First Study of Di-Lepton A_{FB} and Measurement of $\sin^2\theta_W$ at CMS

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for

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LHC Working Group
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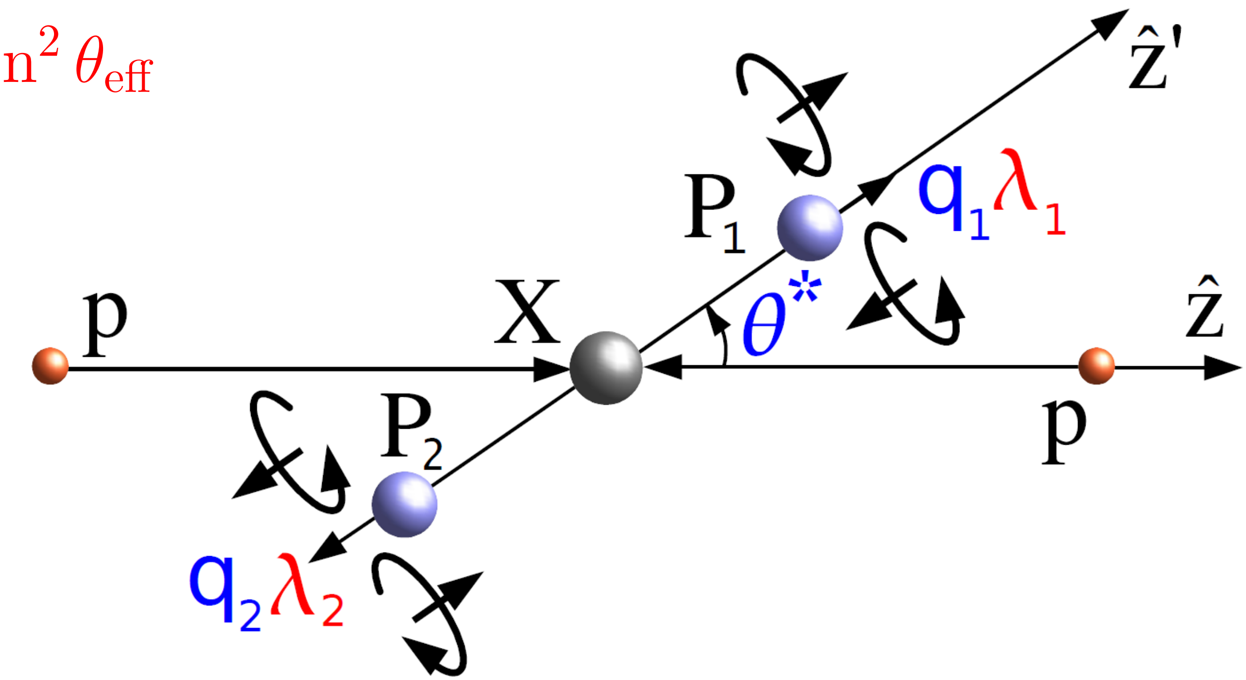
Experts present at this workshop: Efe Yazgan (A_{FB}), A.G. ($\sin^2\theta_W$)

Outline

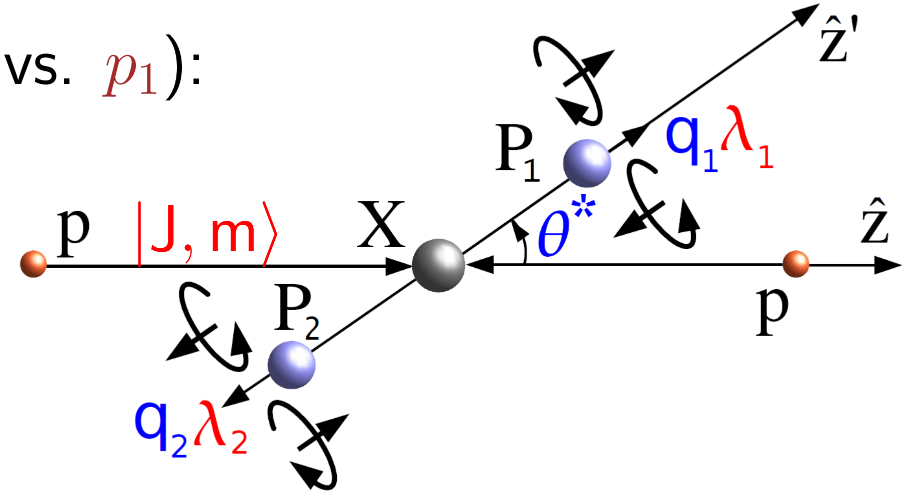
- Introduction: A_{FB} (forward-backward asym.) and EWK couplings
- Measurement: di-lepton A_{FB} and consistency with SM
- Method: likelihood model $p_1 p_2 \to X \to P_1 P_2$
- Method application: $\sin^2\theta_{\rm eff}$



Introduction: A_{FB}

- Forward-backward asymmetry (P_1 vs. p_1):

$$A_{FB} = \frac{N(\theta^* < \frac{\pi}{2}) - N(\theta^* > \frac{\pi}{2})}{N(\theta^* < \frac{\pi}{2}) + N(\theta^* > \frac{\pi}{2})}$$



- Reflect kinematics (arXiv:1001.3396):

$$\frac{d\Gamma(p_1 p_2 \to X_J \to P_1 P_2)}{\Gamma d\cos\theta^*} = \left(J + \frac{1}{2}\right) \times \sum_{\lambda_1,\lambda_2} f_{\lambda_1\lambda_2} \sum_m f_m \left(d^J_{m,\lambda_1-\lambda_2}(\theta^*)\right)^2$$

- $J = 1;\ m, (\lambda_1 - \lambda_2) = \pm 1$: (SM $Z, \gamma^* \leftrightarrow f\bar{f}$)

$$\frac{d\Gamma}{\Gamma d\cos\theta^*} = \frac{3}{8}(1 + \cos^2\theta^*) + A_{FB}\cos\theta^*$$

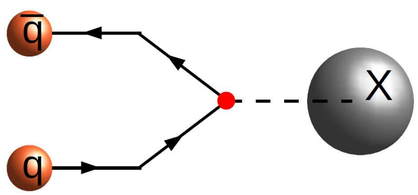
- General case (BSM), including $gg\ \&\ q\bar{q} \to X_{J=2} \to l^- l^+$

$$\frac{d\Gamma}{\Gamma d\cos\theta^*} \propto A_0 + A_1\cos^1\theta^* + A_2\cos^2\theta^* + A_3\cos^3\theta^* + A_4\cos^4\theta^* + \ldots$$

Introduction: $\sin^2\theta_W$ and EWK Couplings

$$A(X_{J=1} \to f\bar{f}) \propto \epsilon^{\mu}\bar{u}_{q_1}\left(\gamma_\mu\left(\rho_1 + \rho_2\gamma_5\right) + \frac{m_q}{\Lambda^2}\Delta q_\mu\left(\rho_3 + \rho_4\gamma_5\right)\right)v_{q_2}$$

- Polarization amplitudes giving $f_{\lambda_1\lambda_2} = \frac{|A_{\lambda_1\lambda_2}|^2}{\sum|A_{ij}|^2}$



$$A_{\pm\pm} = -2\,m_q\left(\pm\rho_1 + \frac{\beta M_X^2}{2\Lambda^2}\left(\rho_4 \mp \rho_3\beta\right)\right) \to 0$$

$$A_{\pm\mp} = \sqrt{2}M_X\left(\rho_1 \pm \beta\rho_2\right)$$

- SM couplings: $\sin^2\theta_{\rm eff} \simeq \sin^2\theta_W \simeq 0.2312$

process	$\rho_1^{(X=\gamma)}$	$\rho_2^{(X=\gamma)}$	$\rho_1^{(X=Z)} = c_V(\theta_W)$	$\rho_2^{(X=Z)} = c_A(\theta_W)$
$X \to l^+l^-$	$-e$	0	$\frac{-3+12\sin^2\theta_W}{6\sin(2\theta_W)}e \simeq -0.045e$	$\frac{+1}{2\sin(2\theta_W)}e \simeq +0.593e$
$X \leftarrow u\bar{u}, c\bar{c}$	$+2e/3$	0	$\frac{+3-8\sin^2\theta_W}{6\sin(2\theta_W)}e \simeq +0.227e$	$\frac{-1}{2\sin(2\theta_W)}e \simeq -0.593e$
$X \leftarrow d\bar{d}, s\bar{s}$	$-e/3$	0	$\frac{-3+4\sin^2\theta_W}{6\sin(2\theta_W)}e \simeq -0.410e$	$\frac{+1}{2\sin(2\theta_W)}e \simeq +0.593e$

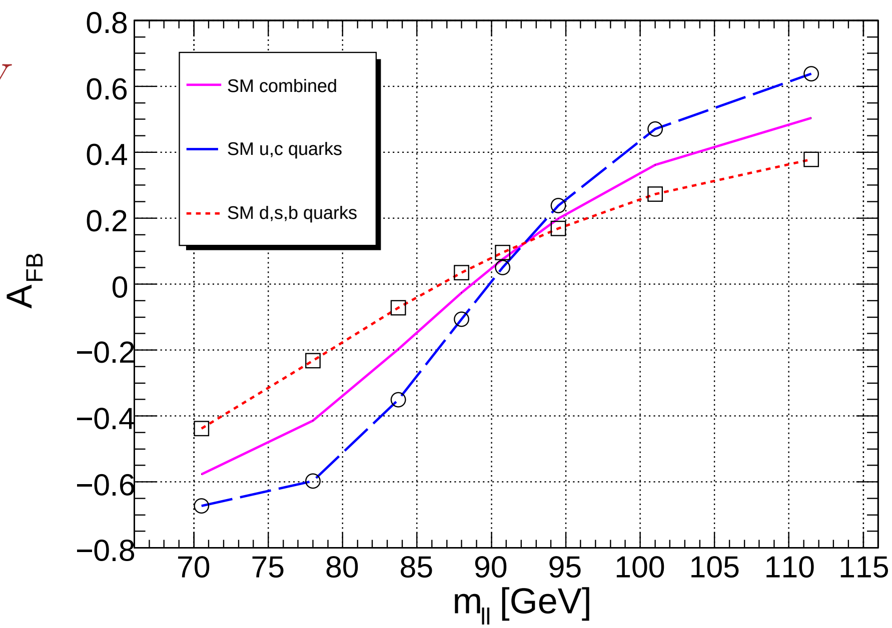
Introduction: $\sin^2\theta_W$ and A_{FB}

$$\hat{\sigma}_{q\bar{q}}(s = {m_{ll}}^2, \theta^*) \propto \frac{1}{s} \sum_{\chi_1,\chi_2,\lambda_1,\lambda_2=\uparrow\downarrow} \left(d^{J=1}_{\chi_1-\chi_2,\lambda_1-\lambda_2}(\theta^*) \right)^2 \times$$

$$\left| A^{(\gamma\to ll)}_{\lambda_1,\lambda_2} B^{(q\bar{q}\to\gamma)}_{\chi_1,\chi_2} + A^{(Z\to ll)}_{\lambda_1,\lambda_2}(\theta_W) B^{(q\bar{q}\to Z)}_{\chi_1,\chi_2}(\theta_W) \times \frac{s}{(s-m_Z^2)+im_Z\Gamma_Z} \right|^2$$

$$\propto \frac{3}{8}(1+\cos^2\theta^*) + {A_{FB}}^{q\bar{q}}(s,\theta_W)\cos\theta^*$$

- measure A_{FB} $\Leftrightarrow$ measure $\sin^2\theta_W$
- A_{FB} depends on
  - q flavor (7 TeV pp $\sim$50% $u+c$)
  - mass $s = {m_{ll}}^2$
  - $\sin^2\theta_W$ (or c_V & c_A)

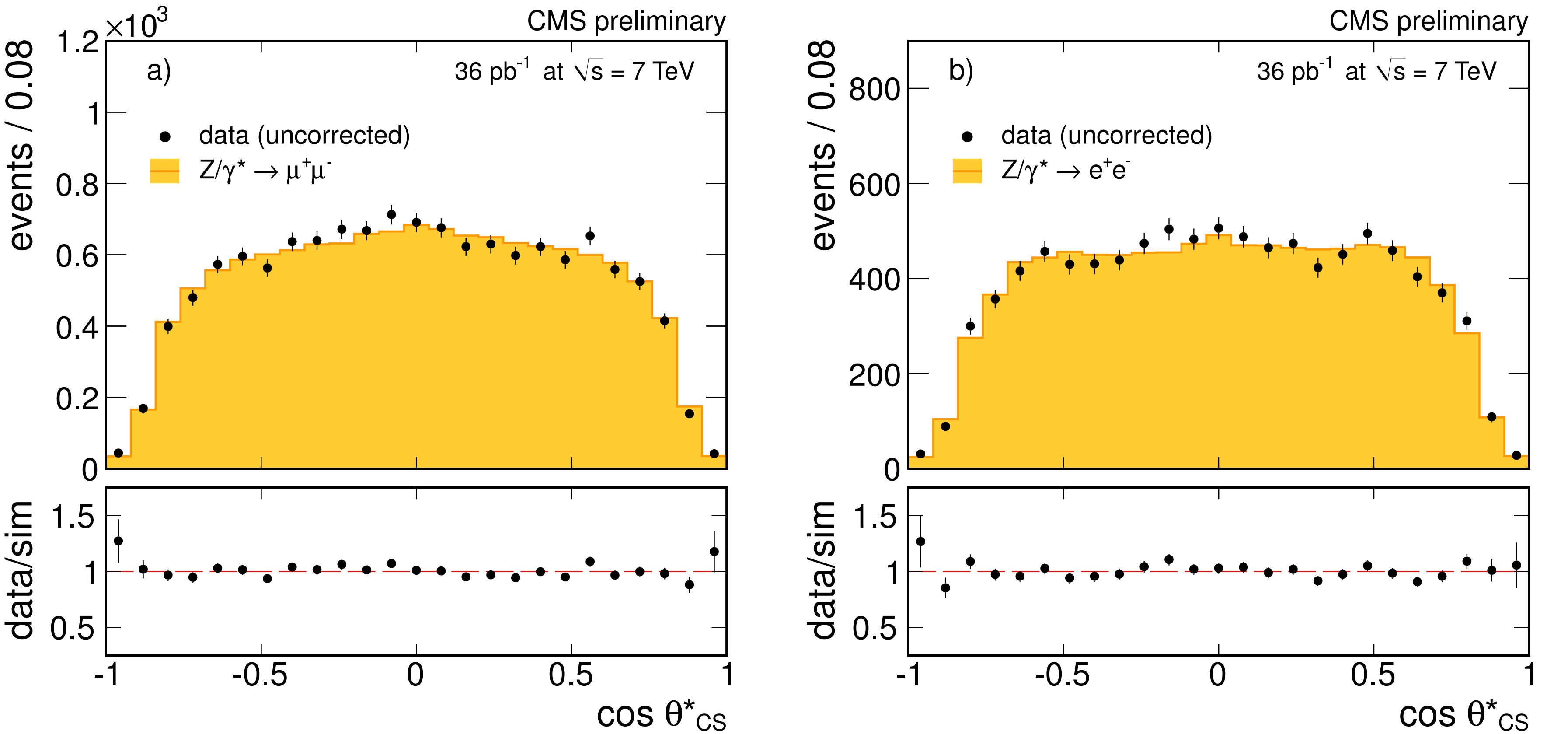


CMS: Integrated $\cos\theta^*$ in $Z/\gamma^* \to l^- l^+$

- Good agreement with POWHEG+CMS simulation

θ^* in Collins-Soper frame with respect to boost direction (Y)

quality $l^{\pm}$: $p_T > 20$ GeV, $|\eta_\mu| < 2.1$, $|\eta_e| = 0-1.44$ & $1.56-2.50$

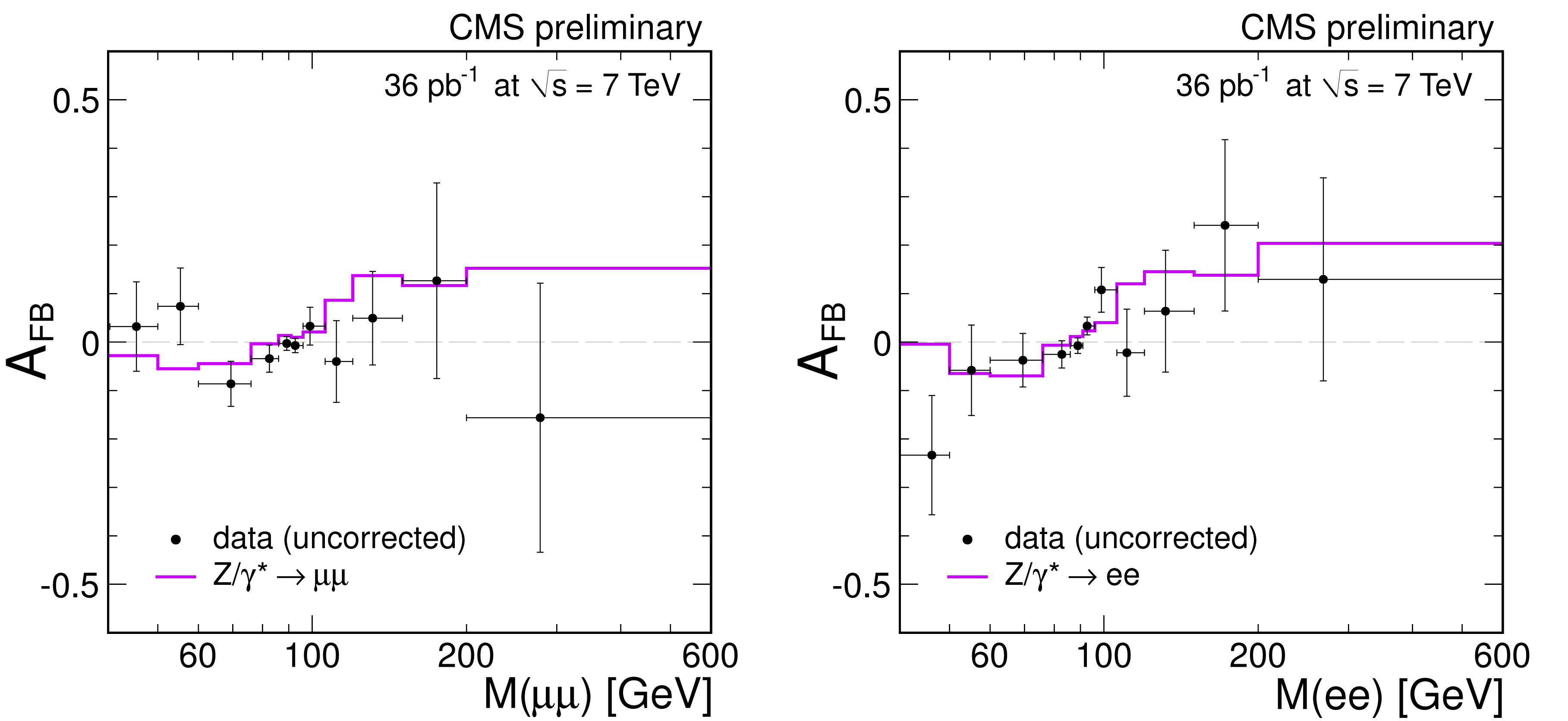


CMS Measurement: Raw A_{FB} in $Z/\gamma^* \to l^-l^+$

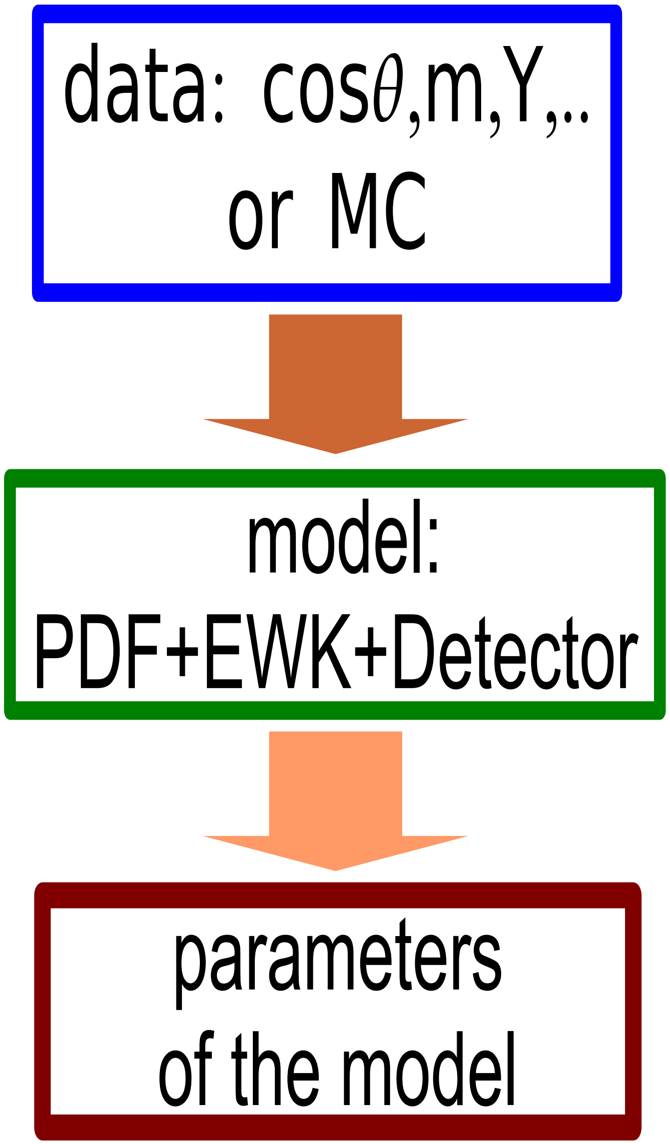
- A_{FB} in good agreement with SM (POWHEG+CMS simulation)

  "dilution" due to mass smearing, quark direction, acceptance

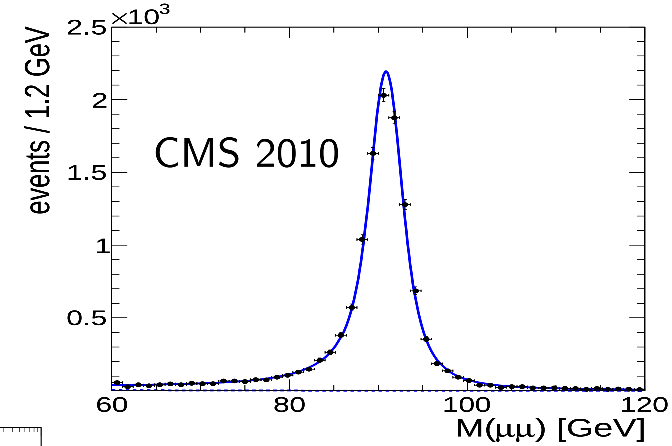
  statistically cleaner: dilute model (SM) to compare to primary data

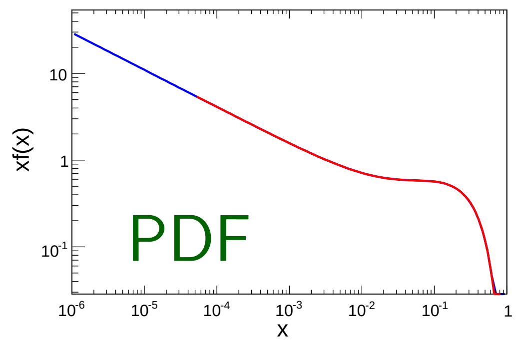


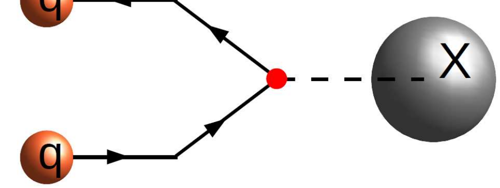
Likelihood Analysis Method



$$\vec{x}_i = (\cos\theta^*, m, Y)$$







$$\mathcal{L} = e^{-n_{\rm sig}-n_{\rm bkg}} \prod_i^N \Big(n_{\rm sig} \times \mathcal{P}_{\rm sig}(\vec{x}_i;\ \vec{\zeta};\ \vec{\xi}) + n_{\rm bkg} \times \mathcal{P}_{\rm bkg}(\vec{x}_i;\ \vec{\xi}) \Big)$$

Fit model parameters $\vec{\zeta}$ (`RooFit/MINUIT`):

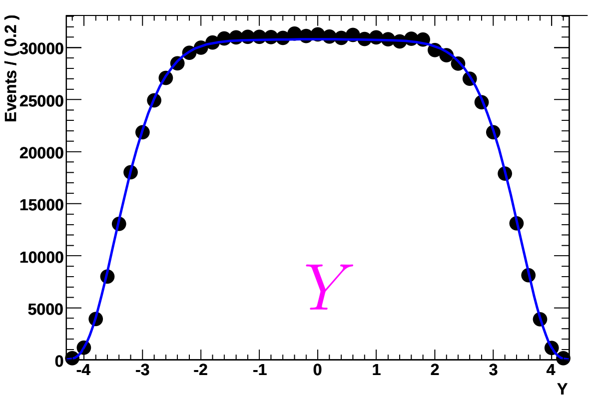
- $\sin^2\theta_W$
- could be c_V, c_A and/or PDFs
- could be New Physics, etc...

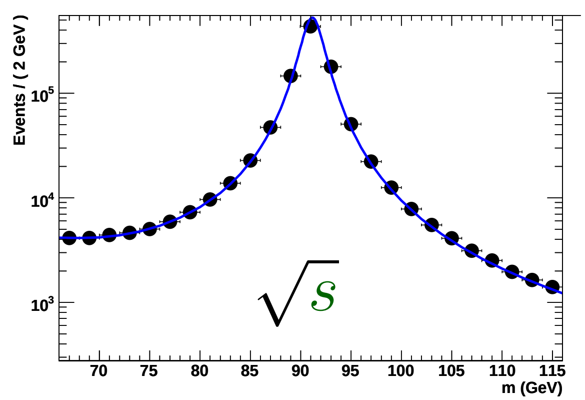
Building PDF+EWK Model

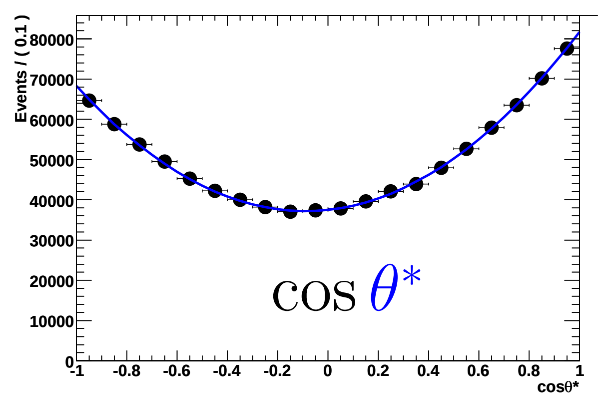
- Build Leading Order (LO) model
  - take LO EWK model $\hat{\sigma}_{q\bar{q}}(s, \theta^*)$ – from previous slides
  - take LO PDF $\tilde{f}_{q,\bar{q}}(x, Q^2)$ – from LO CTEQ6
  - correct fit results for NLO effects (e.g. with POWHEG)

$$\frac{d\sigma_{pp}(Y, s, \theta^*)}{dY\, ds\, d\cos\theta^*} \propto \frac{1}{s_{pp}} \sum_{q=udscb} \hat{\sigma}_{q\bar{q}}(s, \theta^*)\, \tilde{f}_q\left(e^{Y}\sqrt{s/s_{pp}}, s\right)\; \tilde{f}_{\bar{q}}\left(e^{-Y}\sqrt{s/s_{pp}}, s\right)$$

- Good agreement between LO simulation (Pythia) and the LO Model



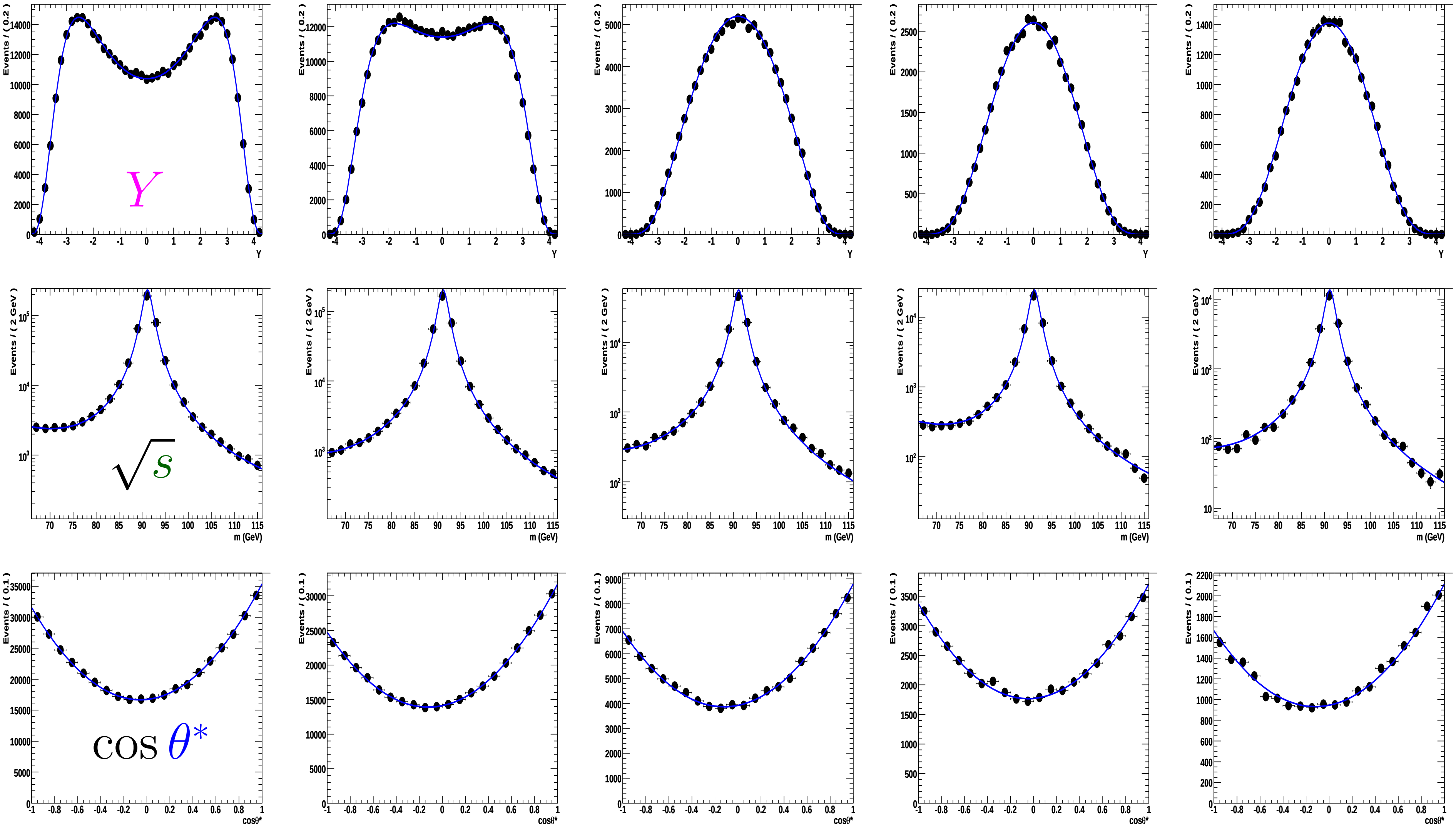




Model: Parton Distribution Functions

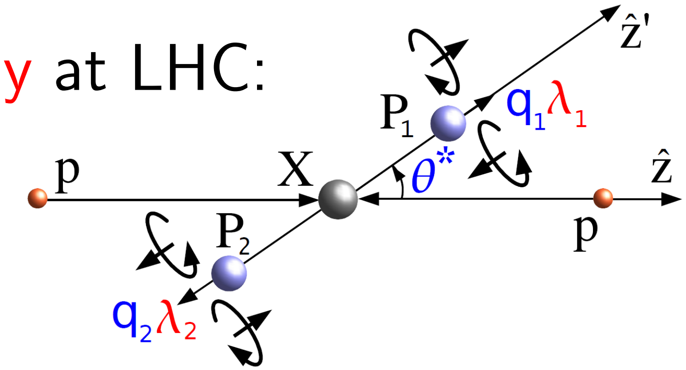
- Each flavor matches well, plot analytical distribution vs LO Pythia

$u\bar{u}$ (45.7%) $d\bar{d}$ (36.8%) $s\bar{s}$ (10.2%) $c\bar{c}$ (4.9%) $b\bar{b}$ (2.5%)



PDF Model: Parton Dilution

- Solved quark direction challenge analytically at LHC:



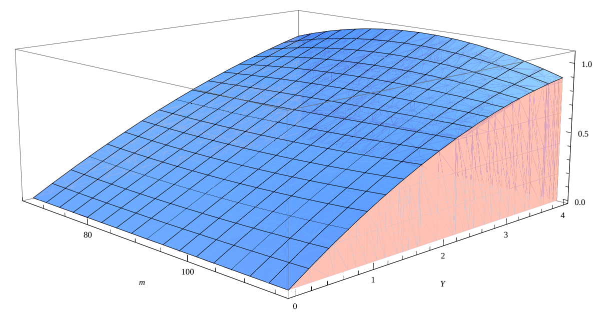
$$\mathcal{P}_{\rm observe}(Y,s,\theta^*;\vec{\zeta}) = \frac{d\sigma_{\rm observe}(Y,s,\theta^*;\vec{\zeta})}{dY\,ds\,d\cos\theta^*} \propto$$

$$\sum_{q=udscb}\left[\hat{\sigma}^{\rm even}_{q\bar{q}}(s,\cos^2\theta^*) + D_{q\bar{q}}(s,Y)\times\hat{\sigma}^{\rm odd}_{q\bar{q}}(s,\cos^1\theta^*)\right]\times F_{q\bar{q}}(s,Y)$$

$$D_{q\bar{q}}(s,Y) = \frac{\tilde{f}_q\left(e^{+|Y|}\sqrt{s/s_{pp}},s\right)\,\tilde{f}_{\bar{q}}\left(e^{-|Y|}\sqrt{s/s_{pp}},s\right) - \tilde{f}_q\left(e^{-|Y|}\sqrt{s/s_{pp}},s\right)\,\tilde{f}_{\bar{q}}\left(e^{+|Y|}\sqrt{s/s_{pp}},s\right)}{\tilde{f}_q\left(e^{+Y}\sqrt{s/s_{pp}},s\right)\,\tilde{f}_{\bar{q}}\left(e^{-Y}\sqrt{s/s_{pp}},s\right) + \tilde{f}_q\left(e^{-Y}\sqrt{s/s_{pp}},s\right)\,\tilde{f}_{\bar{q}}\left(e^{+Y}\sqrt{s/s_{pp}},s\right)}$$

$$F_{q\bar{q}}(s,Y) = \tilde{f}_q\left(e^{+Y}\sqrt{s/s_{pp}},s\right)\,\tilde{f}_{\bar{q}}\left(e^{-Y}\sqrt{s/s_{pp}},s\right) + \tilde{f}_q\left(e^{-Y}\sqrt{s/s_{pp}},s\right)\,\tilde{f}_{\bar{q}}\left(e^{+Y}\sqrt{s/s_{pp}},s\right)$$

- $D_{q\bar{q}}(s,Y)\equiv 0$ for $q=s,c,b$ and for $Y=0$
  – some gain with $u\bar{u}$ and $d\bar{d}$ at higher Y



Detector Model: Acceptance and Efficiency

- Lepton requirements (in CS frame*):

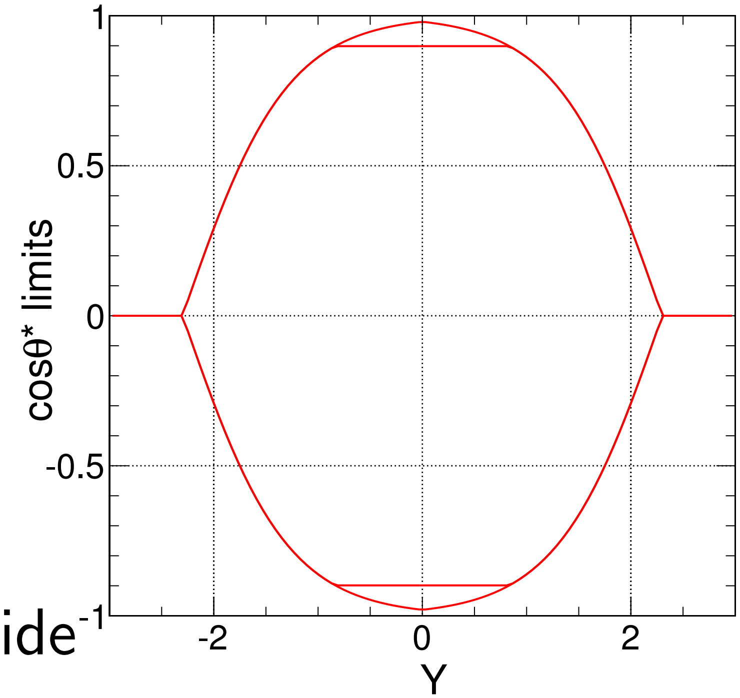
  consider only $\mu^-\mu^+$ here

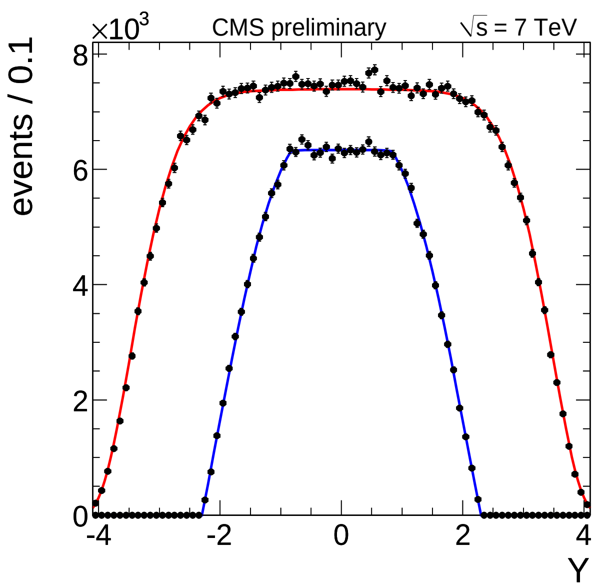
  $|\eta^*| < 2.3$ & $|p_T^*| > 18$ GeV $= p_{\rm min}$

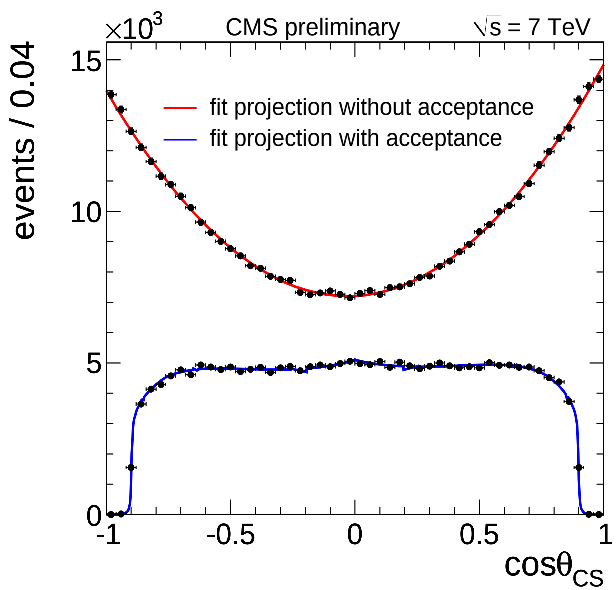
  $\Rightarrow |\cos\theta^*| < \tanh(Y_{\rm max} - |Y|)$

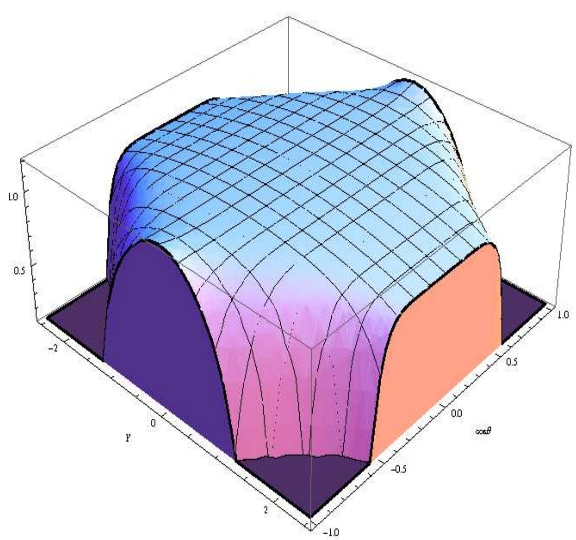
  $\Rightarrow |\cos\theta^*| < \sqrt{1 - (2p_{\rm min}/m)^2}$

  $\mathcal{G}(\theta^*, Y, m) = 0$ outside, efficiency inside







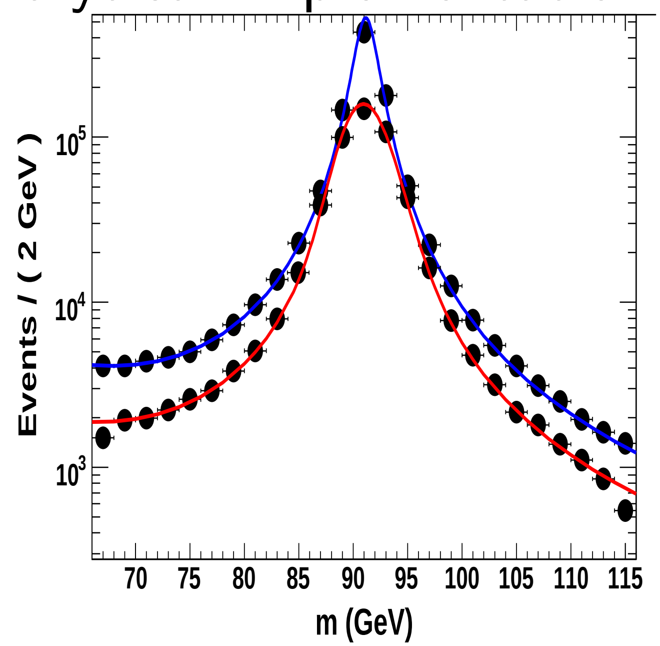


"Detector" Model: Resolution and FSR

- Resolution and FSR: empirical many-Gaussian function $\mathcal{R}(x)$

$$\mathcal{P}_{\text{detect}}(\theta^*, Y, s) = \mathcal{G}(\theta^*, Y, s) \times \int_{-\infty}^{+\infty} dx\, \mathcal{R}(x)\, \mathcal{P}_{\text{observe}}(Y, s - x, \theta^*)$$

RooFit analytical implementation



- $\mathcal{R}(x)$ includes:
  - detector resolution and energy scale
    from simulation (GEANT)
    float energy scale in data ("m_Z")
    alignment/calibration studies – syst.
  - Final State Radiation (FSR)
    from simulation (Pythia)
    alternative model (PHOTOS) – systematics

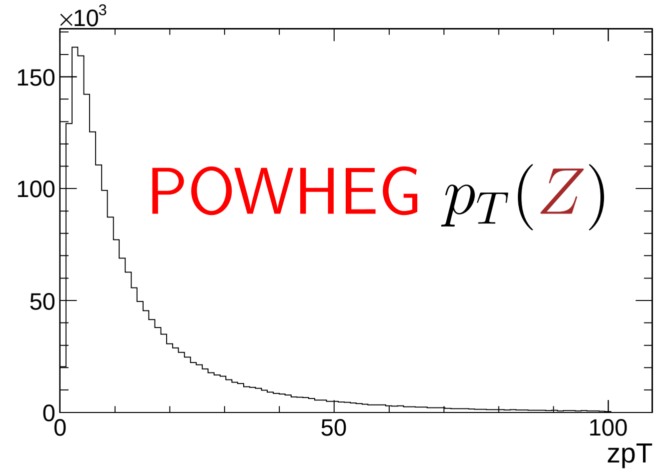
Put It All Together with NLO

- Test ISR with NLO generator (POWHEG)

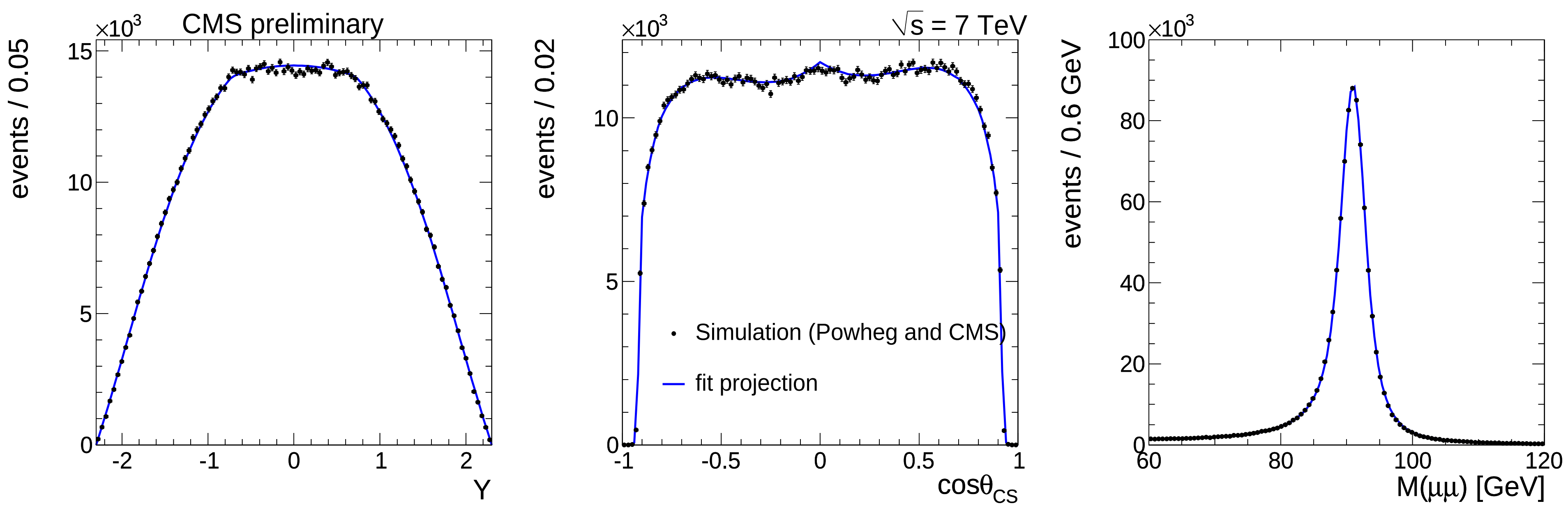
– suppress ISR effects

$p_T(\mu^-\mu^+) < 25$ GeV

result deviations – systematics (correction)



- NLO (POWHEG) + CMS (GEANT) simulation against 3D Model:



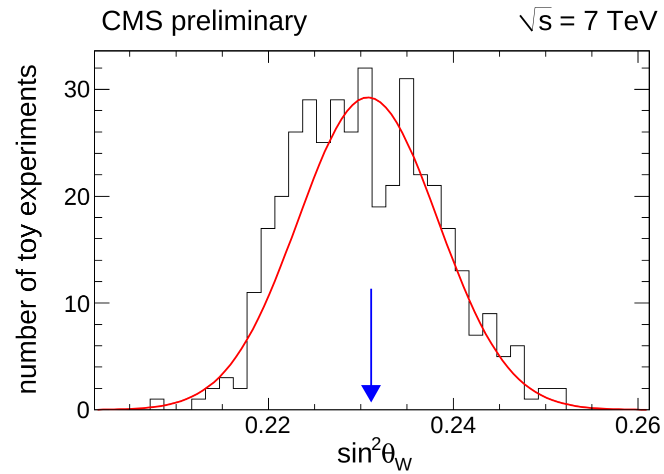
Generated Experiments

- Test with 400 generated experiments:

  $\sin^2\theta_{\rm eff} = 0.2306 \pm 0.0004$
  (0.2311 generated)

  expected error $\sigma = 0.0078 \pm 0.0003$
  (0.0077 in data)

  goodness-of-fit $= \ln(\mathcal{L}_{\rm MC}) / \ln(\mathcal{L}_{\rm data}) = 0.9997 \pm 0.0029$



- Include all expected contributions

  $N = 12\,345$ events

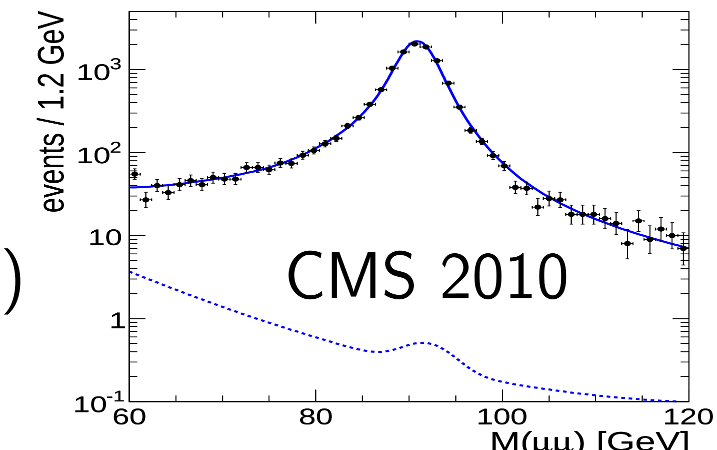
  $n_{\rm bkg} = 36$ background events (- - - - $\longrightarrow$)

  $q\bar{q} \to Z/\gamma^* \to \tau^+\tau^- \sim 50\%$

  QCD $\sim 25\%$ (data-driven, main syst.)

  $t\bar{t}$, ZZ, WZ, WW, $W+$ jets $< 10\%$ each

  veto cosmics (vertex, angle)



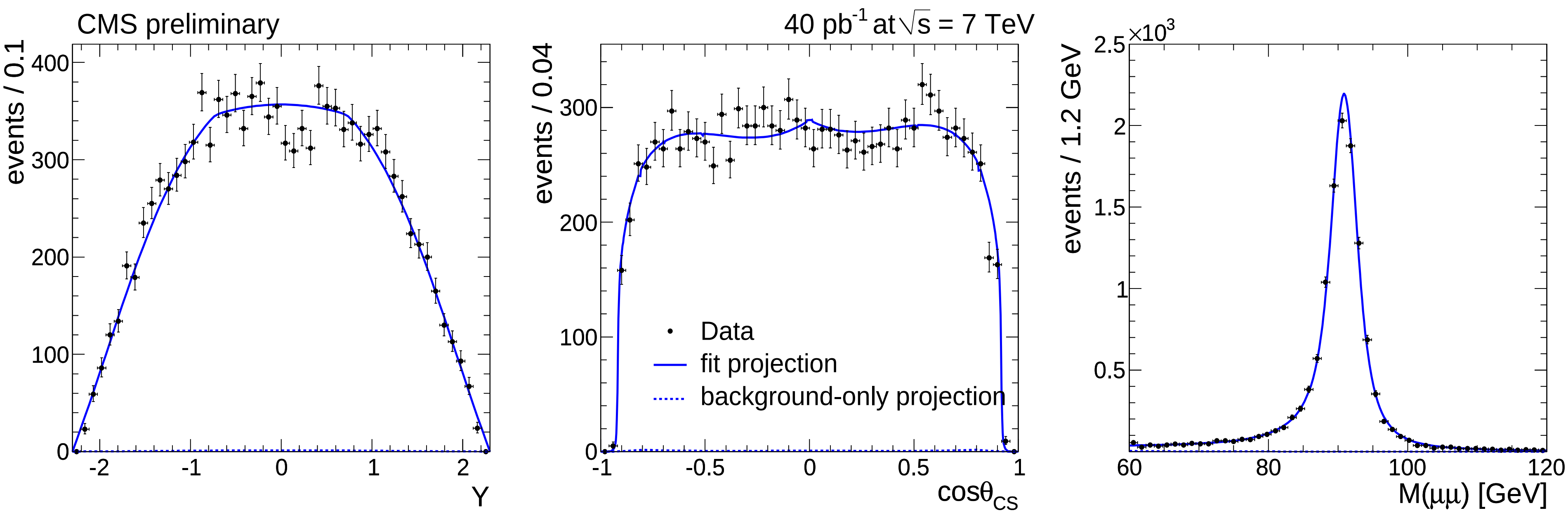
Result with 2010 CMS Data ("blind")

- Chose to float $\sin^2\theta_{\rm eff}$ in the fit to 40 pb^{-1} of CMS data:

$$\sin^2\theta_{\rm eff} = 0.\mathtt{XXXX} \pm 0.0077\ (\text{stat.}) \pm 0.0036\ (\text{syst.})$$

result kept blind until finalized systematics

- 1D projections of CMS data and 3D model:



$\sin^2\theta_{\rm eff}$ Systematics

source	uncertainty	comment
LO model (ISR)	0.0011	deviations with NLO gen. sample
PDFs	0.0015	variation with MSTW2008 sample
FSR	0.0018	deviation with PHOTOS sample
fit model	0.0010	deviations with generated samples
resolution/align.	0.0022	control study to correct p_T
background	0.0007	variation (e.g. QCD by 50%)
total	0.0036	

- Path forward:
  - "theory" systematics is MC statistics limited, likely to improve
    either reduce or become parameter of the fit
    e.g. fit for PDFs (but not now yet)
  - "detector" systematics is in our hands (improve alignment, etc...)

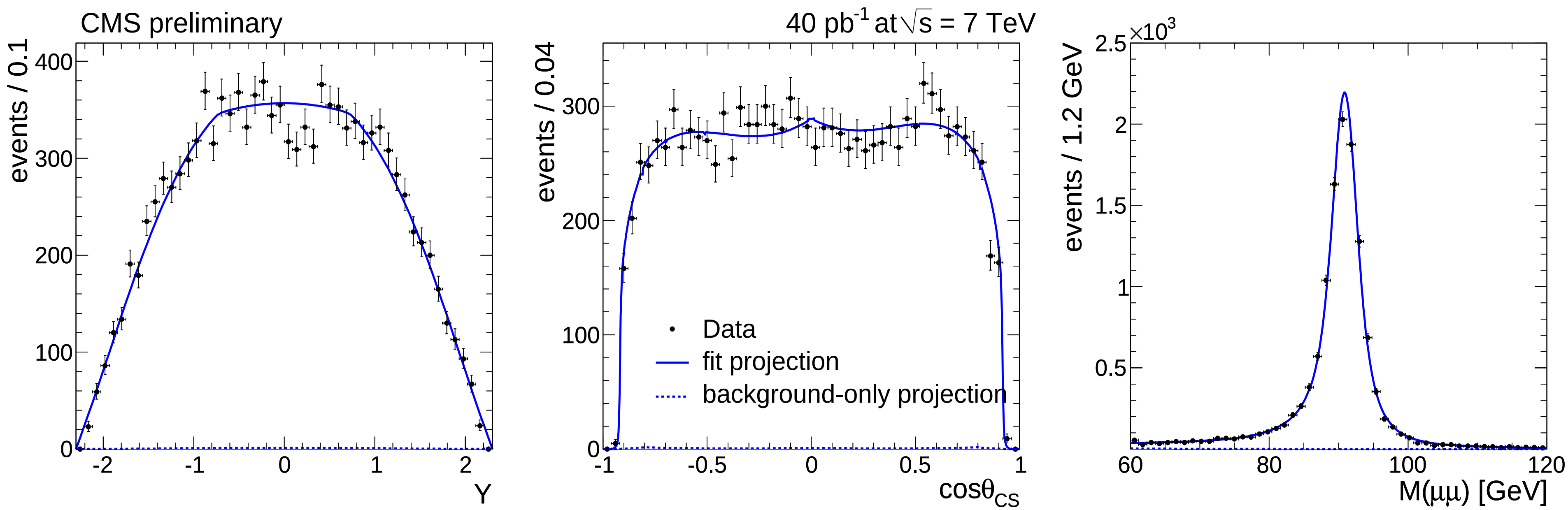
Result with 2010 CMS Data

- Fit for $\sin^2\theta_{\rm eff}$ with 40 pb^{-1} of CMS data:

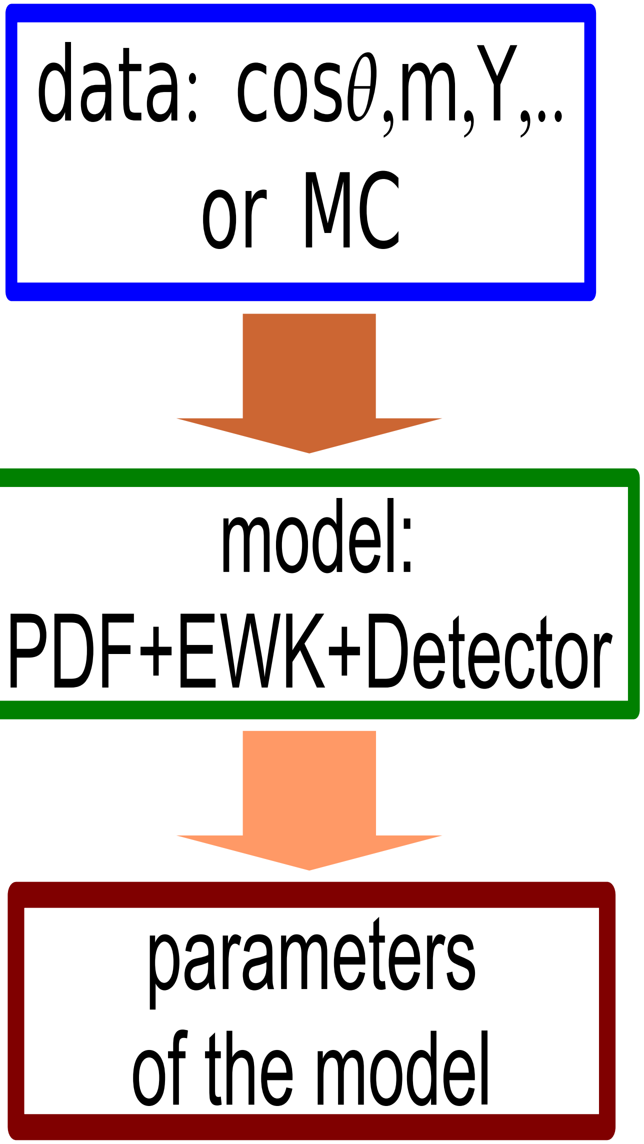
$$\sin^2\theta_{\rm eff} = 0.2287 \pm 0.0077\ (\text{stat.}) \pm 0.0036\ (\text{syst.})$$

consistent with SM (PDG 0.2312)

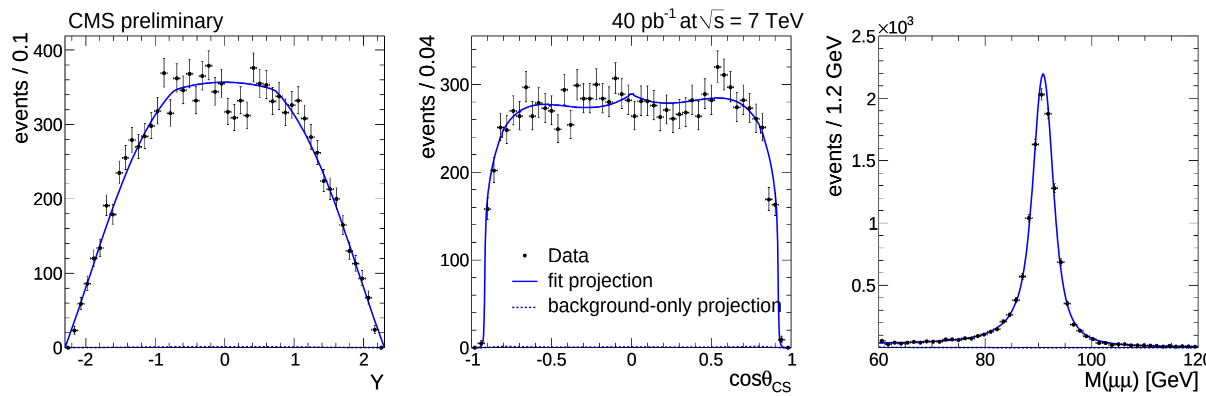
- 1D projections of CMS data and 3D model:



Overview: Multivariate Analysis Model



- Novel analytical MVA model
  - allows extraction of any parameters
  - guarantees maximum sensitivity
  - naturally accounts for quark direction



- Obtain result as a first application:

$$\sin^2\theta_{\rm eff} = 0.2287 \pm 0.0077 \pm 0.0036$$

Summary

- Measurement of A_{FB} with $pp \to Z/\gamma^* \to \mu^-\mu^+$ and e^-e^+
  - sensitive to broad high-mass resonance (BSM), EWK couplings
  - consistent with SM with 2010 data, look for BSM in 2011+
  - corrections for FSR, detector effects, quark direction possible

- First $\sin^2\theta_W$ measurement in $u\bar{u}$ & $d\bar{d} \to Z/\gamma^* \to \mu^-\mu^+$

$$\sin^2\theta_{\text{eff}} = 0.2287 \pm 0.0077\ (\text{stat.}) \pm 0.0036\ (\text{syst.})$$

  - in the ballpark of Tevatron $u\bar{u}$ & $d\bar{d} \to Z/\gamma^* \to e^-e^+$ will be very interesting with 2011 LHC run
  - systematics expected to reduce or become a measurement
  - equivalent $\times 2$ statistics with counting A_{FB} extraction
  - novel technique to extract EWK or PDF or BSM parameters

References

- Original ideas presented for LHC benefit in these slides

  please reference appropriately

- CMS-EWK-10-011 by CMS Collaboration

  "Measurement of Forward-Backward Asymmetry of Lepton Pairs and the Weak-mixing Angle at CMS"

  http://cms-physics.web.cern.ch/cms-physics/public/EWK-10-011-pas.pdf

- Nhan Tran (Johns Hopkins U.) for CMS Collaboration

  "Analysis of $Z \to l^+l^-$ Polarization at CMS"

  presentation at the Moriond-EWK 2011

  http://indico.in2p3.fr/conferenceOtherViews.py?view=standard&confId=4403