Electroweak precision physics with the neutral-current Drell–Yan process

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Outline

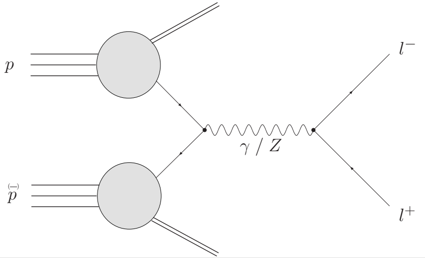
Drell–Yan processes at the LHC

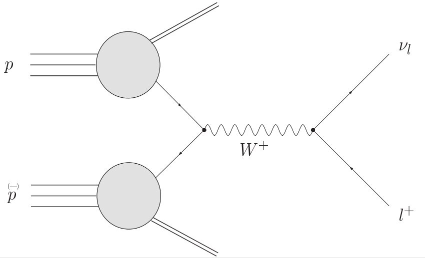
Electroweak and QCD corrections at the LHC

Retrospection: Electroweak precision physics at LEP/SLD

Forward-backward asymmetry and $\sin^2\theta^l_{\mathrm{eff}}$ at the LHC

Drell–Yan processes at the LHC

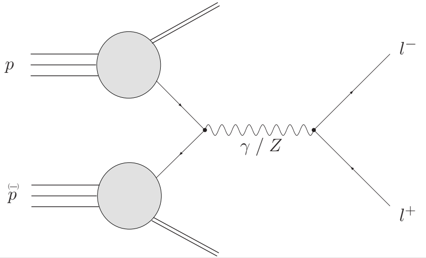




At the LHC with $10\,\mathrm{fb}^{-1}$ of data:

- $\sim 2 \cdot 10\,\mathrm{fb}^{-1} \cdot 20\,\mathrm{nb} = 2 \cdot 200 \cdot 10^6$ $\mathrm{W}^{\pm}$ events
- $\sim 10\,\mathrm{fb}^{-1} \cdot 2\,\mathrm{nb} = 20 \cdot 10^6$ Z events

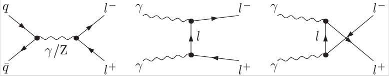
Drell–Yan processes at the LHC



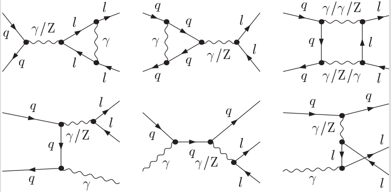
- Standard candles for hadronic high-energy colliders
  - Luminosity monitor
  - Detector calibration
  - Constrain quark PDFs
- Important background, e.g. for W'- and Z'-boson searches
- Precision measurements with W and Z bosons
  - W-mass measurement
  - Z-pole observables: Effective weak mixing angle

NC Drell–Yan process

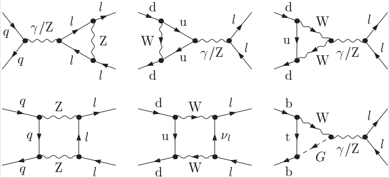
Born



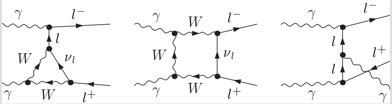
QED, e.g.



Weak, e.g.



γγ NLO, e.g.

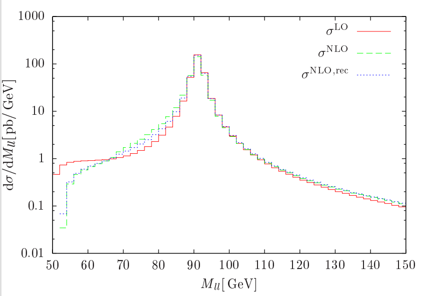


[Dittmaier,Huber, JHEP 01, (2010) 060]

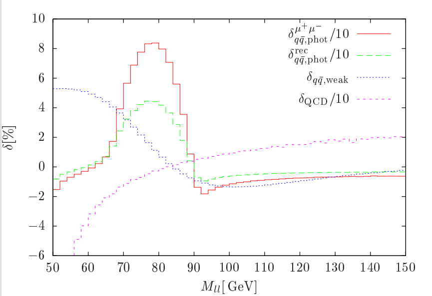
- NLO EW and QCD corrections
- all photon-induced channels including EW corrections to $\gamma\gamma \to l^- l^+$
- leading higher order corrections
- NLO EW and QCD corrections within the MSSM

Di-lepton invariant-mass distribution

$\mathrm{d}\sigma/\mathrm{d}M_{ll}$



δ: NLO



$$M_{ll} > 50\,\mathrm{GeV} \qquad p_{\mathrm{T},l^\pm} > 25\,\mathrm{GeV} \qquad |y_{l^\pm}| < 2.5$$

Di-lepton invariant-mass distribution

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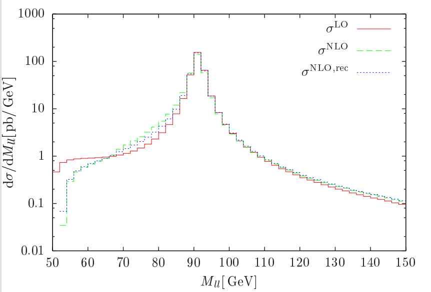
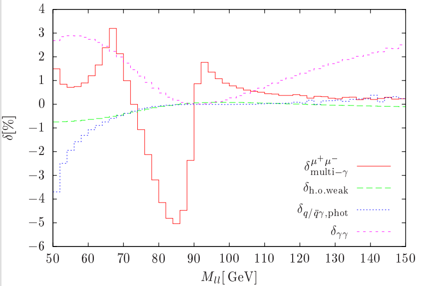


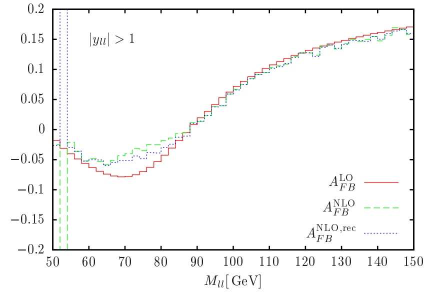
δ: photon induced and higher order



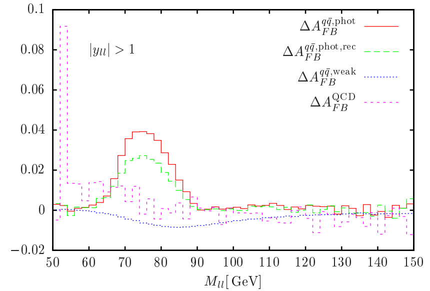
$$M_{ll} > 50\,\mathrm{GeV} \qquad p_{\mathrm{T},l^\pm} > 25\,\mathrm{GeV} \qquad |y_{l^\pm}| < 2.5$$

Forward-backward asymmetry

A_{FB}



Δ: NLO



$$A_{FB}(M_{ll}) = \frac{\sigma_F(M_{ll}) - \sigma_B(M_{ll})}{\sigma_F(M_{ll}) + \sigma_B(M_{ll})}, \qquad \sigma_{F/B}(M_{ll}) = \int_{\theta^* \lessgtr \frac{\pi}{2}} \mathrm{d}\cos\theta^* \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}$$

with the *Collins–Soper angle* θ^*

Forward-backward asymmetry

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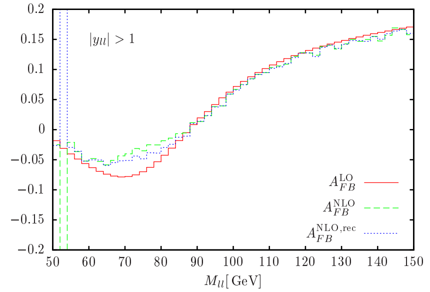

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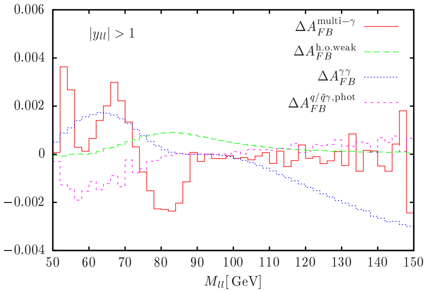
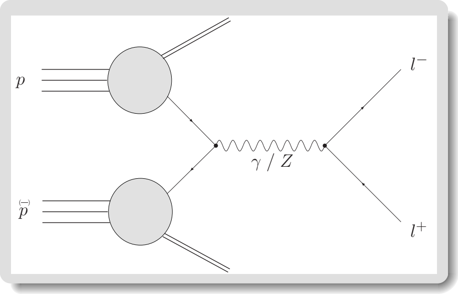


$$A_{FB}(M_{ll}) = \frac{\sigma_F(M_{ll}) - \sigma_B(M_{ll})}{\sigma_F(M_{ll}) + \sigma_B(M_{ll})}, \qquad \sigma_{F/B}(M_{ll}) = \int_{\theta^* \lessgtr \frac{\pi}{2}} \mathrm{d}\cos\theta^* \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}$$

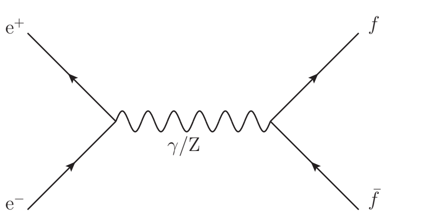
with the *Collins–Soper angle* θ^*

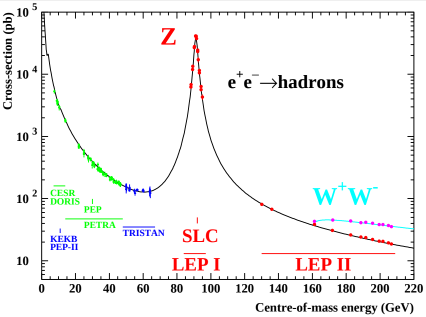
Precision physics with the NC Drell–Yan process



- similar to LEP/SLC $\mathrm{e}^+\mathrm{e}^- \to f\bar{f}$, but more involved due to PDF convolution
- LEP/SLC: very high precision reached
- LEP measurements used as input, e.g. M_Z and Γ_Z for detector calibration
- But: Can LHC measurements of effective weak mixing angle $\sin^2\theta^l_\mathrm{eff}$ and effective couplings improve/complement earlier measurments?

Electroweak precision physics at LEP/SLD





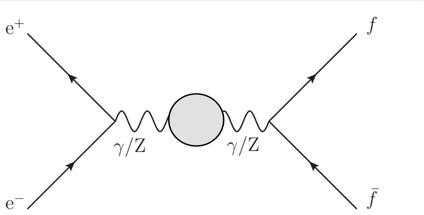
Electroweak precision physics at LEP/SLC

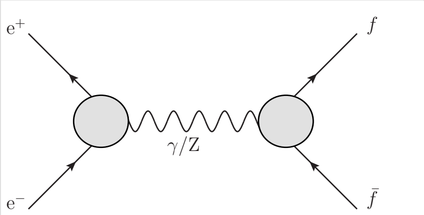
- not “realistic” observables, but pseudo observables related to realistic observables some *unfolding/deconvolution procedure*
- remove QED/QCD effects as well as SM backgrounds
- weak and possible BSM effects remain

$$\mathcal{O}^{\text{real.}} = H^{\text{QED/QCD}} \otimes \mathcal{O}^{\text{pseudo}}$$

Electroweak precision physics at LEP/SLD

At the resonance: virtual self-energy and vertex corrections

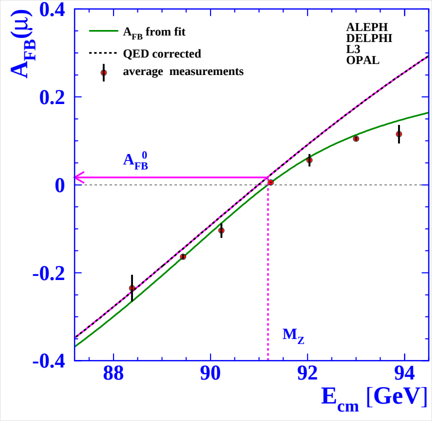




Improved Born approximation:

$$\left(\frac{\mathrm{d}\sigma^{\mathrm{IBA}}}{\mathrm{d}\Omega}\right) = \frac{1}{4\,s} N_f^{\mathrm{c}} \Bigg\{ \Big[\alpha(s)^2 Q_{\mathrm{e}}^2 Q_f^2 + 2\,\alpha(s) Q_{\mathrm{e}} Q_f \operatorname{Re}\left[\mathcal{G}_V^{\mathrm{e}} \mathcal{G}_V^f \chi_{\mathrm{Z}}(s)\right] + (|\mathcal{G}_V^{\mathrm{e}}|^2 + |\mathcal{G}_A^{\mathrm{e}}|^2)(|\mathcal{G}_V^f|^2 + |\mathcal{G}_A^f|^2)|\chi_{\mathrm{Z}}(s)|^2 \Big] (1 + \cos^2\theta) + \Big[2\,\alpha(s) Q_{\mathrm{e}} Q_f \operatorname{Re}\left[\mathcal{G}_A^{\mathrm{e}} \mathcal{G}_A^f \chi_{\mathrm{Z}}(s)\right] + 4 \operatorname{Re}\left[\mathcal{G}_V^{\mathrm{e}} \mathcal{G}_A^{\mathrm{e}\,*}\right] \operatorname{Re}\left[\mathcal{G}_V^f \mathcal{G}_A^{f\,*}\right] |\chi_{\mathrm{Z}}(s)|^2 \Big] (2\cos\theta) \Bigg\}$$

Forward-backward asymmetry at LEP



$$A_{FB}(s) = \frac{\sigma_F(s) - \sigma_B(s)}{\sigma_F(s) + \sigma_B(s)}\,,$$

$$\text{with} \quad \sigma_{F/B}(s) = \int_{\theta \lessgtr \frac{\pi}{2}} \mathrm{d}\cos\theta \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta}$$

Effective weak mixing angle and A_{FB}

Effective weak mixing angle

$$4|Q_f|\sin^2\theta_{\text{eff}}^f = 1 - \frac{\text{Re}\left[\mathcal{G}_V^f\right]}{\text{Re}\left[\mathcal{G}_A^f\right]}$$

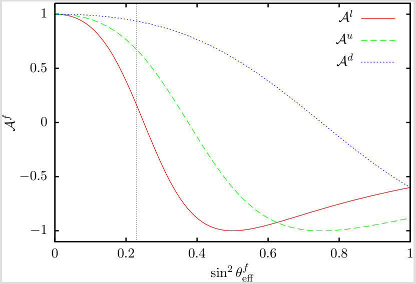
Effective weak mixing angle and A_{FB}

Effective weak mixing angle

$$4|Q_f|\sin^2\theta^f_{\text{eff}} = 1 - \frac{\mathrm{Re}\left[\mathcal{G}^f_V\right]}{\mathrm{Re}\left[\mathcal{G}^f_A\right]}$$

Pole forward-backward asymmetry

$$A^0_{FB} = \frac{3}{4}\mathcal{A}_{\mathrm{e}}\mathcal{A}_f$$



Asymmetry parameter

$$\mathcal{A}^f = \frac{2\,\mathrm{Re}\left[\mathcal{G}^f_V\right]\mathrm{Re}\left[\mathcal{G}^f_A\right]}{\mathrm{Re}\left[\mathcal{G}^f_V\right]^2 + \mathrm{Re}\left[\mathcal{G}^f_A\right]^2} = \frac{1-4|Q_f|\sin^2\theta^f_{\text{eff}}}{1-4|Q_f|\sin^2\theta^f_{\text{eff}} + 8Q_f^2(\sin^2\theta^f_{\text{eff}})^2}$$

Effective weak mixing angle and A_{FB}

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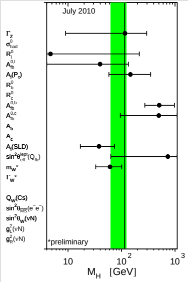

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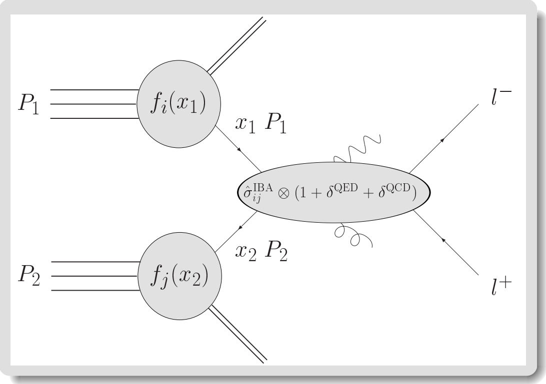
Z-pole observables at the LHC

Improved Born approximation:

$$\sigma^{\mathrm{IBA}}(P_1, P_2) = \sum_{i,j} \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \; f_i(x_1)\, f_j(x_2)\; \hat{\sigma}_{ij}^{\mathrm{IBA}} \otimes (1 + \delta^{\mathrm{QED}} + \delta^{QCD})$$

- use IBA for partonic cross section
- convolution with QED and QCD corrections
- fold with PDF
- neglects non-resonant $q\bar{q}$ contributions: boxes, etc.
- neglects photon-induced initial states



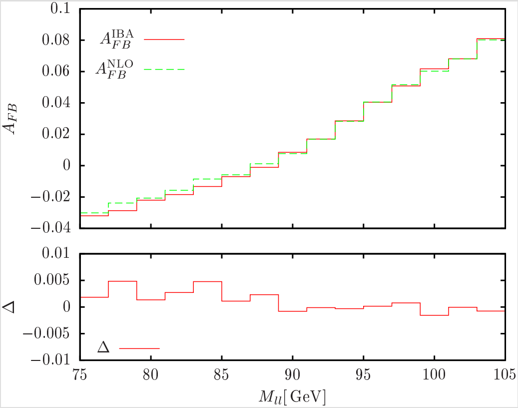
Effective weak mixing angle and A_{FB} at the LHC

Improved Born approximation:

$$\sigma^{\rm IBA}(P_1,P_2)=\sum_{i,j}\int_0^1 {\rm d}x_1{\rm d}x_2\ f_i(x_1)\ f_j(x_2)\ \hat\sigma_{ij}^{\rm IBA}\otimes(1+\delta^{\rm QED}+\delta^{QCD})$$

- direct comparison between NLO and IBA result
- extract effective mixing angle from NLO "data" using the IBA

➨ $\delta\sin^2\theta^l_{\rm eff}\Big|^{\rm IBA}\approx 0.6\times10^{-4}$



Effective weak mixing angle: uncertainties

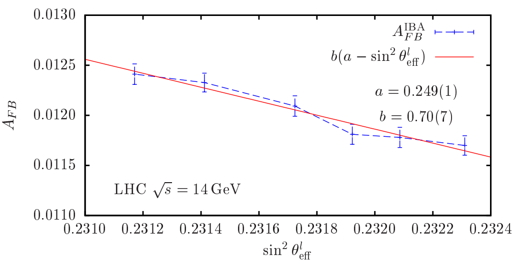
For $\sin^2\theta^l_{\text{eff}}$ close to $1/4 \Rightarrow$

linear approximation:

$$A_{FB} \approx b(a - \sin^2\theta^l_{\text{eff}})$$

$$\delta \sin^2\theta^l_{\text{eff}} = \frac{\delta A_{FB}}{b}$$

Statistical uncertainty:



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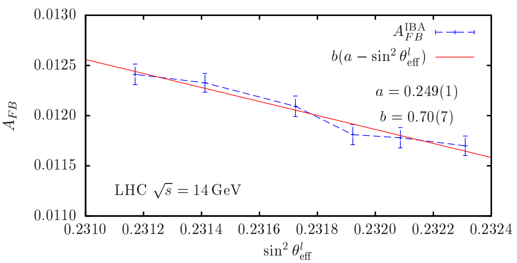


For the LHC with $\sqrt{s} = 14\,\text{TeV}$ and $100\,\text{fb}^{-1}$ of data:

$$\delta\sin^2\theta^l_{\text{eff}}\Big|^{\text{stat}} \approx 2.4\times10^{-4}$$

Effective weak mixing angle: uncertainties

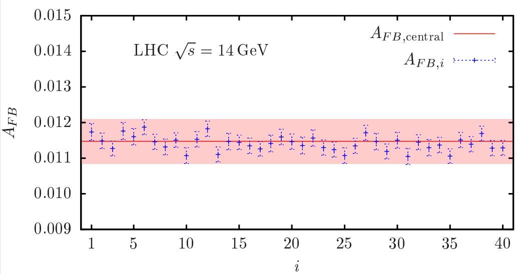
For $\sin^2\theta^l_{\text{eff}}$ close to $1/4 \Rightarrow$

linear approximation:

$$A_{FB} \approx b(a - \sin^2\theta^l_{\text{eff}})$$

$$\delta \sin^2\theta^l_{\text{eff}} = \frac{\delta A_{FB}}{b}$$

PDF uncertainty:



$$\delta A_{FB}\Big|^{\text{PDF}} = \frac{1}{2}\sqrt{\sum_{i=1}^{N}\left(A^{+}_{FB,i} - A^{-}_{FB,i}\right)^2}$$

MTSW2008 PDF

Effective weak mixing angle: uncertainties

For $\sin^2\theta^l_{\text{eff}}$ close to $1/4 \Rightarrow$

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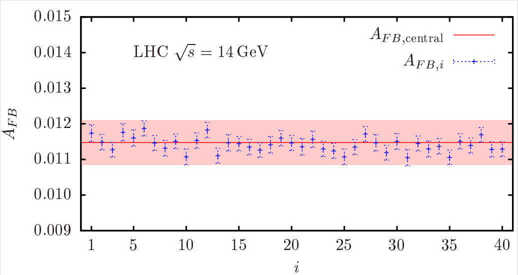
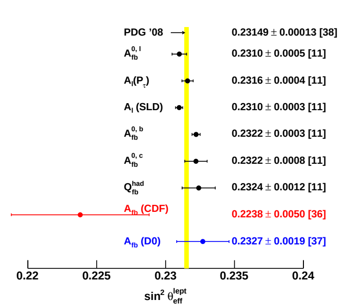


For the LHC with $\sqrt{s} = 14\,\text{TeV}$:

$$\delta \sin^2\theta^l_{\text{eff}}\Big|^{\text{PDF}} \approx 8 \times 10^{-4}$$

Effective weak mixing angle: Summary

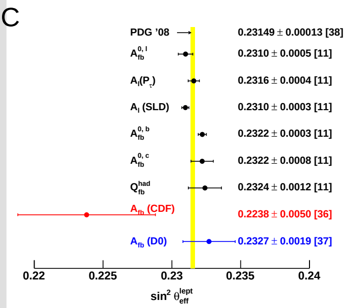
- Current world average: $\sin^2\theta^l_{\text{eff}} = 0.23149 \pm 0.00013$



Effective weak mixing angle: Summary

- Current world average: $\sin^2\theta^l_{\text{eff}} = 0.23149 \pm 0.00013$

- Conservative uncertainty estimate for LHC
  - $\delta \sin^2\theta^l_{\text{eff}}\big|^{\text{stat}} \approx 2.4 \times 10^{-4}$
  - $\delta \sin^2\theta^l_{\text{eff}}\big|^{\text{PDF}} \approx 8 \times 10^{-4}$
  - $\delta \sin^2\theta^l_{\text{eff}}\big|^{\text{IBA}} \approx 0.6 \times 10^{-4}$



Conclusions

- State-of-the-art NC Drell–Yan calculation presented
- Pseudo-observables
- Electroweak precision measurements possible at the LHC
- In particular, forward-backward asymmetry useful for a precision determination of effective weak mixing angle