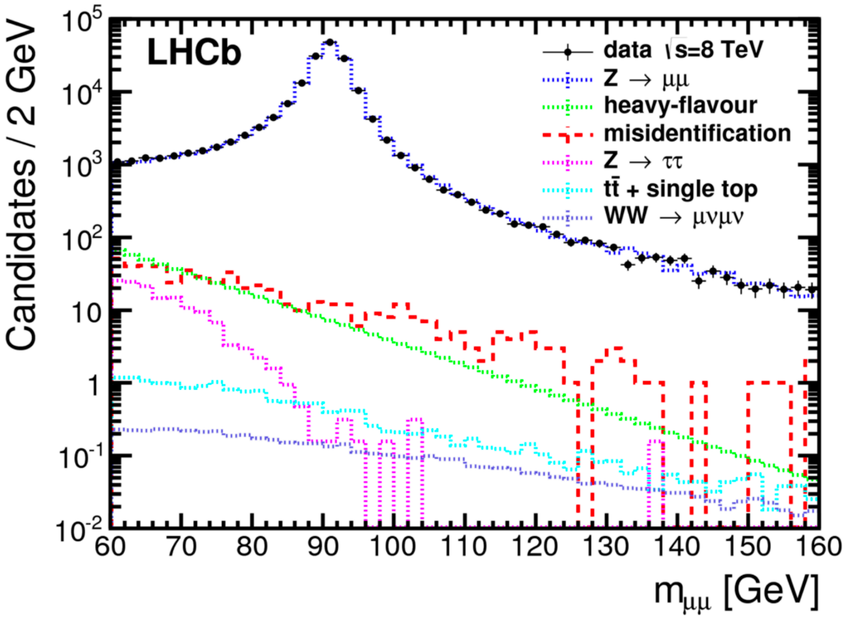
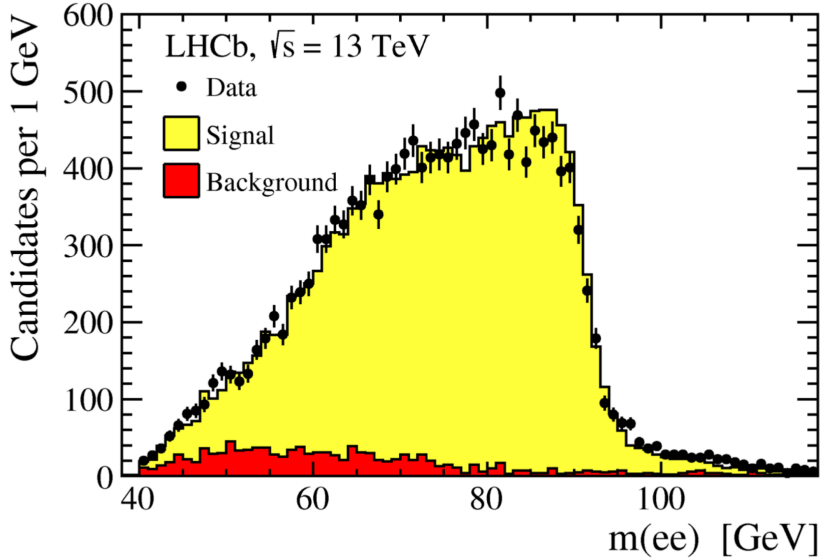
$$\sigma_E/E = 10\%/\sqrt{E/\mathrm{GeV}} \oplus 0.8\%$$ [low ET]

    - ...but saturates at higher ET (designed for lower energy flavour physics)

Increasing the dynamic range in the ECAL to cover high ET will significantly increase the range and precision of measurements we can make.



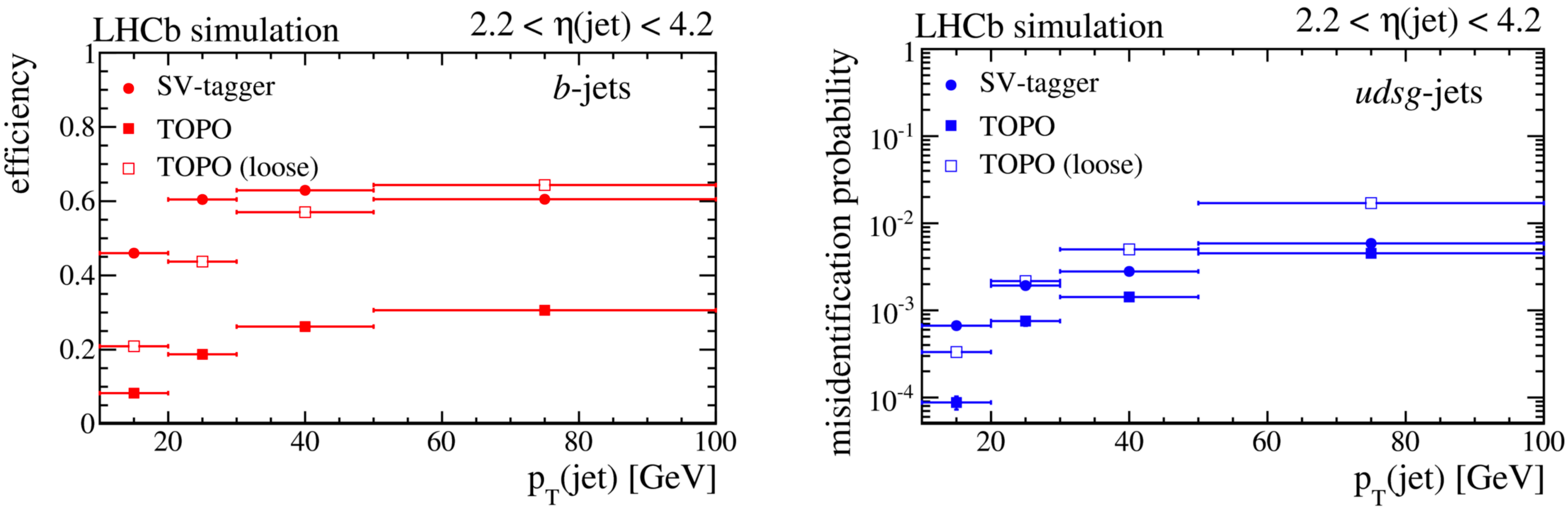


Top Pair Production @ LHCb

- What do we need to reconstruct jets?
- Reconstruct jets using tracks for charged particle information, with neutral information taken from calorimeters.
- Current resolution on jet pT is 15-20% for jets with 20 < pT < 100 GeV.
- Rely on all detector subsystems:
  - ➢HCAL currently important for otherwise unreconstructed hadronic energy: Neutral particles or unreconstructed charged hadrons(due to high multiplicity within jet)
  - ➢Removing HCAL information from current jet energy resolution worsens performance by about 5% (i.e. 15% → 20%, not 15% → (15*1.05)%).
  - ➢Need to investigate if this can be recovered in other ways: less than 10% of jet energy ultimately due to neutral hadrons.

Top Pair Production @ LHCb

- What do we need to reconstruct b-jets?
  - b-jet tagging relies on algorithm similar to topological trigger; if we can trigger on B, we should be able to tag b-jets.



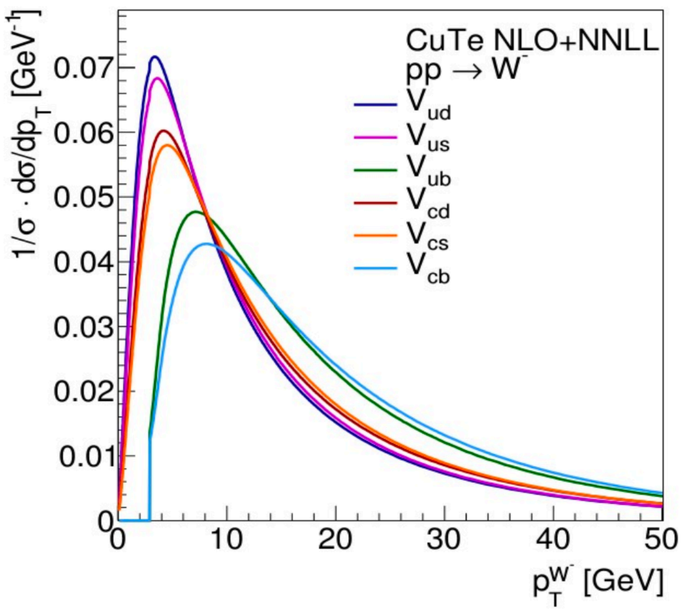
W Mass measurement at LHCb

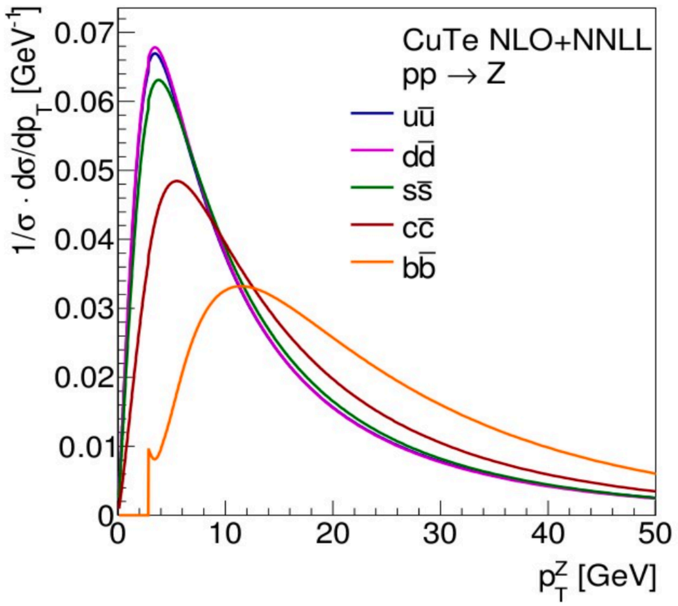
- Current world best measurement: 80.387 ± 0.019 GeV [CDF]
- Current world average: 80.385 ± 0.015 GeV [PDG]
- Prediction in global EW fit: 80.358 ± 0.008 GeV [arxiv:1407.3792]

- One of the most important SM measurements at the LHC.
- A key test of SM consistency – new physics could show up as tension in global EW fit.
- ATLAS measurement currently has uncertainty of 19 MeV (14 MeV from modeling)
- Expected ILC precision – 6-7 MeV [ILC-REPORT-2013-040]

W Mass measurement at LHCb

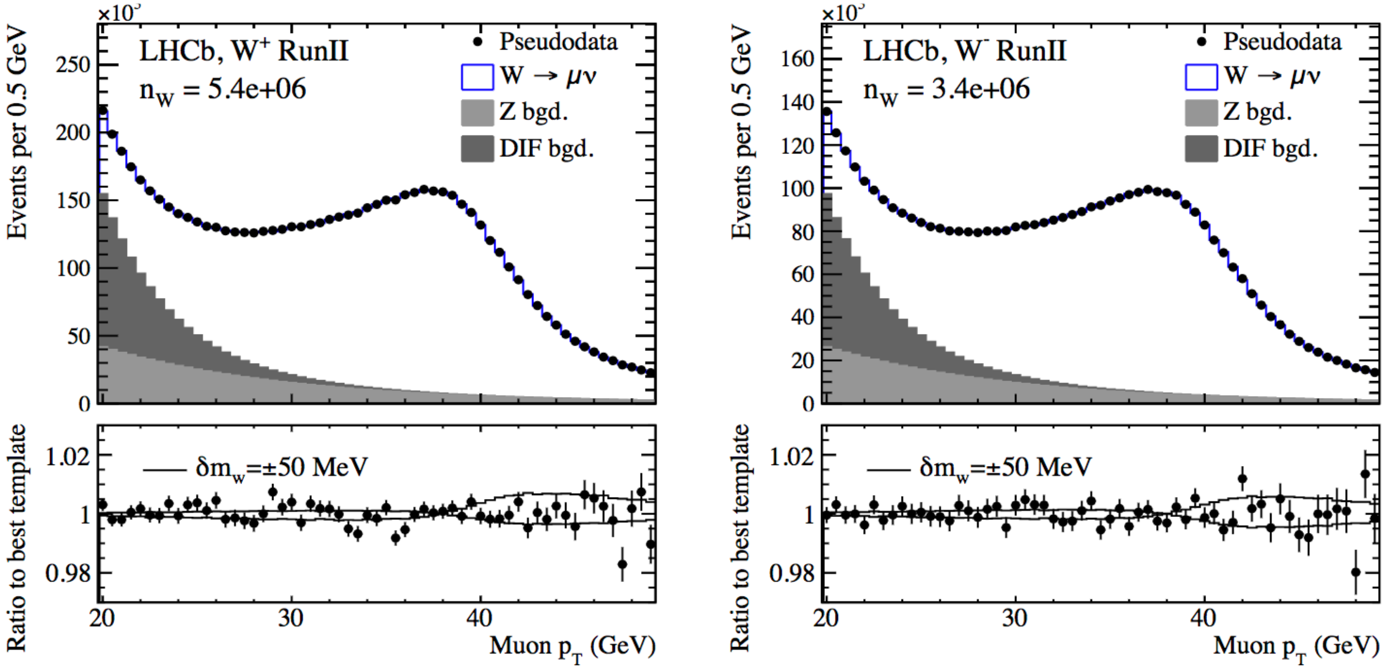
- The result is extracted by fitting the pT(lepton) spectrum for different W masses [*or m_T spectrum if available*].
- The Parton Distribution Functions matter and are a key uncertainty – they change the W boson pT spectrum, and through it the lepton pT spectrum.





W Mass measurement at LHCb

- A measurement at LHCb:
  - Could achieve a statistical precision of 10 MeV (W^+) and 13 MeV (W^-) using just Run II data.
  - PDF uncertainty is 28 MeV (W^+), 49 MeV (W^-) – but is anticorrelated with ATLAS and CMS.



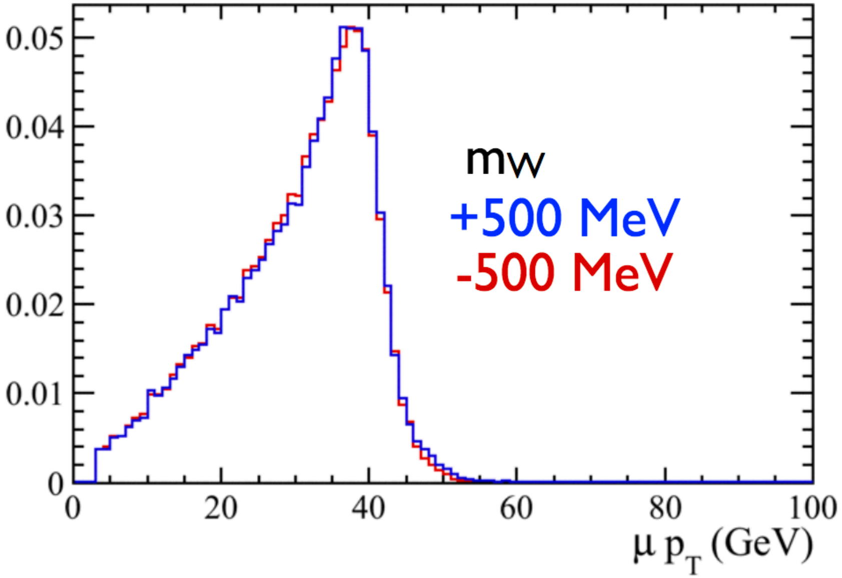
A W mass measurement at LHCb contributes more to any LHC combination than a second measurement from ATLAS/CMS – overall combination could reach uncertainty < 10 MeV.

"The weighted average of the ATLAS, CMS and LHCb results, based only on the PDF uncertainties, would be 30% more precise than an average of ATLAS and CMS alone."

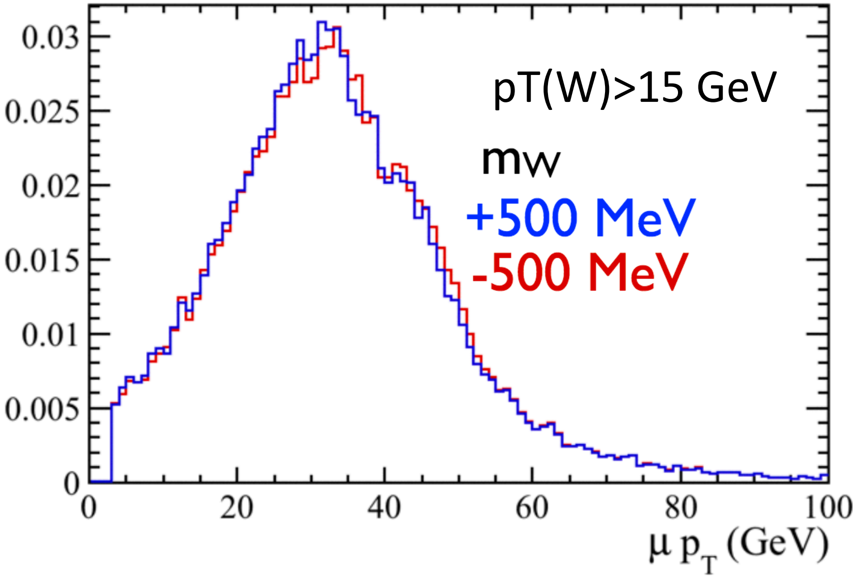
W Mass measurement at LHCb

- But that's Run II?
  - Argument presented neglects uncertainties from modelling of pT(W).
  - Greater precision is achieved by restricting measurement to a region where QCD model/additional radiation has smaller effect.

Clear Jacobian peak: pT(W)<15 GeV



Smeared "noise": pT(W)>15 GeV

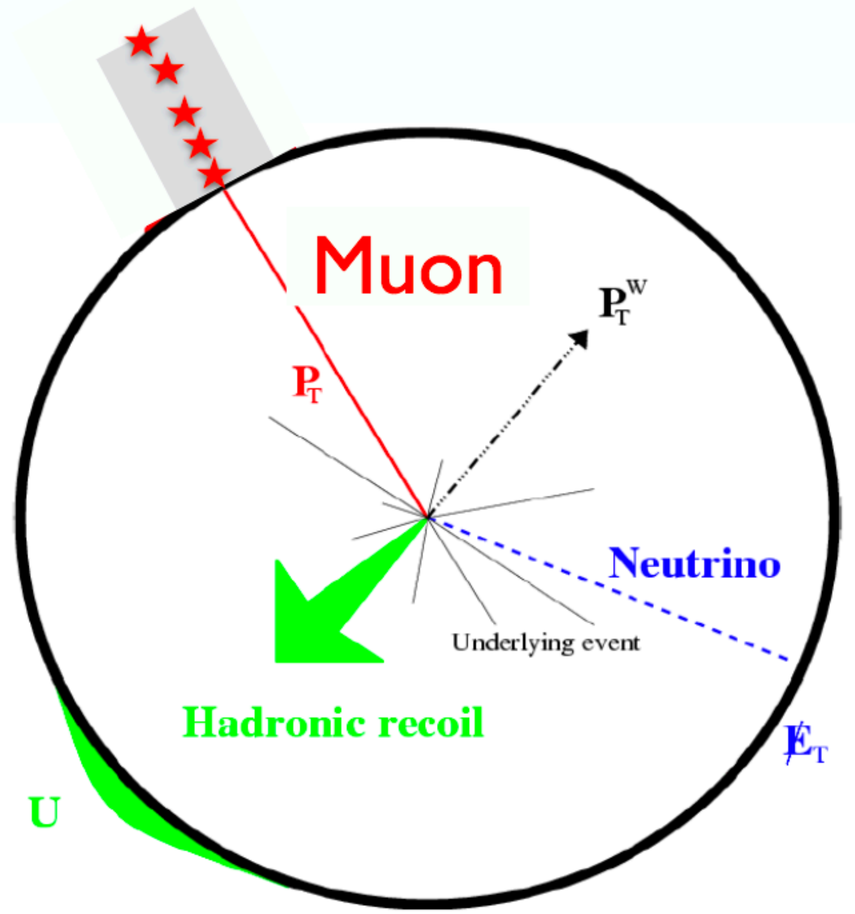


W Mass measurement at LHCb

- If/we are limited by QCD model in post Run II W mass measurement, then improvements will be possible through:
  - Improving the overall QCD modelling. [Theoretical improvement]
  - Restricting measurement to region where QCD is better modelled. [Analysis level improvement → is there something LHCb could do?]
- **Even if Run II W mass measurement not limited by QCD modelling, techniques that rely on detector coverage/performance are also instructive for Future Upgrade measurements.**

W Mass measurement at LHCb

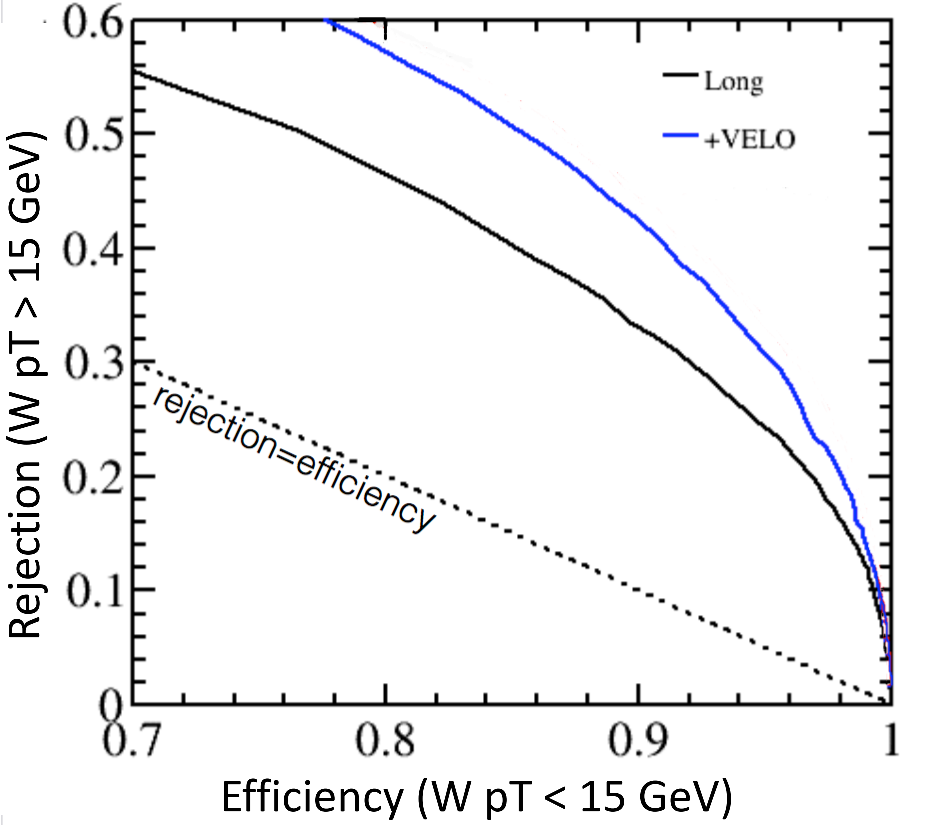
- How can we restrict ourselves to a region where QCD is better modelled?
  - LHCb is not a hermetic detector: we cannot cut on missing energy or recoil to reduce backgrounds or reduce the W boson pT.
  - …that's what we've always said.
  - But reasonable estimates of recoil available from PF jet finding tools and estimating other activity in event.
  - Can we potentially use this?



W Mass measurement at LHCb

- (Generator level) toy study estimating recoil from long tracks in LHCb acceptance and assigning pT = 400 MeV to VELO-only tracks.
  - Can select low pT region with reasonable efficiency.
- LHCb will never have great ability to reconstruct complete recoil, but clear that significant gains possible in analysis.
  - Also significant gains with every piece more coverage (even if only upstream).
- This technique and argument holds for other measurements too.

Can create a forward recoil or MET variable.



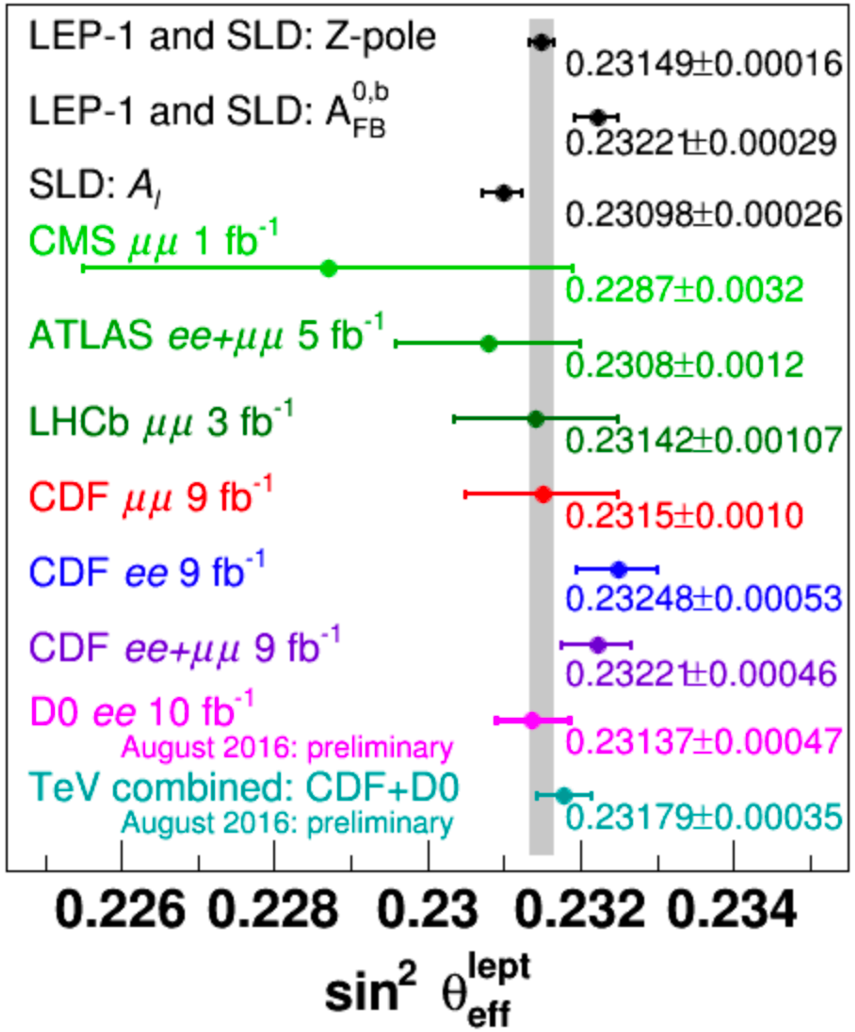
A hope *to consider*, obviously only where reasonable, affordable and possible, further eta coverage, since even if change in coverage is limited, significant gains possible.

W Mass measurement at LHCb

- With an improved ECAL the measurement could also be made with the electron final state:
  - Uncorrelated statistical and experimental systematic uncertainties.

- Such a measurement would also greatly benefit from reductions in the material budget before the magnet.
  - Reduced bremsstrahlung aids measurement, even with excellent ECAL performance.
  - This is also true of our other measurements that seek to use electrons.

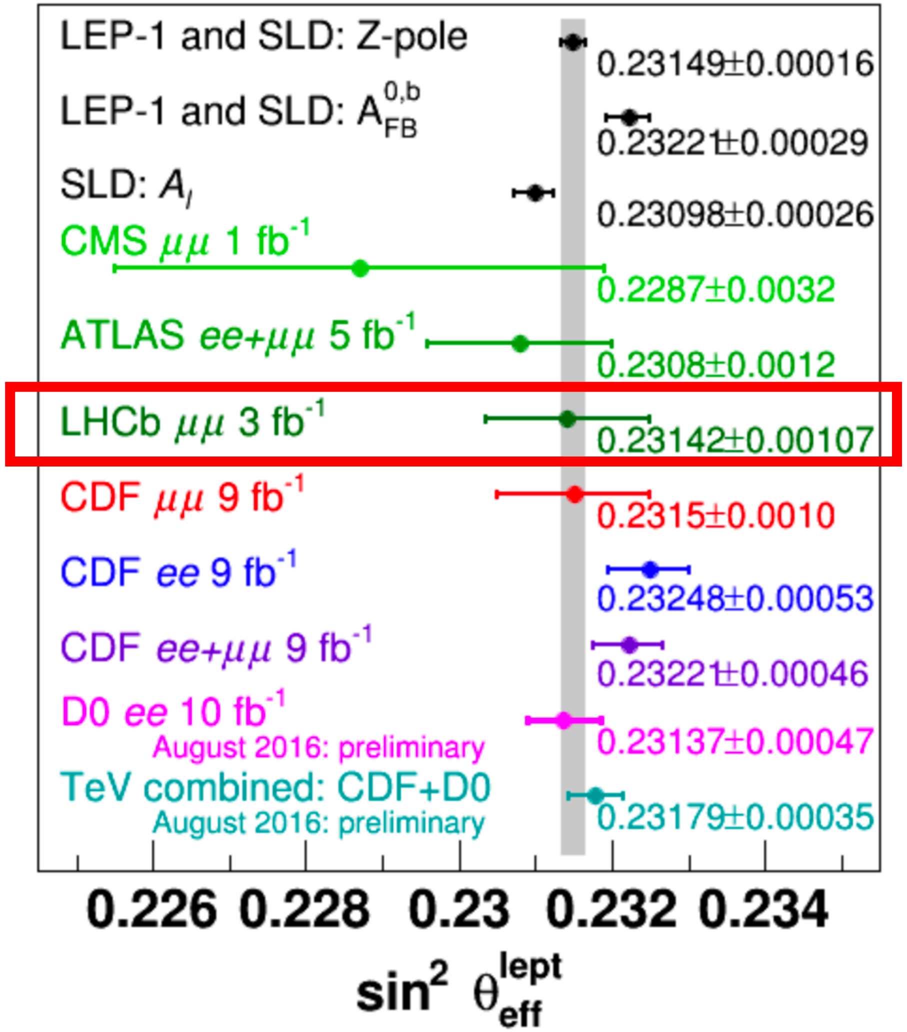
Weak Mixing Angle at LHCb



- Most precise LEP/SLD results are >3 sigma apart. Mandates further investigation for process dependence angle extracted using in different methods.
  - ➢forward-backward asymmetry in ee→bb
  - ➢left-right asymmetry.

- Within the global EW fit, an uncertainty of about 16×10^{-5} corresponds to an uncertainty of 8 MeV on the W boson mass.
  - ➢Such measurements together provide a crucial consistency test of SM.

Weak Mixing Angle at LHCb



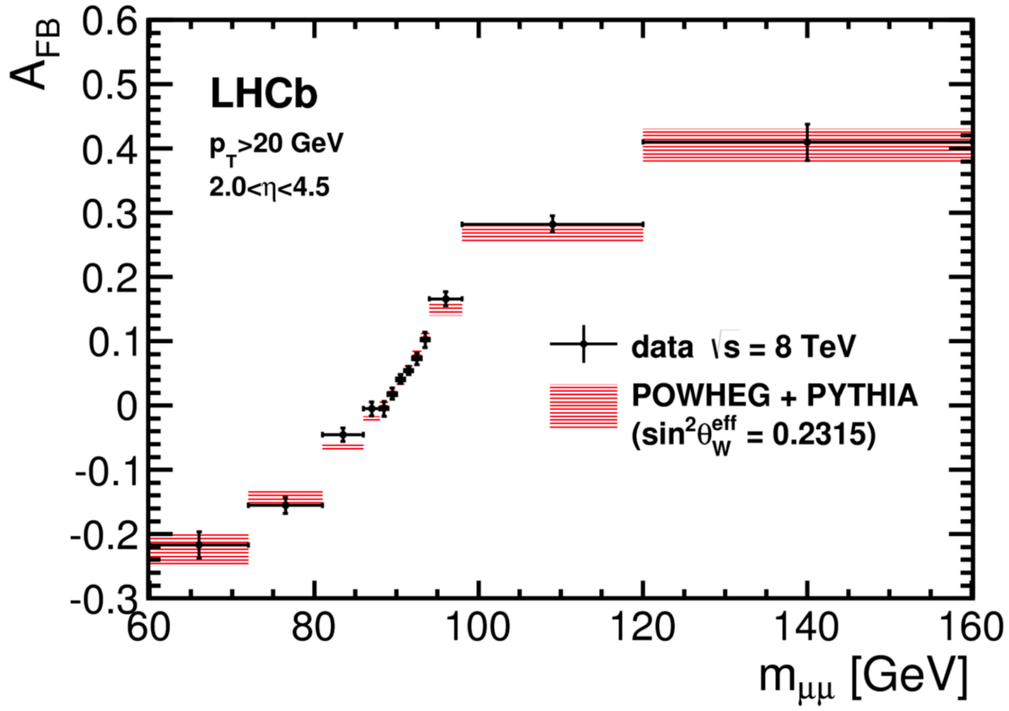
- LHCb measurement the most precise at the LHC.
- Still statistically limited:

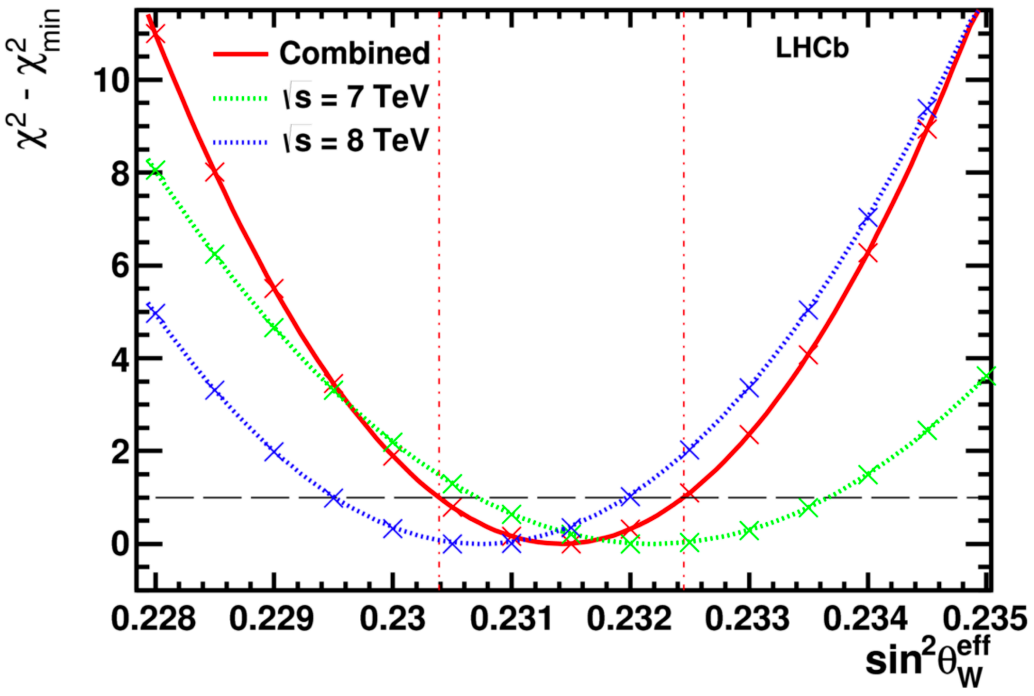
$$sin^2\theta_W^{eff} = 0.23142 \pm 0.00073 \pm 0.00052 \pm 0.00056$$

- But clear that before long we will also need to consider how to reduce other uncertainties:
  - Momentum scale, PDF uncertainties.
- Measurements around the level of $30\text{x}10^{-5}$ will also need to consider higher order effects: vertex dependent mixing angle.

Weak Mixing Angle at LHCb

- Measurement performed by comparing measured forward-backward asymmetry in dilepton Z boson decays to theoretical predictions from different values of the angle in bins of the dimuon invariant mass.

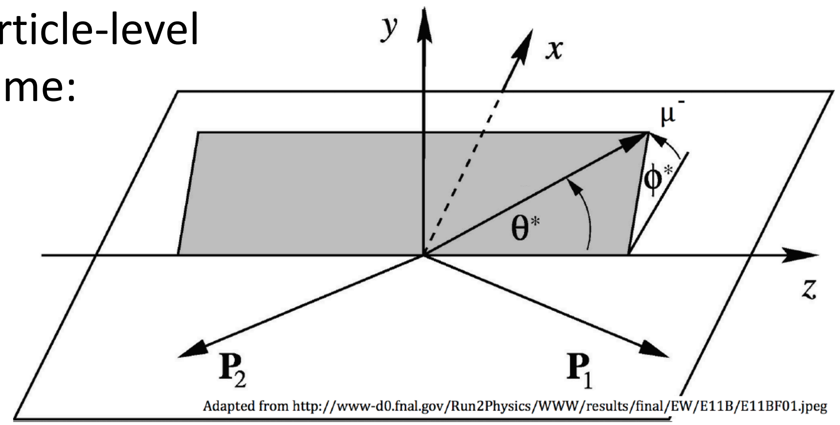




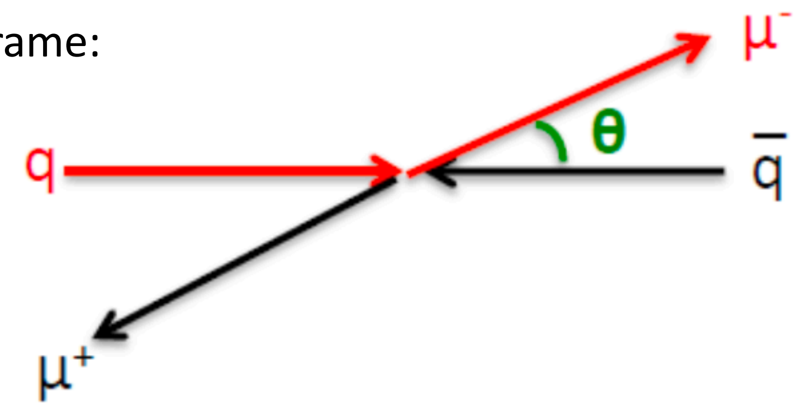
Weak Mixing Angle at LHCb

- At rapidity = 0, symmetric initial state means no sensitivity.
- LHCb most precise at LHC as less dilution between particle-level forward-backward asymmetry in the forward direction relative to parton-level: the quark tends to be travelling towards LHCb, since the quark tends to be at high Bjorken-x (relative to the anti-quark).

Particle-level frame:



Parton-level frame:



Weak Mixing Angle at LHCb

- Statistical sensitivity:
  - Run 1 measurement achieved stat unc 73 x 10^{-5} with about 200k events.
  - Pythia (LO) MC suggests that change in $\frac{\Delta \sin^2 \theta^{eff}_{lept}}{\Delta A_{fb}}$ changes little (within 10%) at LHCb with change in collision energy.
  - For now simply scale Run 1 stat. unc. on the weak mixing angle by $\sqrt{n}$
  - Assume efficiency from 13 TeV Z boson cross-section measurement.

Period	Yield	Statistical Sensitivity (naïve scaling) $\sin^2 \theta^{eff}_{lept}$ / 10^{-5}
End of Run 2	700k	50
End of Run 3	7M	20
300/fb	40M	7

Naïve scaling

Naïve scaling

Weak Mixing Angle at LHCb

- Experimental systematic uncertainties?
  - Dominated til now by knowledge of momentum scale.
  - Run-1 measurement used knowledge of muon momentum scale at level better than 0.1%.

  - With a larger calibration sample this will improve.
  - Analysis strategy can also mitigate effect of momentum scale – e.g. the choice of bin width in dimuon mass when fitting templates. This provides a trade-off between the statistical uncertainty and the momentum-scale uncertainty.
  - Using only one bin in $60 < m(ll) < 160$ GeV yields a much small momentum-scale effect, but some loss of statistical power.
  - This uncertainty can reasonably be expected to reduce in future measurements.

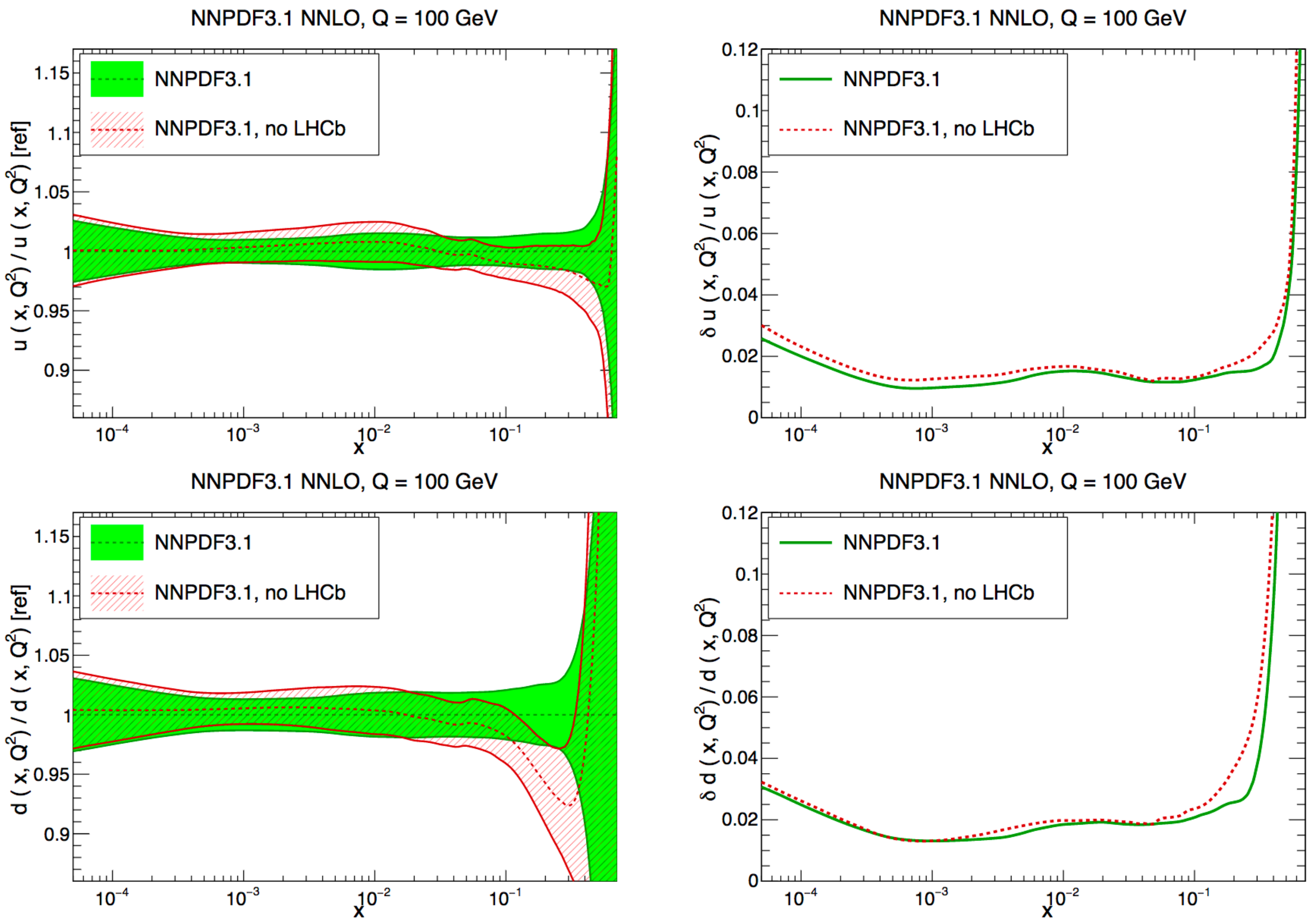
- Here too the measurement could be made with electrons, and the result compared with muons, but the theory uncertainties are shared…

Plots from Juan Rojo, DIS proc. 2017

LHCb data reduce PDF uncertainties in region of Bjorken-x probed by LHCb by up to a factor of 2

Weak Mixing Angle at LHCb

- Theory uncertainties?
- Those due to PDFs are already reducing, due to LHC measurements of differential cross-sections.
- Can also create own LHCb versions of PDFs from fits to LHCb data if desired.
- Can also make measurements as function of rapidity to pick out most sensitive regions/constrain PDF effects.



Other Physics with W and Z bosons

- Total cross-sections (13 TeV) for W and Z boson production are ~200 nb and ~50 nb.

- Forward region contains about 10% of $Z \to ll$ decays.
- With 300/fb and **excellent particle identification**, LHCb could place limits/observe rare (exclusive) decays.

- Will also have the ability to measure WW, WZ, ZZ production.

Conclusions

- Presented interesting measurements and techniques in a potential future LHCb Upgrade.
- Will rely on excellent ECAL performance (with ability to ID electrons – currently reliant on ECAL and HCAL) with good energy scale knowledge.
  - Ensuring ECAL has dynamic range to high ET allows significant physics with electrons.
- Jets reconstruction also makes noticeable gains from presence of HCAL.
- Will rely on continued ability to reconstruct muons with an excellent momentum scale and resolution. The ability to do the same with electrons will open up intriguing new possibilities.