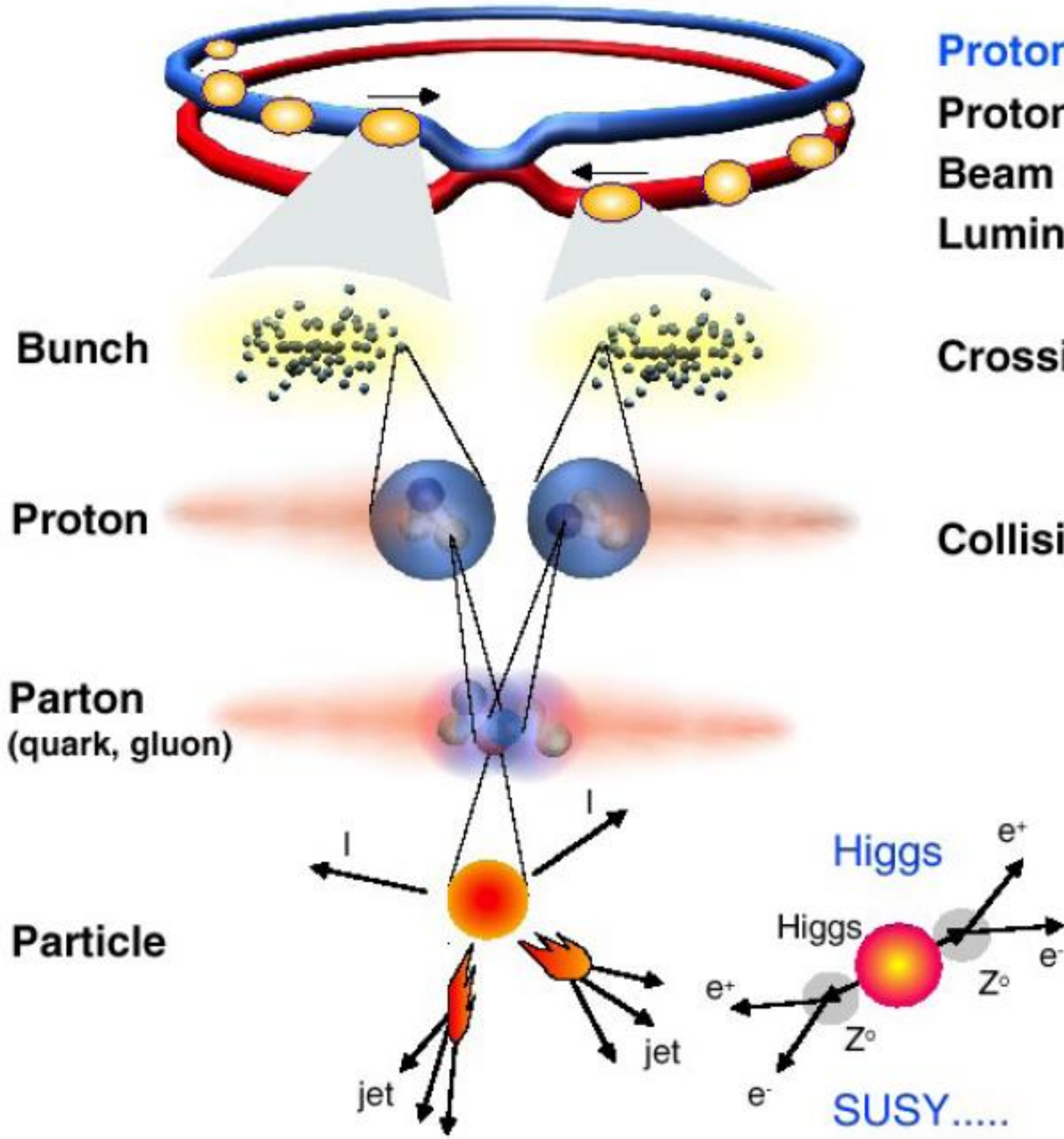
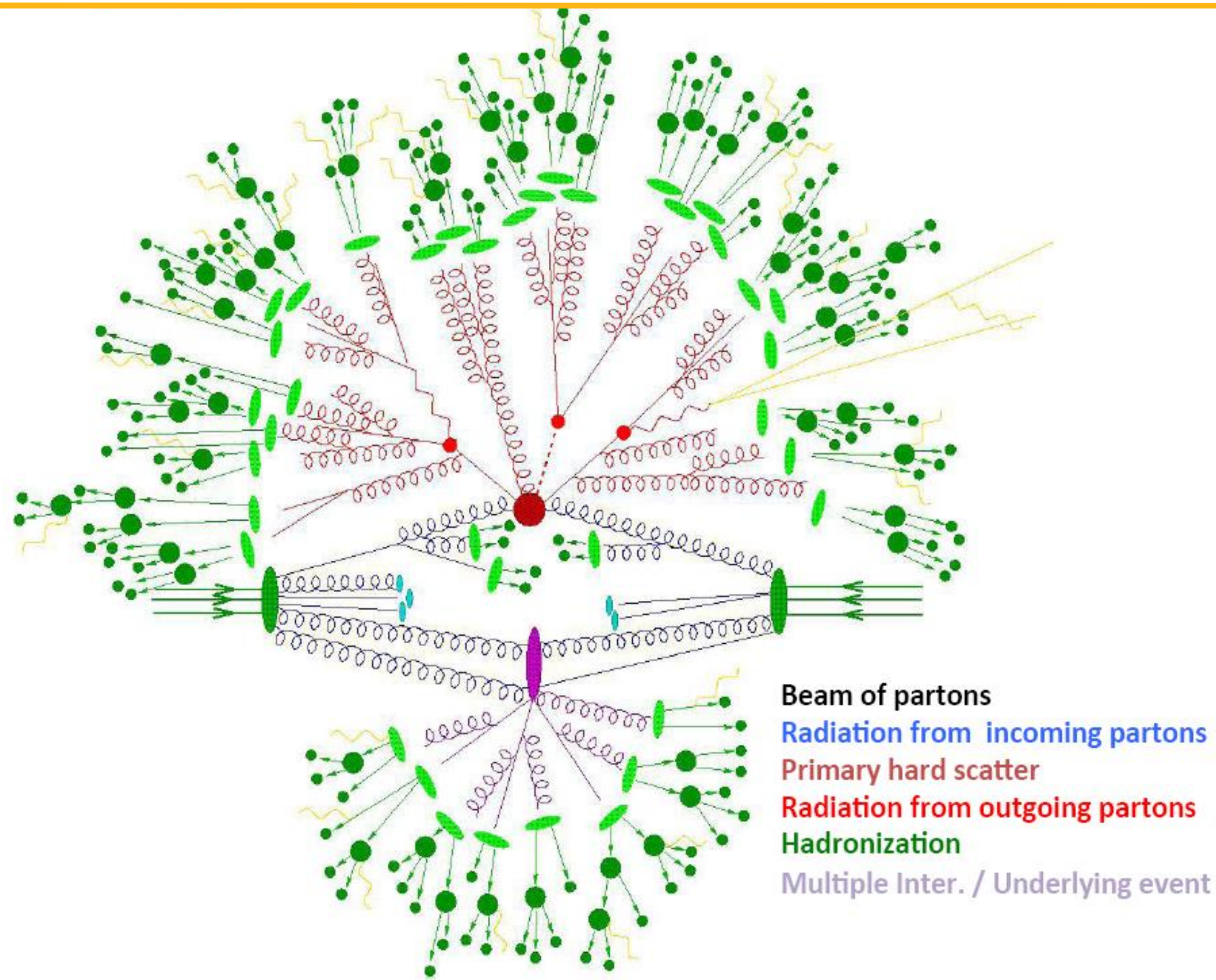
Collisions at LHC



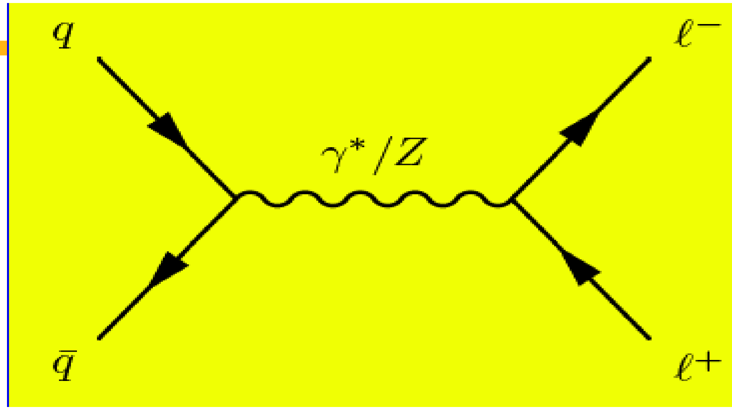
Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

Selection of 1 in 10,000,000,000,000

Typical pp collision



Drell-Yan production



- Direct access to vector and axial couplings

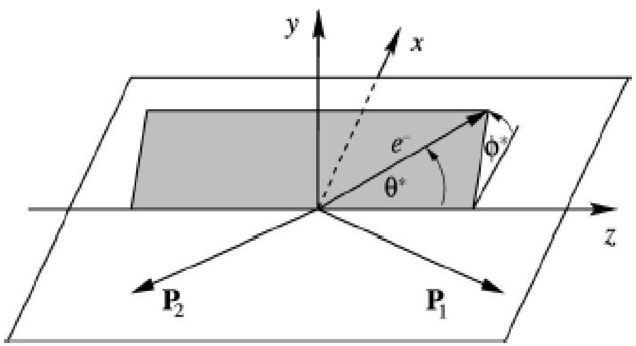
$g_v^f = I_3^f - 2q_f \sin^2\theta_W$ both γ^*-f and Z-f couplings

$g_a^f = I_3^f$ Z-f only coupling

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

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

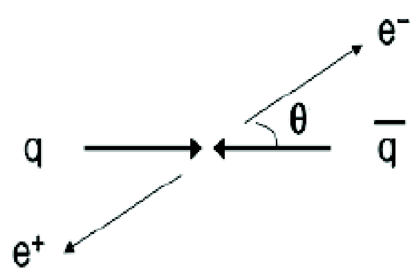
- **$\cos\theta^*$ > (<) 0 → forward** (backward) events
- θ^* is the angle of the negative lepton relative the quark momentum in the dilepton centre-of-mass frame
- Minimize the effect of unknown p_T of incoming quark by measuring θ^* in the **Collins-Soper** frame



Collins-Soper frame

- Collins-Soper frame : the center of mass frame of dilepton

$$q\bar{q} \to Z/\gamma* \to \ell^+\ell^-$$



in lepton plane

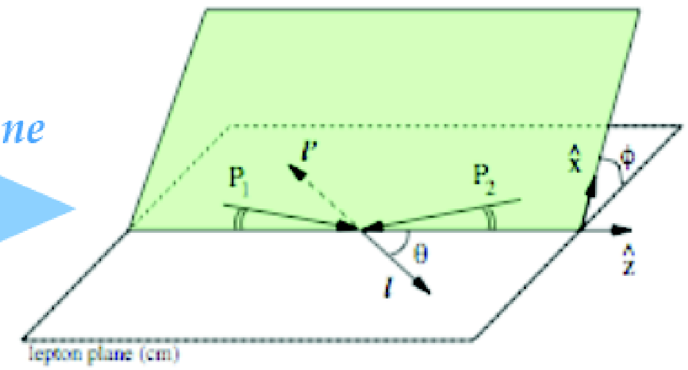


FIG. 1: The Collins-Soper frame.

- Differential cross section of cosθ and ϕ

$$\frac{\mathbf{d}\sigma}{\mathbf{dP_T^2dyd}\cos\theta\mathbf{d}\phi} \propto (1+\cos^2\theta)$$ → ***LO term***

$$+\ \frac{1}{2}A_0(1-3\cos^2\theta)$$ → ***cos²θ : higher order term***

$$+\ A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi$$ → ***(θ, ϕ) terms***

$$+\ A_4\cos\theta$$ → ***LO term : determine A_{fb}***

$$+\ A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi$$ → ***very small terms***

****All higher order terms are zero at Pt=0***

Z/g* Angular Coefficients

- First measurement of the $p\bar{p} \rightarrow Z/\gamma^{*} + X \rightarrow e^{+}e^{-} + X$ angular distributions with 2.1 fb^{-1}
- Angular distributions of the lepton decay in the Collins-Soper frame are:

$$\frac{d\sigma}{d\cos\theta} \propto (1 + cos^2\theta) + \frac{1}{2}A_0(1 - 3cos^2\theta) + A_4\cos\theta$$

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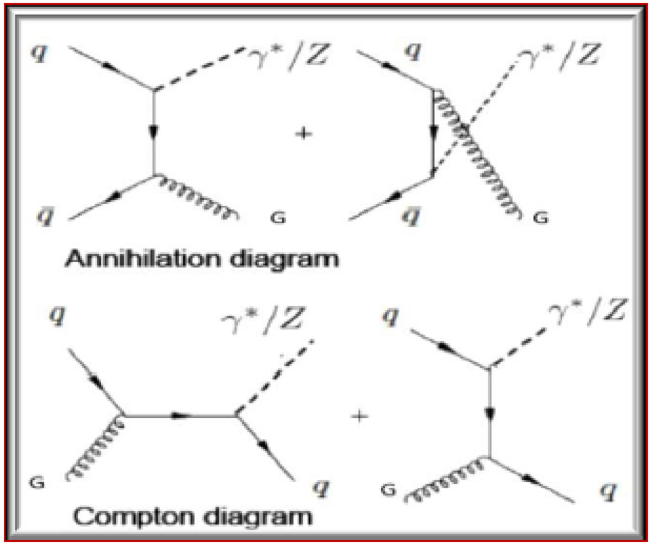
$$\frac{d\sigma}{d\varphi} \propto 1 + \frac{3\pi}{16}A_3\cos\varphi + \frac{1}{4}A_2\cos 2\varphi$$

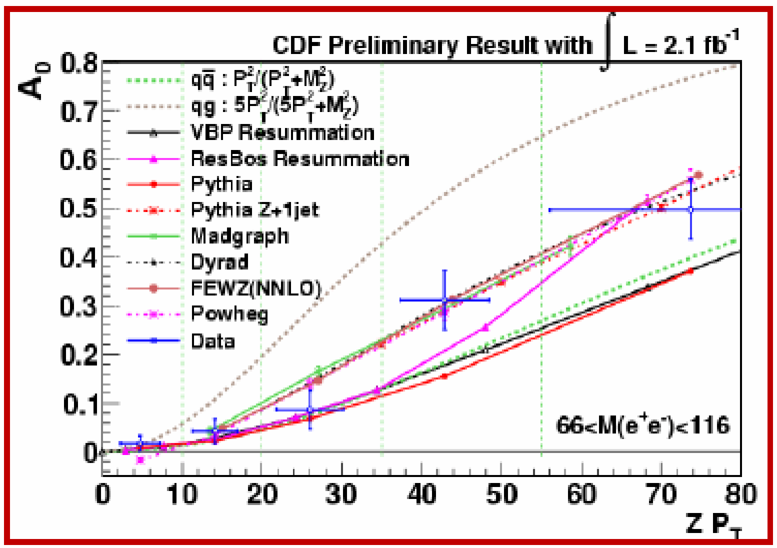
- **Perturbative QCD makes definite predictions on $A_{0,2,3,4}$ depending on the dilepton p_T**
- **At order α_s the Z/γ^{*} boson can be produced via annihilation or Compton scattering**
- **Probe the contribution of different productions mechanisms contributions**

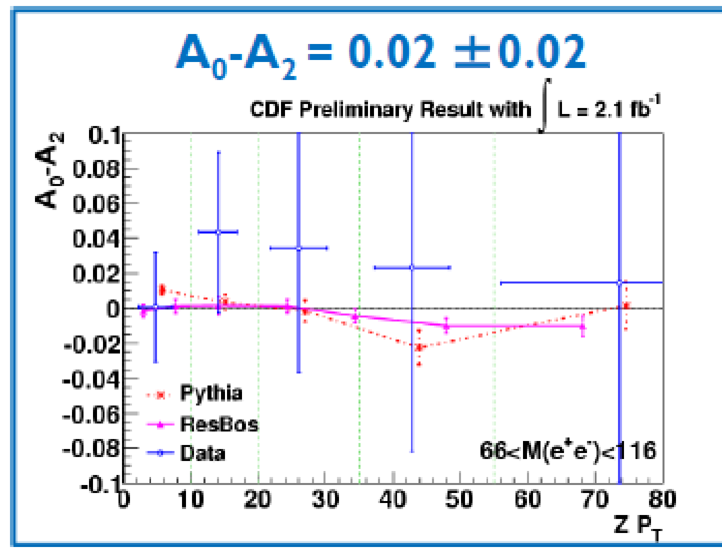


Z/γ^* Angular Coefficients ($A_{0,2}$)

- At order α_s, both A_0 and A_2 should be the same for Z and γ^*, but they have distinct Z p_T dependencies for annihilation or Compton scattering
- The $A_{0,2}$ trends as a function of Z p_T reveals the two Z production processes contributions, e.g. in Z +1 Jet PYTHIA simulation a significant Compton scattering contribution is expected (~30%)

- **Lam-Tung** relation predicts **$A_0=A_2$ at LO** and nearly the same at all orders
- Lam-Tung relation is **valid for spin-1 gluons**, but it is broken for scalar gluons
- First measurement of the Lam-Tung relation at large dilepton mass and high transverse dilepton p_T
- **Fundamental test of the vector nature of gluons**





QCD modeling in Monte Carlo

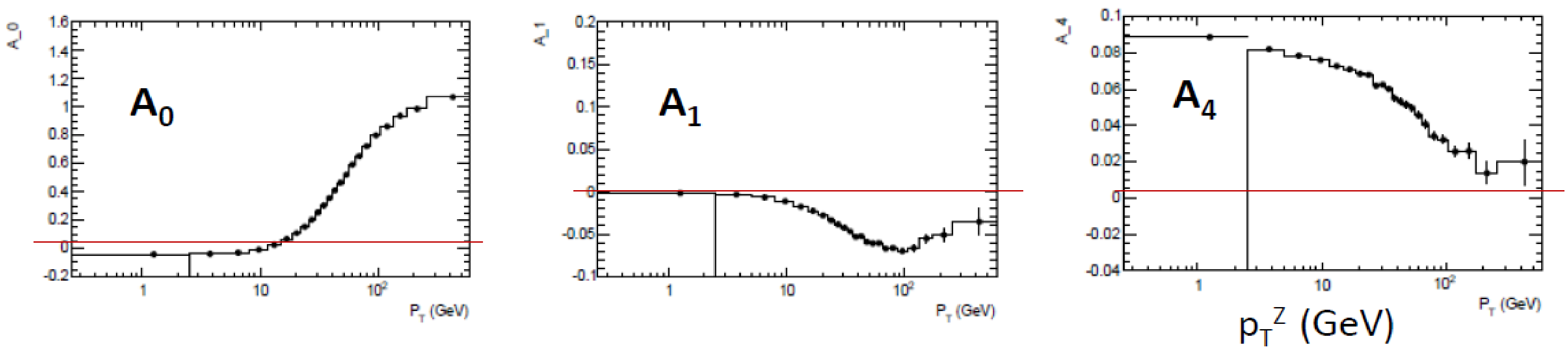
- We can access numerical values of coefficients by calculating repesptive moments of events distributions MC samples. Method Does not require fitting procedure allows to study impact from QED/QCD shower, different PDFs etc.
- Calculation can be done in p_T^{ll}, y_{ll}, m_{ll} bins or integrated.

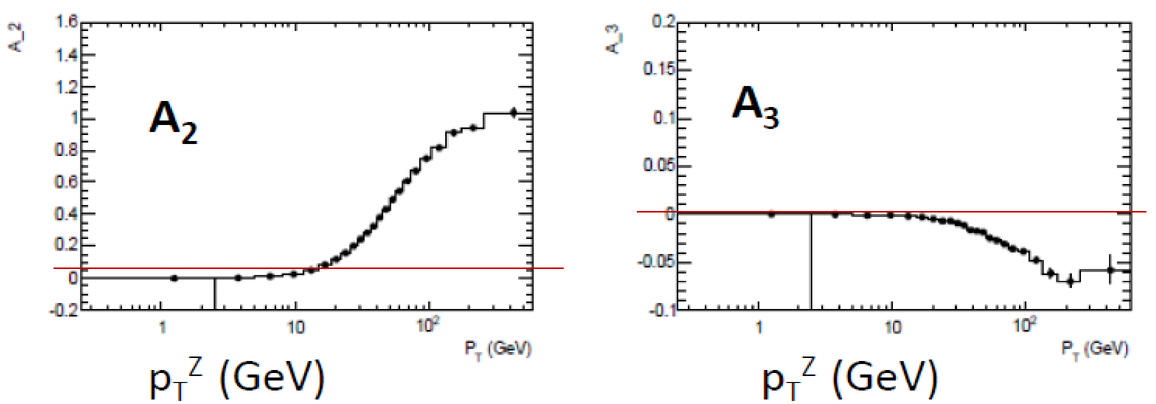
$$
\begin{aligned}
< \frac{1}{2}(1 - 3\cos^2\theta) > &= \frac{3}{20}(A_0 - \frac{2}{3}) \\
< \sin 2\theta \cos\phi > &= \frac{1}{5}A_1 \\
< \sin^2\theta \cos 2\phi > &= \frac{1}{10}A_2 \\
< \sin\theta \cos\phi > &= \frac{1}{4}A_3 \\
< \cos\theta > &= \frac{1}{4}A_4 \\
< \sin\theta \sin 2\phi > &= \frac{1}{5}A_5 \\
< \sin 2\theta \sin\phi > &= \frac{1}{5}A_6 \\
< \sin\theta \sin\phi > &= \frac{1}{4}A_7
\end{aligned}
$$

$$
< m > = \frac{\int d\sigma(p_T, y, \theta, \phi) m \, d\cos\theta \, d\phi}{\int d\sigma(p_T, y, \theta, \phi) \, d\cos\theta \, d\phi}
$$

QCD modeling in Monte Carlo

The interesting ones, others close to zero.

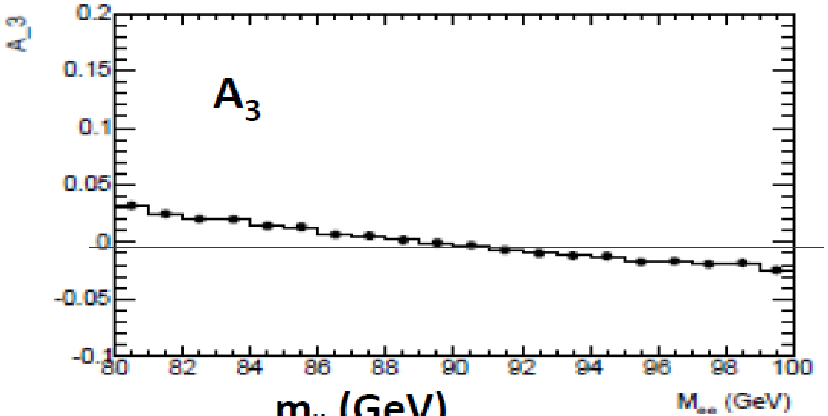


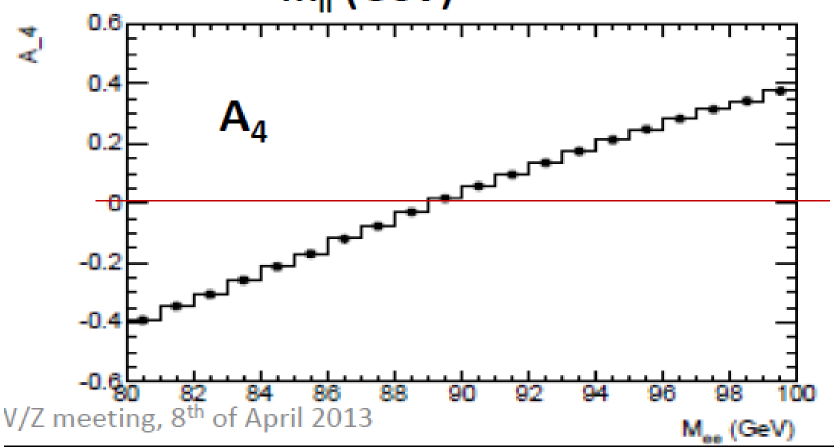


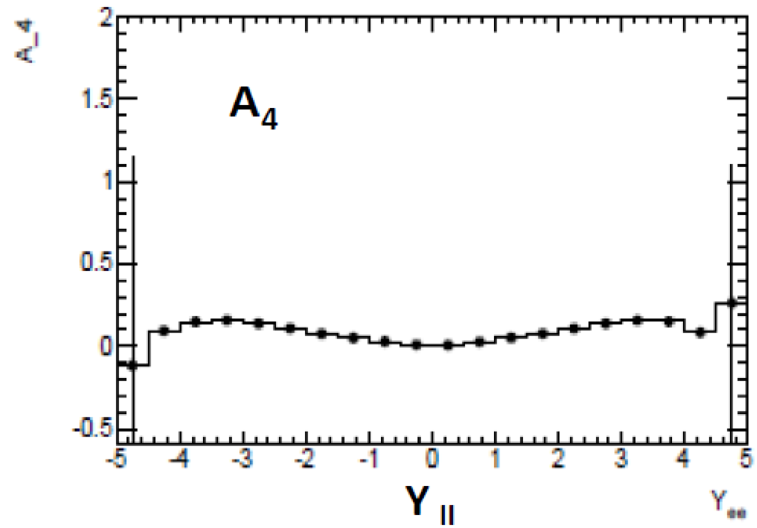
PowHeg LHEF events
mc12 production

QCD modeling in Monte Carlo

- Only A_3 and A_4 show some dependence on m_{ll}
- Only A_4 shows residual dependence on y_{ll}
- For the moment, study how to extract A_i as a function of p_T^{ll}





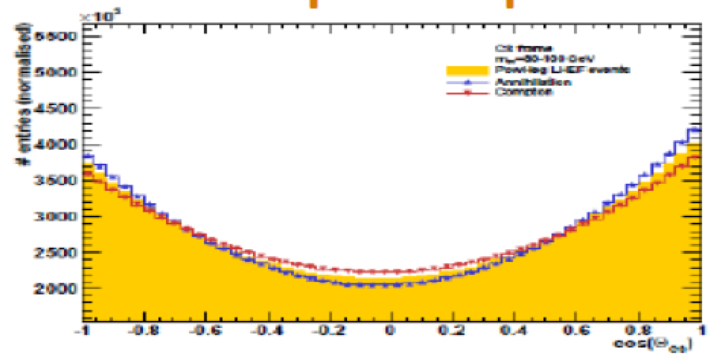


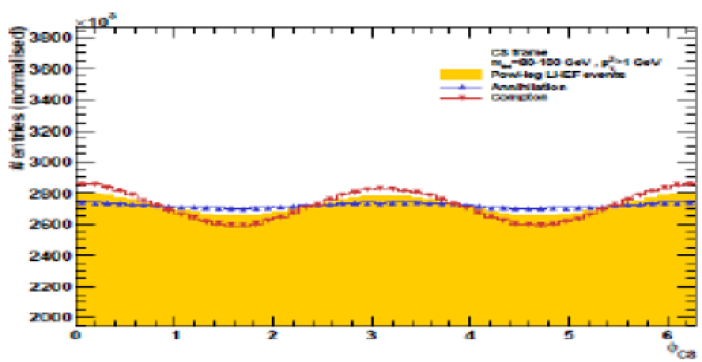
PowHeg LHEF events
MC12 production

Discriminating distributions

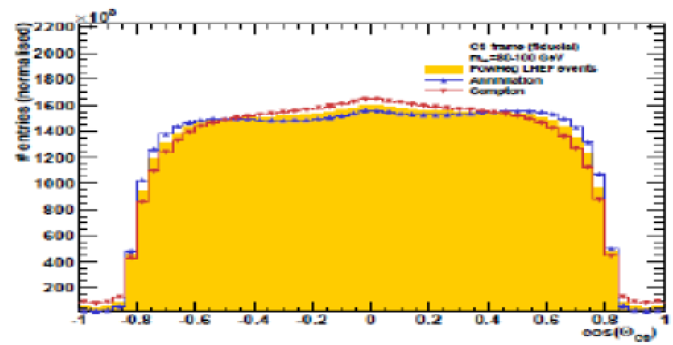
- Distributions are sensitive to the production sub-process, and the shapes change rapidly with p_T^Z
- In fiducial volume, the shapes are dominated by kinematic effects, as shown below for $\cos\theta_{CS}$ and ϕ_{CS} (integrated over p_T^Z).

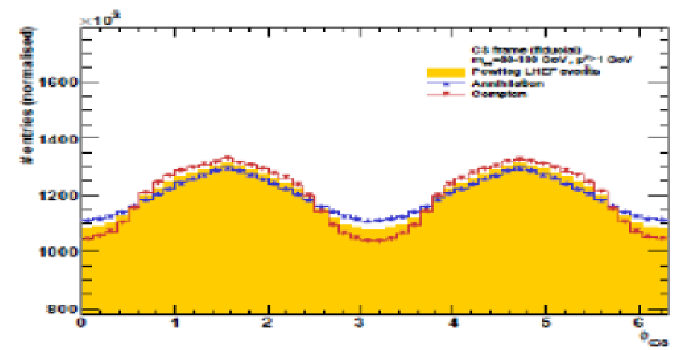
Full phase-space





Fiducial phase-space





Reweighting to isotropic events

- **We can verify extracted coefficients in MC by reweighting to isotropic events (flat in both cos θ and ϕ) with weight**

$$w_{iso} = \frac{1.}{\sum_{i=0}^{i=8} < A_i^{ref} > P_i(\theta, \phi)}$$

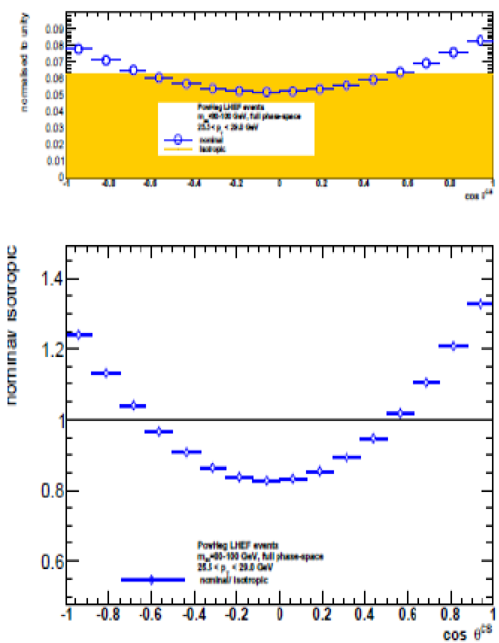
Coefficients extracted from moments

- **Reweighting can be done per individual sub-process with possibly better control on systematics due to PDFs**
- **Isotropic events can be used build required template shape in the fiducial volume (see latter)**

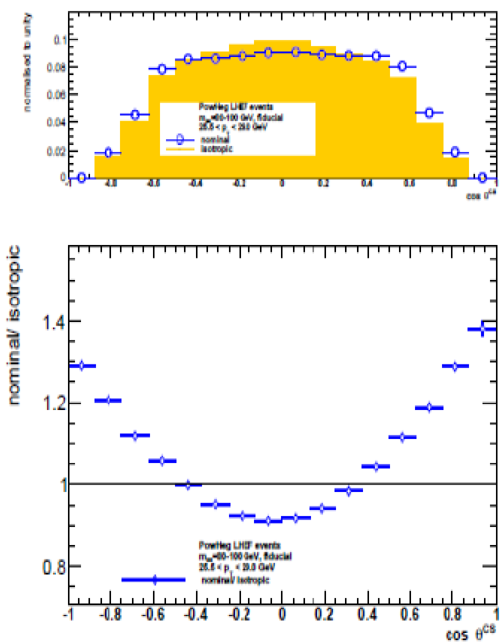
Sensitivity in the fiducial region

- Shown below are $\cos\theta_{CS}$ distributions of isotropic (yellow) and nominal (blue) events in the full phase-space (left) and fiducial region (middle) for one bin in p_T^Z.
- The ratios nominal/isotropic (bottom plots) quantify the sensitivity to the angular coefficients themselves.
- The double ratio (right) shows the potential biases introduced in this p_T^Z bin if one would extract coefficients in a too simplistic way.

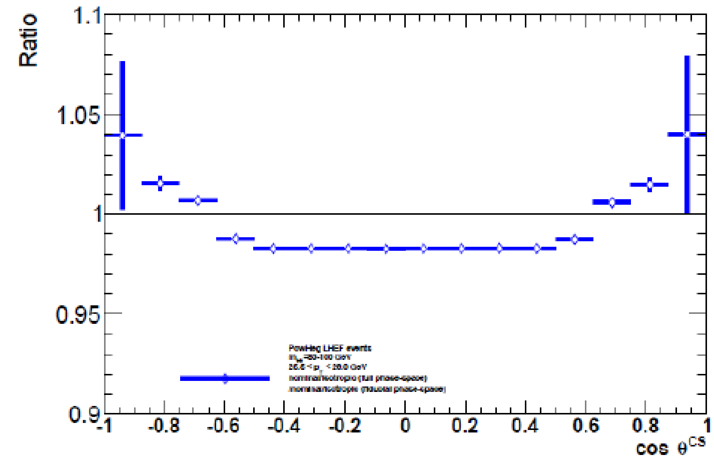
Full phase-space



Fiducial region



Ratio of ratios

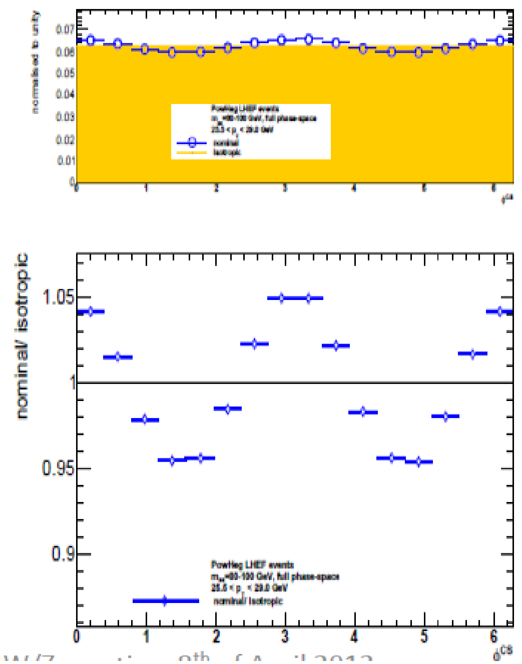


p_T^Z = 26-29 GeV

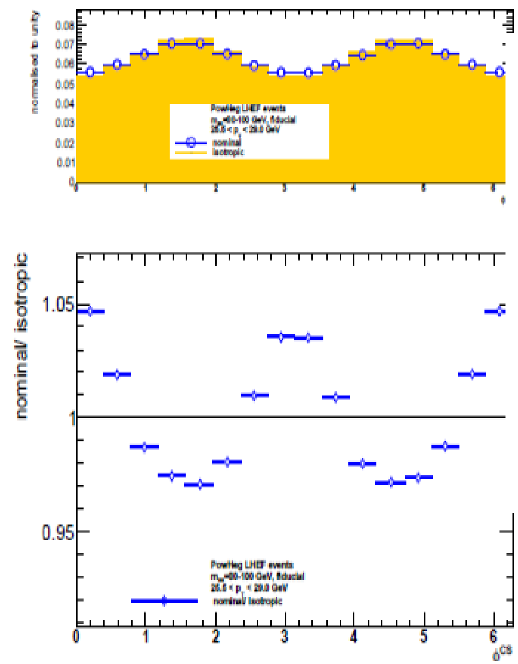
Sensitivity in the fiducial region

- Shown below are ϕ_{CS} distributions of isotropic (yellow) and nominal (blue) events in the full phase-space (left) and fiducial region (middle) for one bin in p_T^Z.
- The ratios nominal/isotropic (bottom plots) quantify the sensitivity to the angular coefficients themselves.
- The double ratio (right) shows the potential biases introduced in this p_T^Z bin if one would extract coefficients in a too simplistic way.

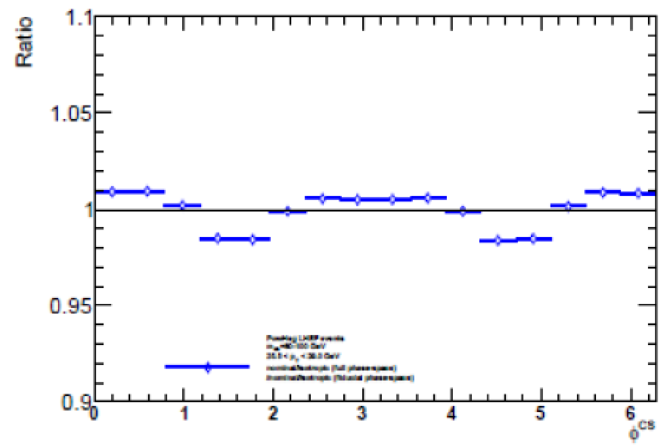
Full phase-space



Fiducial phase-space



Ratio of ratios



p_T^Z = 26-29 GeV