Physics at the LHC, LIP, June 15th, 2015

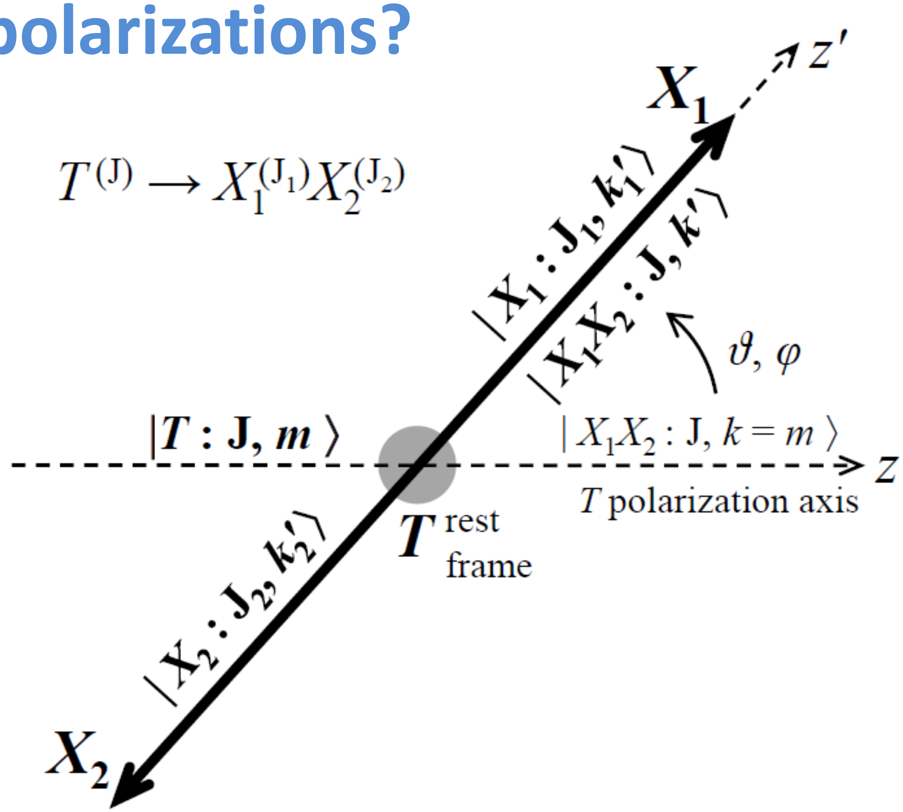
Particle polarizations in LHC physics

Pietro Faccioli

- Motivations
- Basic principles: angular momentum conservation, helicity conservation, parity properties
- Example: dilepton decay distributions of quarkonium and vector bosons
- Reference frames for polarization measurements
- Frame-independent polarization
- Understanding the production mechanisms of vector particles:
  The Lam-Tung relation and its generalizations
- Polarization as a discriminant of physics signals

Why do we study particle polarizations?

Measure **polarization** of a particle =
measure the **angular momentum state** in which the particle is produced,
by studying the **angular distribution** of its **decay**



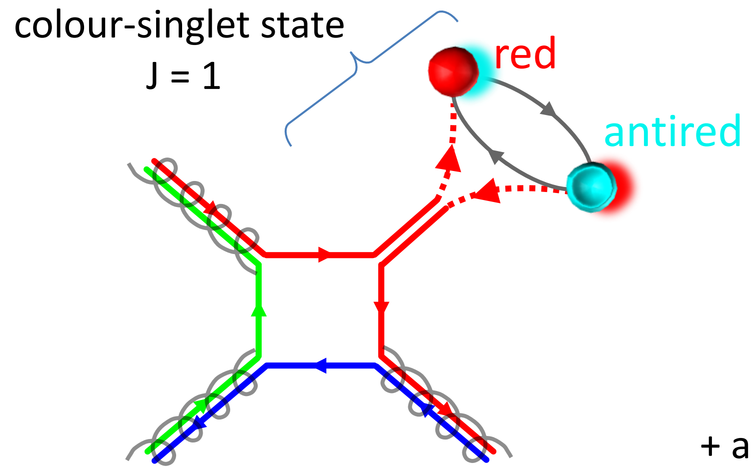
Very **detailed** piece of information! Allows us to

- test of perturbative QCD [***Z*** and ***W*** decay distributions]
- constrain universal quantities [**sinθ_W** and/or **proton PDFs** from *Z*/*W*/ γ^* decays]
- accelerate discovery of new particles or characterize them [**Higgs, *Z'*, anomalous *Z*+γ, graviton**, ...]
- understand the formation of hadrons (non-perturbative QCD)

Example: how are hadron properties generated?
A look at quarkonium (J/ψ and ϒ) formation

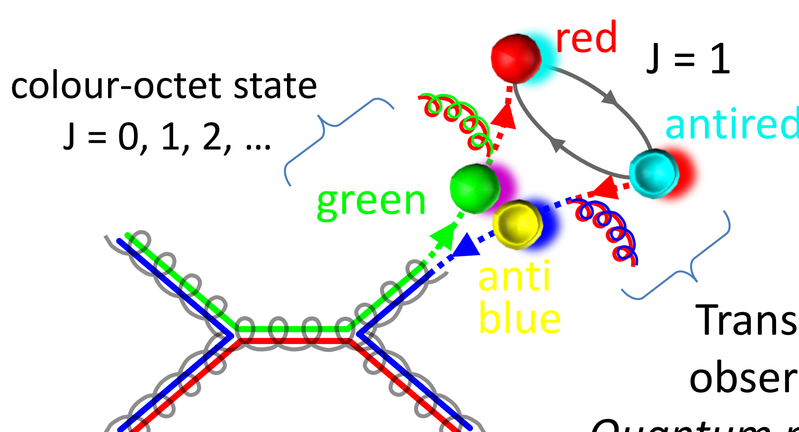
Presently we do not yet understand how/when the observed ***Q-Qbar* bound states** (produced at the LHC in gluon-gluon fusion) acquire their quantum numbers.
Which of the following production processes are more important?

- **Colour-singlet processes**: quarkonia produced directly as observable ***colour-neutral*** *Q*-*Q*bar pairs



+ analogous colour combinations

- **Colour-octet processes**: quarkonia are produced through ***coloured*** *Q*-*Q*bar pairs *of any possible quantum numbers*



Transition to the observable state.
Quantum numbers change!
J can change! → ***polarization***!

perturbative
⊗ ?
non-perturbative

Polarization of vector particles

J* = 1** → three J_z eigenstates **| 1, +1 ⟩, | 1, 0 ⟩, | 1, -1 ⟩** wrt a certain ***z

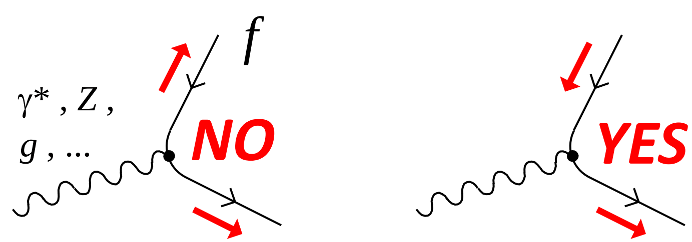
Measure polarization = measure (average) angular momentum composition

Method: study the **angular distribution of the particle decay** in its rest frame

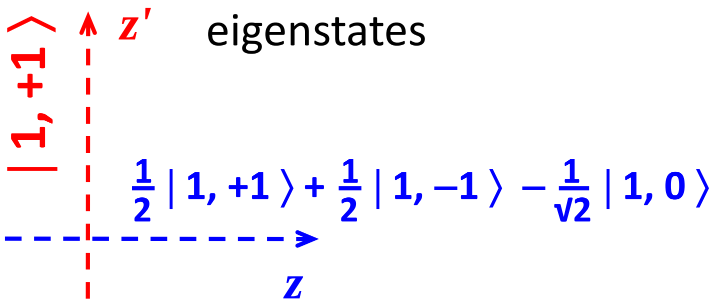
The decay **into a fermion-antifermion pair** is an especially clean case to be studied

The shape of the observable angular distribution is determined by a few basic principles:

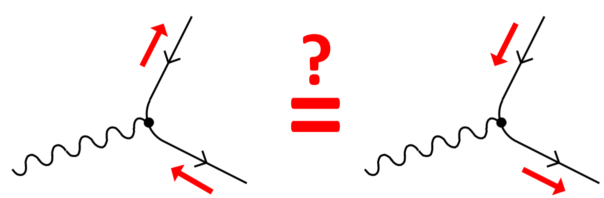
1) "helicity conservation"



2) rotational covariance of angular momentum eigenstates

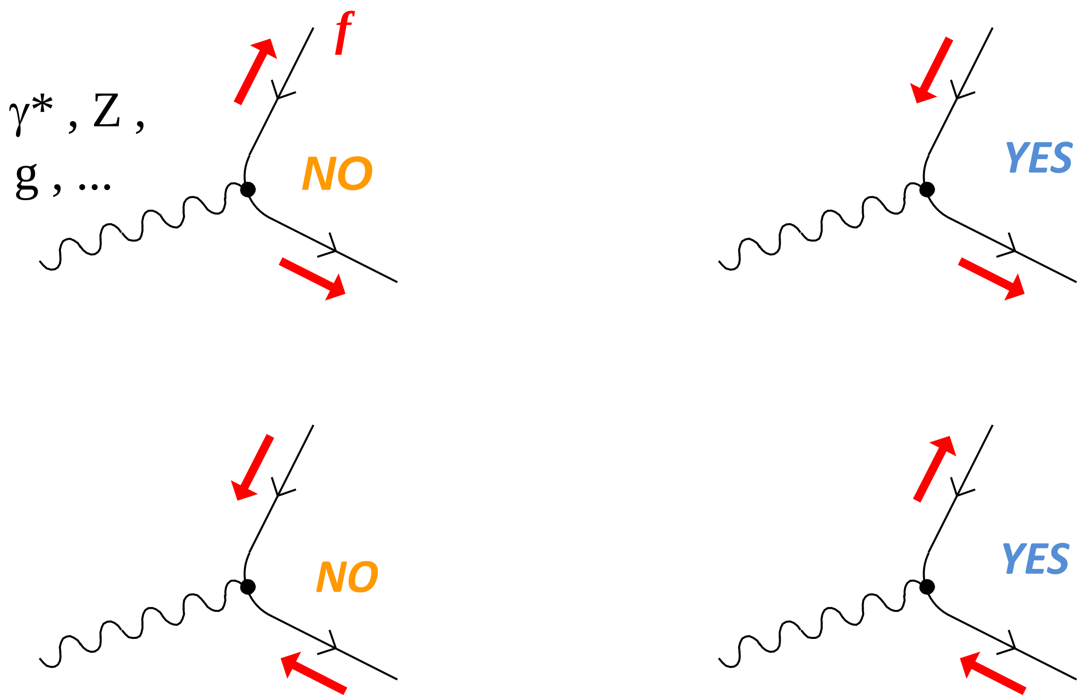


3) parity properties

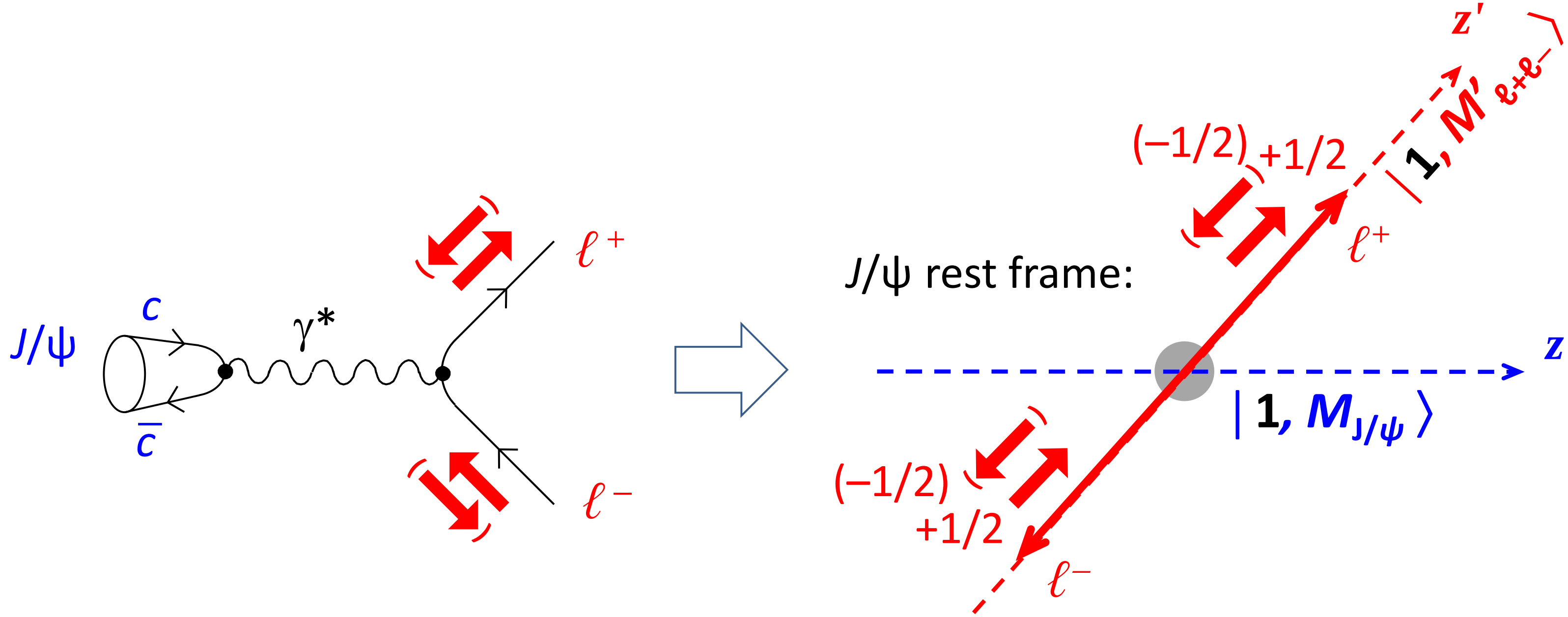


1: helicity conservation

EW and strong forces preserve the *chirality* (L/R) of fermions.
In the relativistic (massless) limit, *chirality* = ***helicity*** **= spin-momentum alignment**
→ the **fermion spin never flips** in the coupling to gauge bosons:



example: dilepton decay of *J*/ψ



J*/ψ** angular momentum component along the polarization axis ***z:

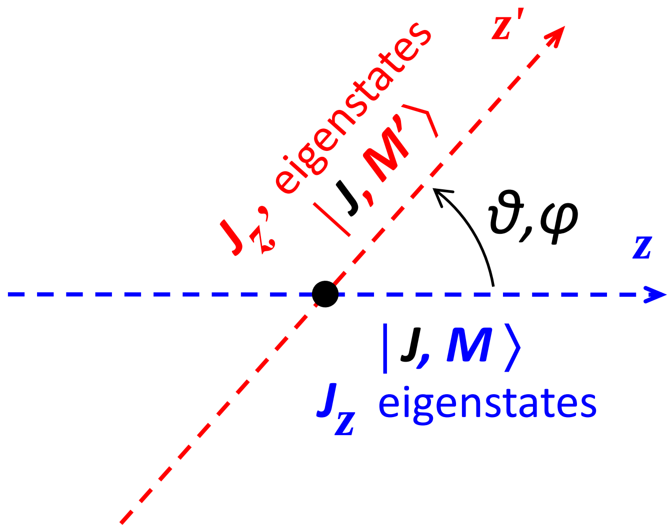
$M_{J/\psi}$ = -1, 0, +1 (determined by *production mechanism*)

The **two leptons** can only have total angular momentum component

$M'_{\ell^+\ell^-}$ = +1 or -1 along their common direction ***z'***

0 is forbidden

2: rotation of angular momentum eigenstates



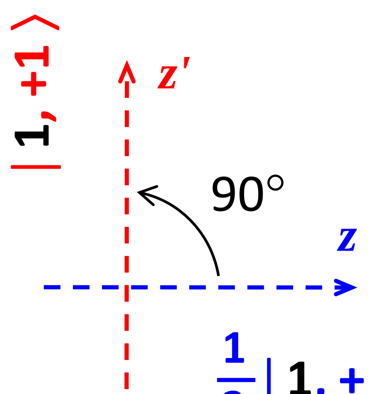
change of quantization frame:

$R(\vartheta,\varphi)$: $z \to z'$
$y \to y'$
$x \to x'$

$$|J, M'\rangle = \sum_{M=-J}^{+J} D^{J}_{MM'}(\vartheta,\varphi)\ |J, M\rangle$$

↑ Wigner D-matrices

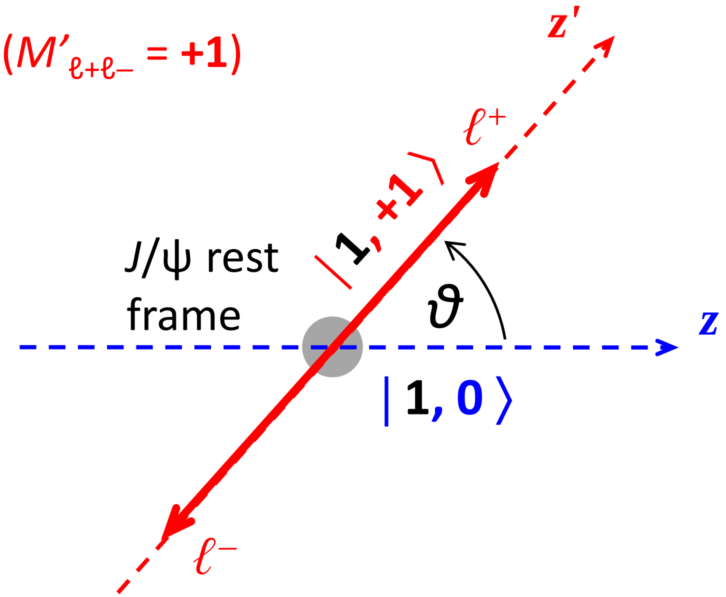
Example:



$$\frac{1}{2}|1,+1\rangle + \frac{1}{2}|1,-1\rangle - \frac{1}{\sqrt{2}}|1,0\rangle$$

example: $M = 0$

$J/\psi\ (M_{J/\psi} = 0) \rightarrow \ell^+\ell^-(M'_{\ell^+\ell^-} = +1)$



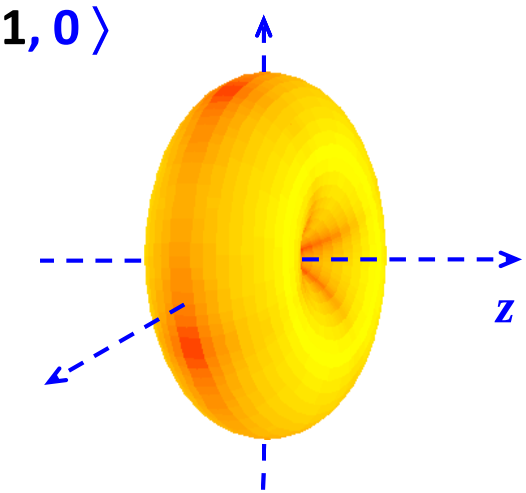
$$|\,1, +1\,\rangle = D^1_{-1,+1}(\vartheta,\varphi)\ |\,1, -1\,\rangle + D^1_{0,+1}(\vartheta,\varphi)\ |\,1, 0\,\rangle + D^1_{+1,+1}(\vartheta,\varphi)\ |\,1, +1\,\rangle$$

→ the $J_{z'}$ eigenstate $|\,1, +1\,\rangle$ "contains" the J_z eigenstate $|\,1, 0\,\rangle$ with component amplitude $D^1_{0,+1}(\vartheta,\varphi)$

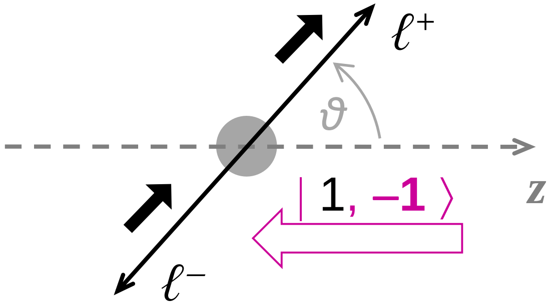
→ the decay distribution is

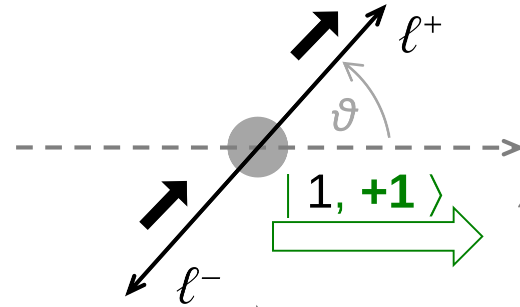
$$|\langle\,1, +1\,|\,\mathcal{O}\,|\,1, 0\,\rangle|^2 \propto |D^{1*}_{0,+1}(\vartheta,\varphi)|^2 = \frac{1}{2}\,(\,1 - \cos^2\vartheta\,)$$

$\ell^+\ell^- \leftarrow J/\psi$

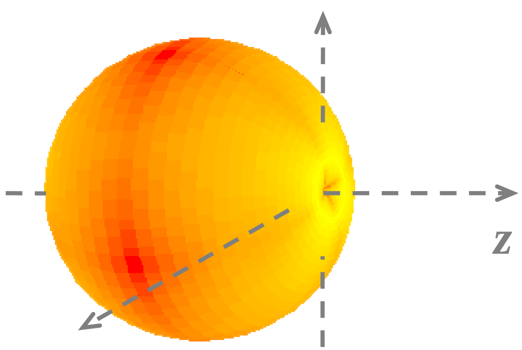


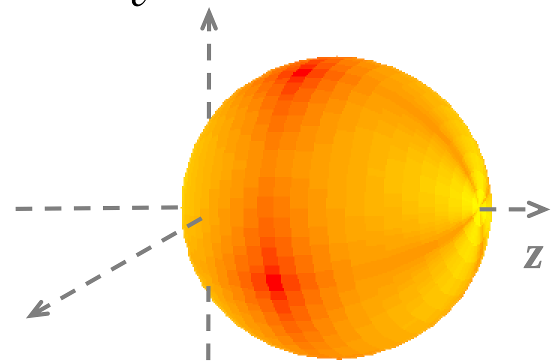
3: parity





| 1, –1 ⟩ and | 1, +1 ⟩
distributions
are mirror reflections
of one another

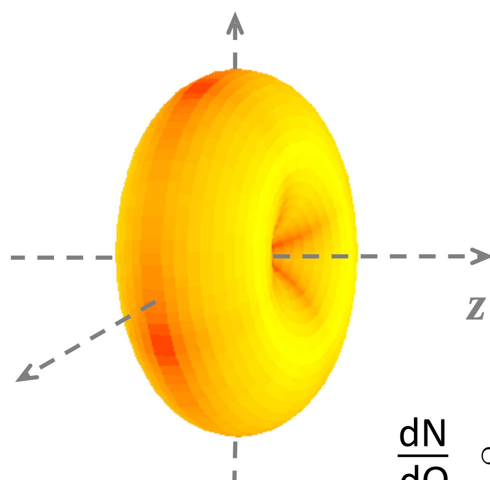




$$\frac{dN}{d\Omega} \propto |D^{1*}_{-1,+1}(\vartheta,\varphi)|^2 \propto 1 + \cos^2\vartheta - \mathbf{2\cos\vartheta}$$

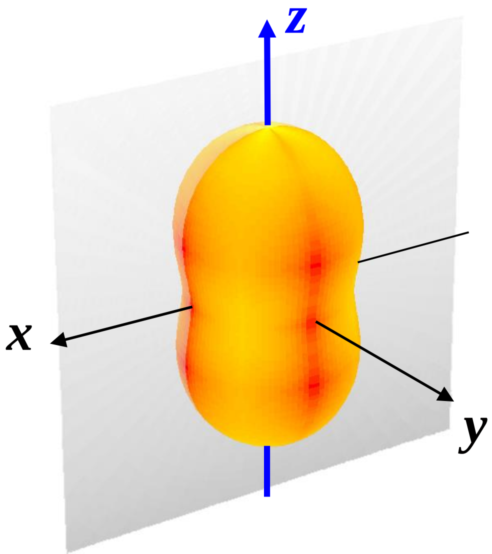
$$\frac{dN}{d\Omega} \propto |D^{1*}_{+1,+1}(\vartheta,\varphi)|^2 \propto 1 + \cos^2\vartheta + \mathbf{2\cos\vartheta}$$

Decay distribution of | 1, 0 ⟩ state is always parity-symmetric:



$$\frac{dN}{d\Omega} \propto |D^{1*}_{0,+1}(\vartheta,\varphi)|^2 \propto 1 - \cos^2\vartheta$$

"Transverse" and "longitudinal"

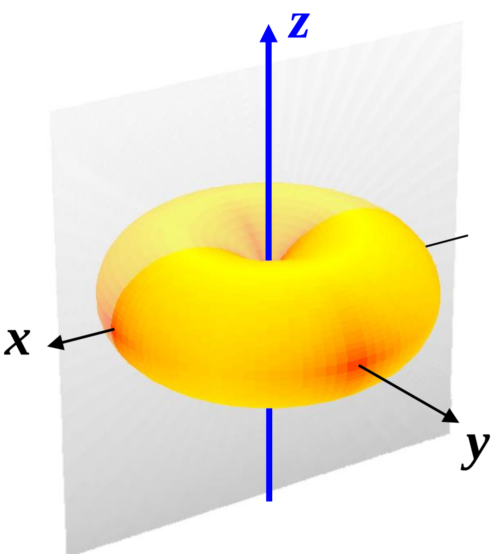


$|\, J/\psi \,\rangle = |\, 1, \mathbf{+1} \,\rangle$ or $|\, 1, \mathbf{-1} \,\rangle$

$$\frac{dN}{d\Omega} \propto 1 + \cos^2\vartheta$$

(parity-conserving case)

"Transverse" polarization, like for *real photons*. The word refers to the alignment of the *field* vector, not to the *spin* alignment!



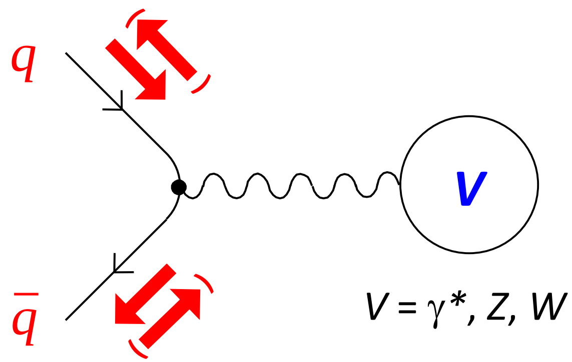
$|\, J/\psi \,\rangle = |\, 1, \mathbf{0} \,\rangle$

$$\frac{dN}{d\Omega} \propto 1 - \cos^2\vartheta$$

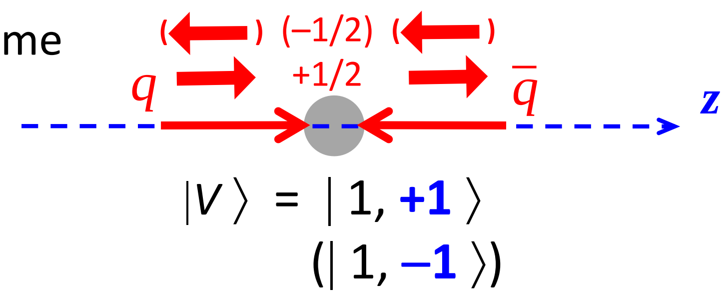
"Longitudinal" polarization

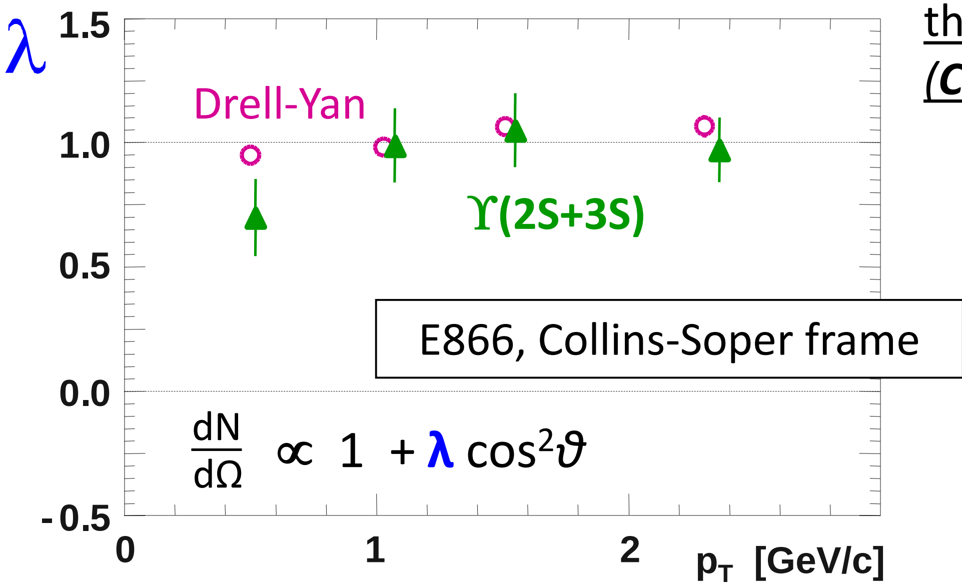
Why "photon-like" polarizations are common

We can apply **helicity conservation at the *production* vertex** to predict that all *vector* states produced in ***fermion-antifermion annihilations* (q-$\bar{q}$ or e^+e^-)** at Born level have *transverse* polarization



q-$\bar{q}$ rest frame
= V rest frame





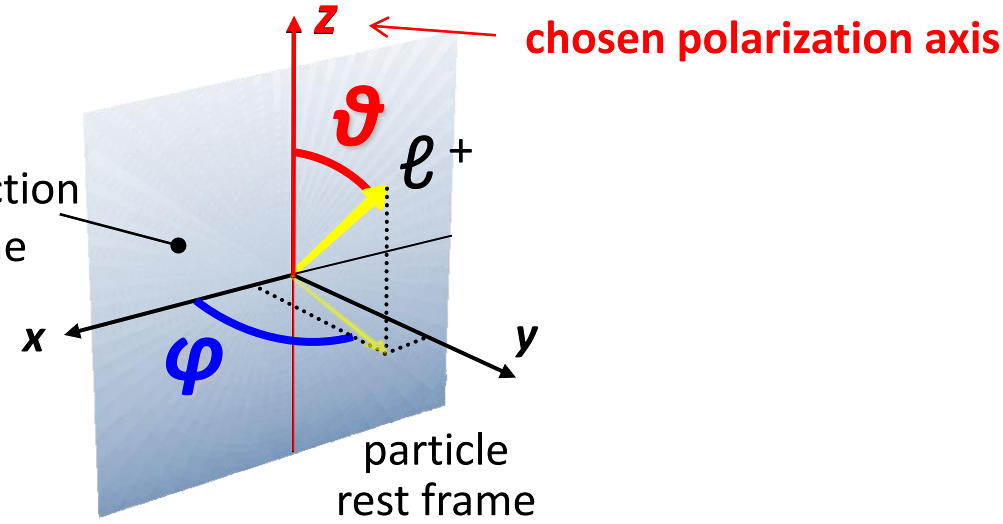
$$\frac{dN}{d\Omega} \propto 1 + \lambda \cos^2\vartheta$$

The "natural" polarization axis in this case is the *relative direction of the colliding fermions* ***(Collins-Soper axis)***

Drell-Yan is a paradigmatic case

But not the only one

The most general distribution



average polar anisotropy — average azimuthal anisotropy — correlation polar - azimuthal

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

$$+ 2A_\theta \cos\theta + 2A_\varphi \sin\theta \cos\varphi$$

parity violating

Polarization frames

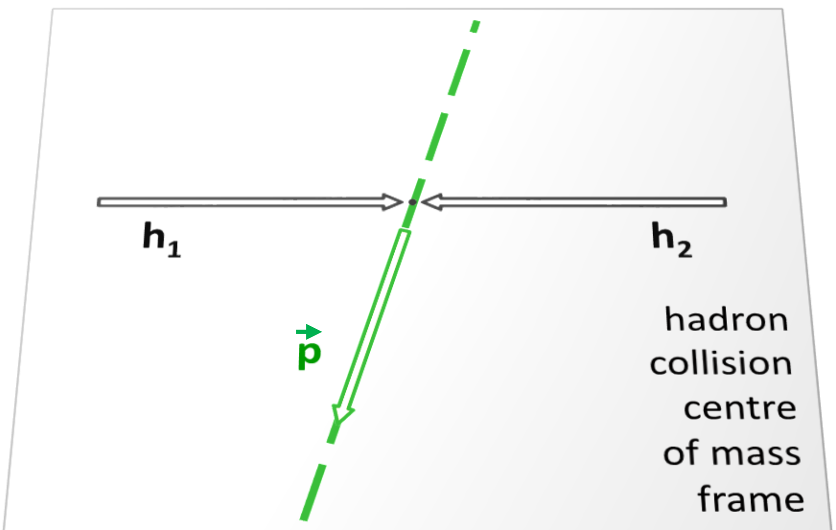
Helicity axis (HX): quarkonium momentum direction

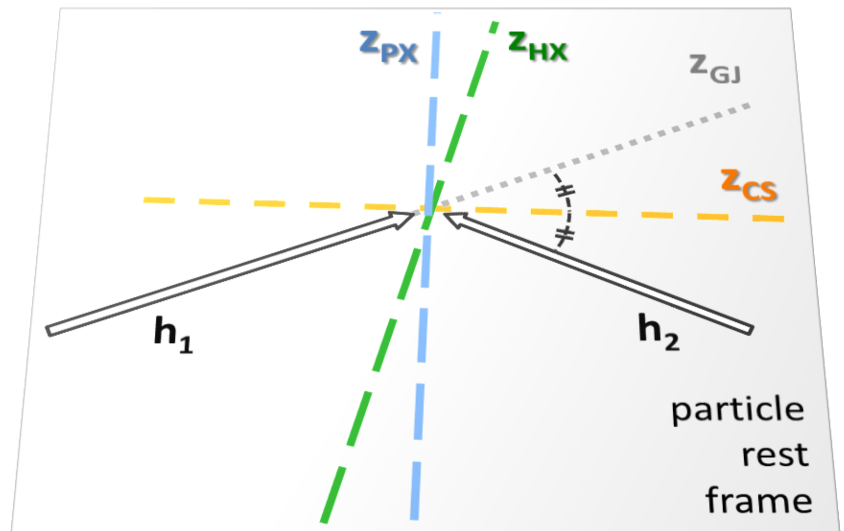
Gottfried-Jackson axis (GJ): direction of one or the other beam

Collins-Soper axis (CS): average of the two beam directions

Perpendicular helicity axis (PX): perpendicular to CS

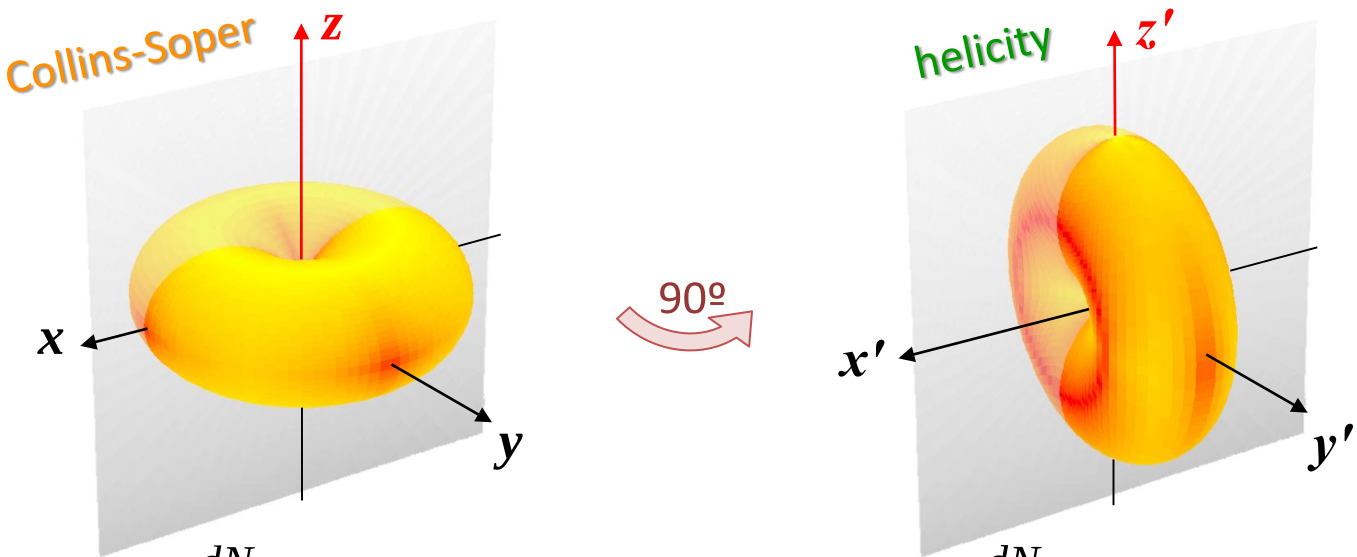
production plane





The observed polarization depends on the frame

For $|p_L| << p_T$, the CS and HX frames differ by a rotation of 90º



$$\frac{dN}{d\Omega} \propto 1 - \cos^2\theta$$

longitudinal

$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta - \sin^2\theta \cos 2\varphi$$

"transverse"

$$|\psi\rangle = |0\rangle$$

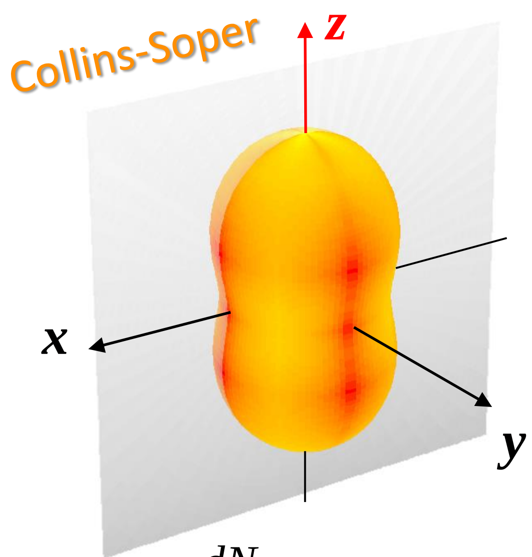
(pure state)

$$|\psi\rangle = \frac{1}{\sqrt{2}}|+1\rangle - \frac{1}{\sqrt{2}}|-1\rangle$$

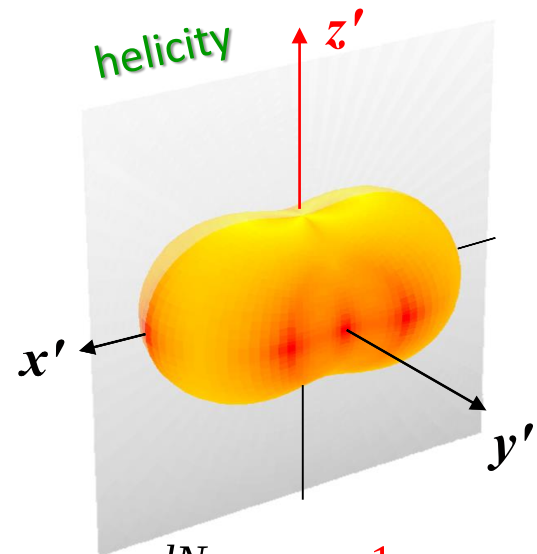
(mixed state)

The observed polarization depends on the frame

For $|p_L| << p_T$, the CS and HX frames differ by a rotation of 90º



90º



$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta$$

transverse

$$\frac{dN}{d\Omega} \propto 1 - \frac{1}{3}\cos^2\theta + \frac{1}{3}\sin^2\theta\cos 2\varphi$$

moderately “longitudinal”

$$|\psi\rangle = |+1\rangle \; or \; |-1\rangle$$

(pure state)

$$|\psi\rangle = \frac{1}{2}|+1\rangle + \frac{1}{2}|-1\rangle \mp \frac{1}{\sqrt{2}}|0\rangle$$

(mixed state)

All reference frames are equal…
but some are more equal than others

What do different detectors measure with *arbitrary* frame choices?

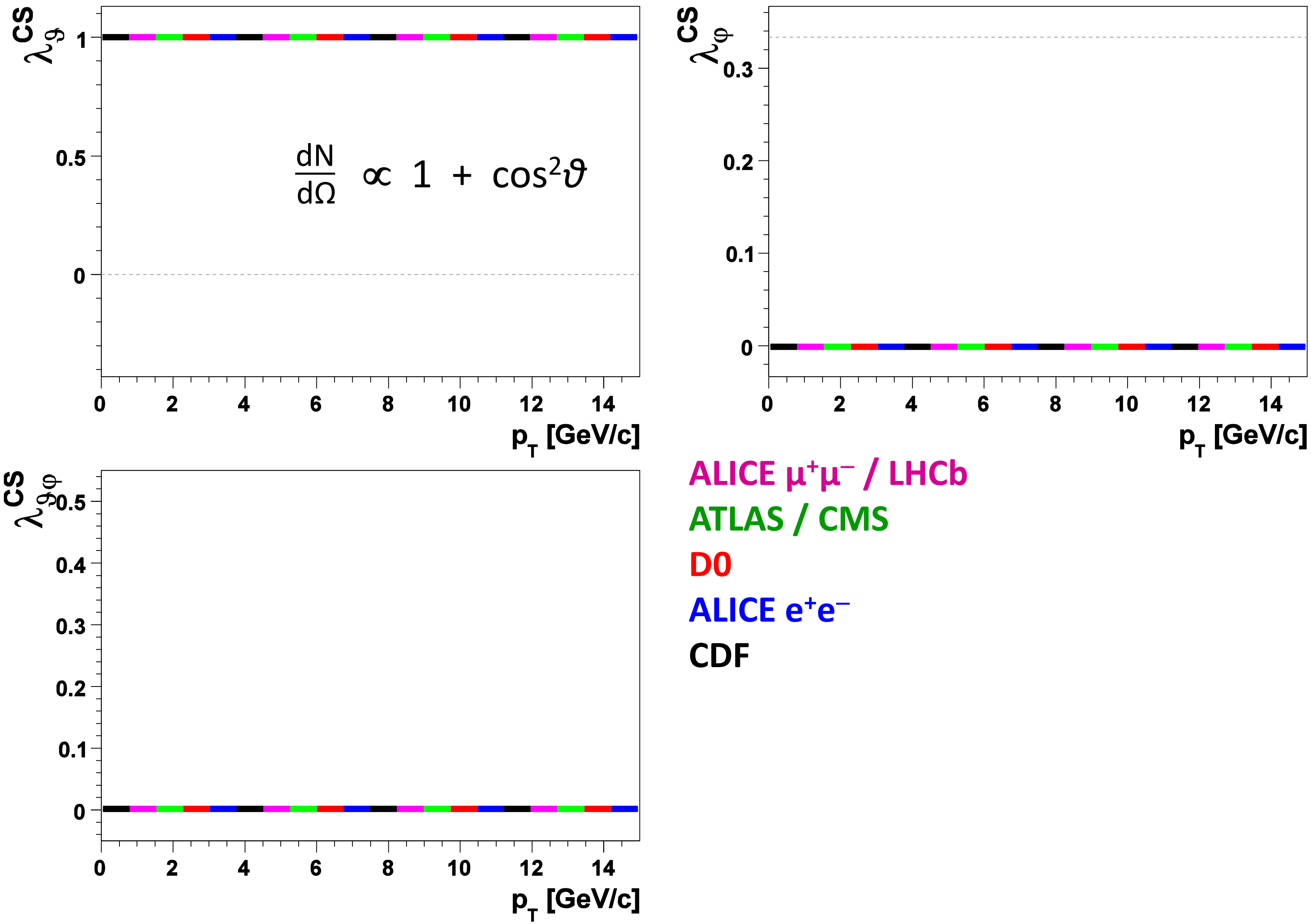
Gedankenscenario:

- **dileptons are fully transversely polarized in the CS frame**
- the decay distribution is measured at the Υ(1S) mass
  by 6 detectors with different **dilepton acceptances**:

CDF	$\|y\| < 0.6$
D0	$\|y\| < 1.8$
ATLAS & CMS	$\|y\| < 2.5$
ALICE e^+e^-	$\|y\| < 0.9$
ALICE $\mu^+\mu^-$	$2.5 < y < 4$
LHCb	$2 < y < 4.5$

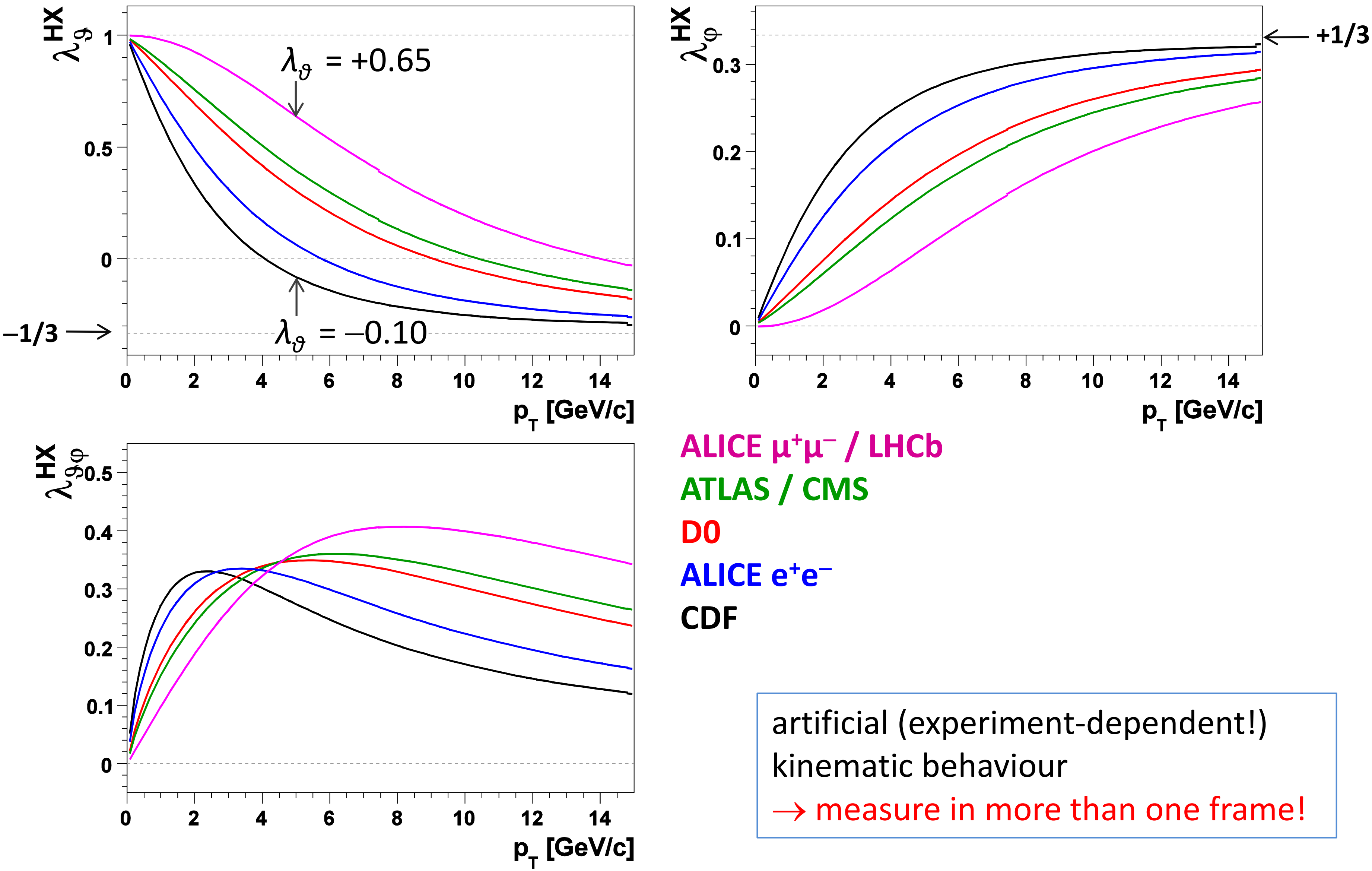
The lucky frame choice

(CS in this case)



Less lucky choice

(HX in this case)



ALICE $\mu^+\mu^-$ / LHCb

ATLAS / CMS

D0

ALICE e^+e^-

CDF

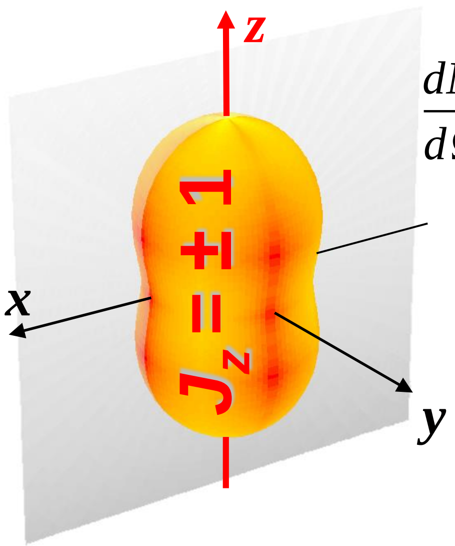
artificial (experiment-dependent!) kinematic behaviour

→ measure in more than one frame!

The azimuthal anisotropy is not a detail

Quarkonium measurements used to ignore the azimuthal component of the distribution. This is a mutilation of the measurement!

Case 1: natural transverse polarization

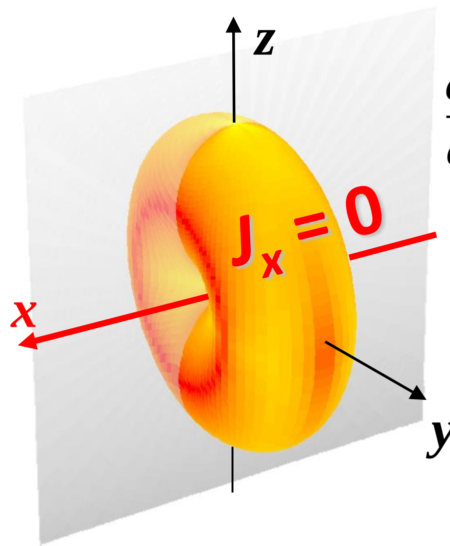


$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta$$

$\lambda_\vartheta = +1$

$\lambda_\varphi = 0$

Case 2: natural longitudinal polarization, observation frame ⊥ to the natural one



$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta - \sin^2\theta \cos 2\varphi$$

$\lambda_\vartheta = +1$

$\lambda_\varphi = -1$

- Two very different (opposite) physical cases, with same λ_ϑ
- distinguishable only by measuring λ_φ (no integration over φ !)

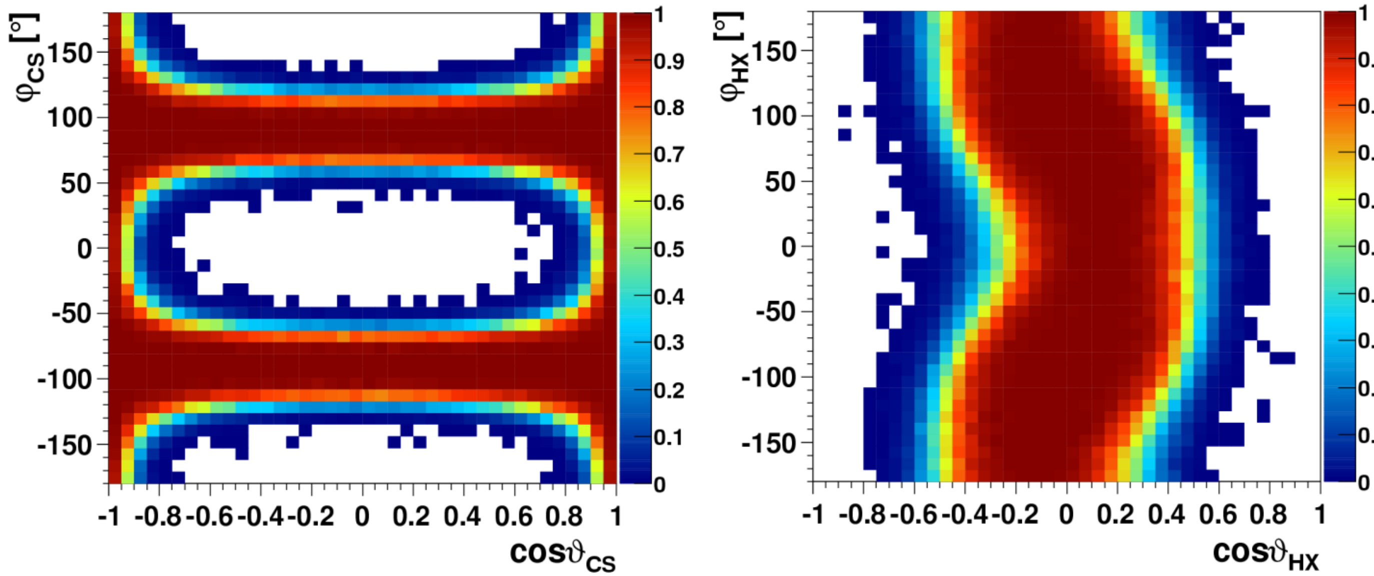
One-dimensional analyses can give *wrong* results

Ignoring the azimuthal dimension is an analysis mistake!

Usually cosϑ and φ “acceptances” are strongly intercorrelated:

CMS-like toy MC for UNPOLARIZED J/ψ with

$p_T(\mu) > 3$ GeV/c,
$9 < p_T < 12$ GeV/c,
$|y| < 1$



The experimental efficiency for the projected cosϑ distribution *depends* on the “real” φ distribution (and vice versa)

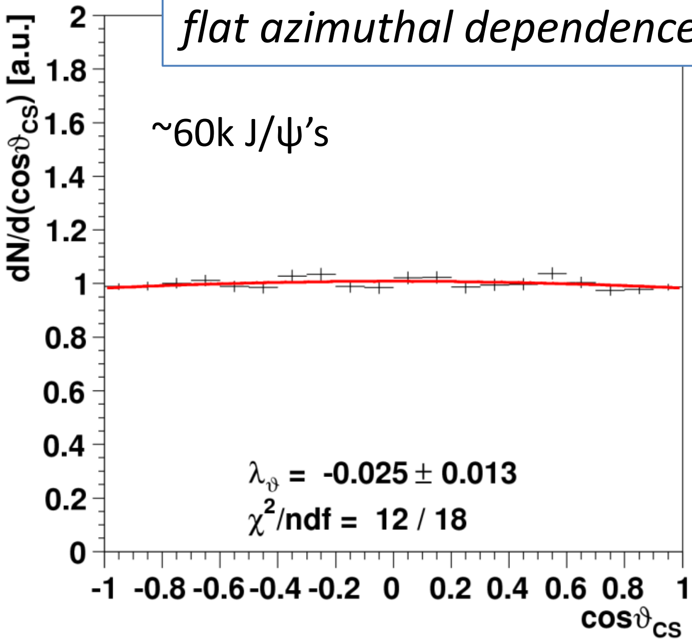
If the φ dimension is integrated out and ignored, the λ_ϑ measurement is strongly dependent on the specific “prior hypothesis” (implicitly) made for the angular distribution (e.g.: flat azimuthal dependence)

One-dimensional analyses can give *wrong* results

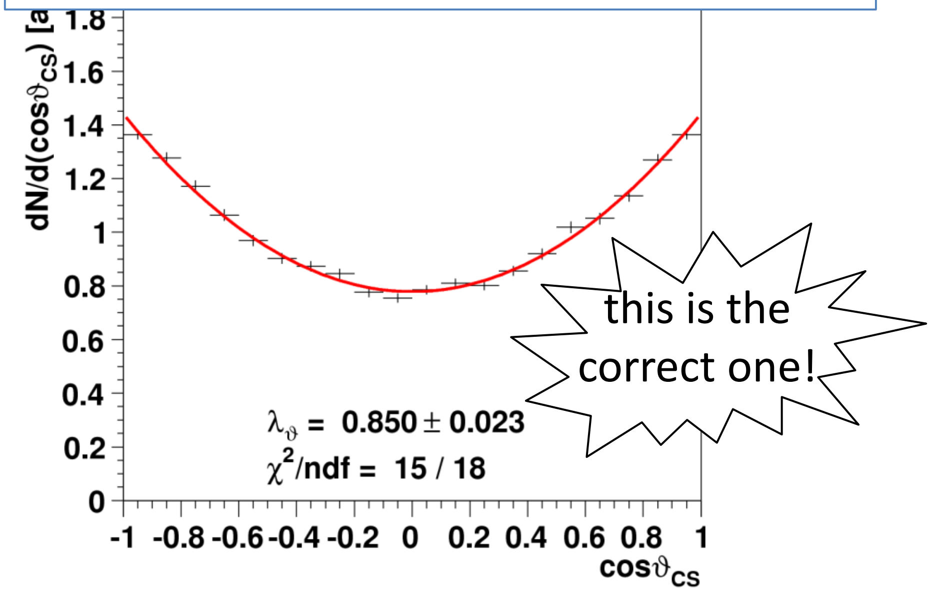
Example scenario:

- *fully longitudinal* polarization in the *HX frame*
- one-dimensional measurement performed in the CS frame, integrating out φ dependence

1D "acceptance" correction with MC generated assuming *flat azimuthal dependence*

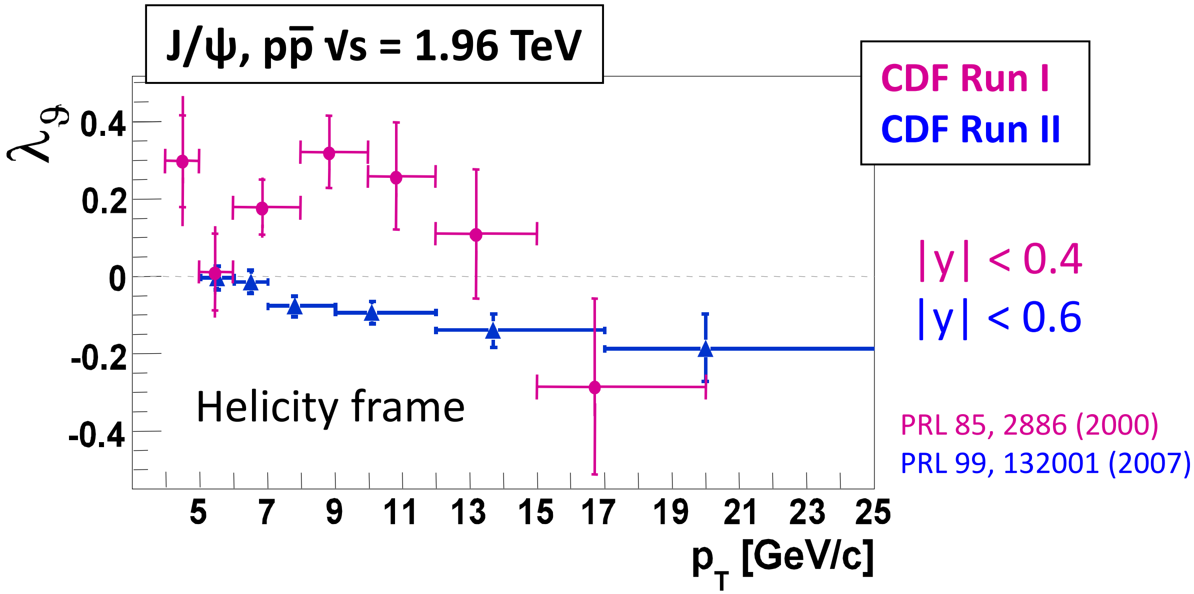


MC *reweighted* to the "true" polarization (a 2D ingredient!) [or event-by-event multi-dimensional efficiency correction]

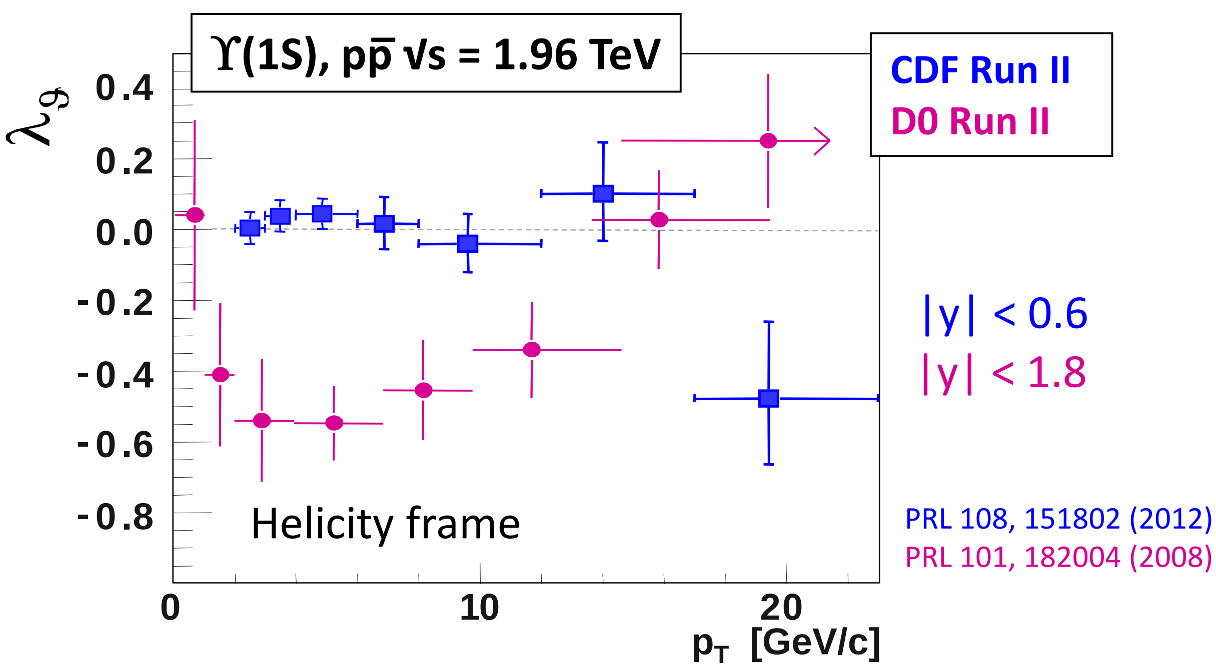


If we can / want to only measure a 1D projected distribution, the efficiency description *must*, nevertheless, be maintained multi-dimensional!
Avoid 1D $\cos\vartheta$ "acceptance" corrections or 1D "template" fits, unless the MC is iteratively re-generated with the *correct* φ distribution!

One-dimensional analyses gave *puzzling* results…



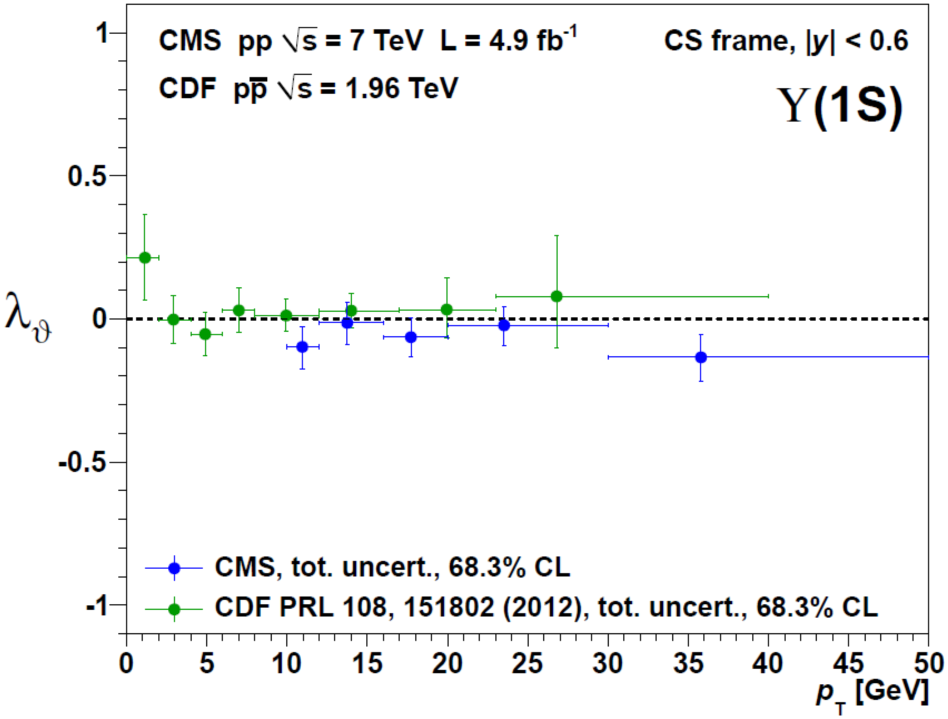
- **CDF II** vs **CDF I**

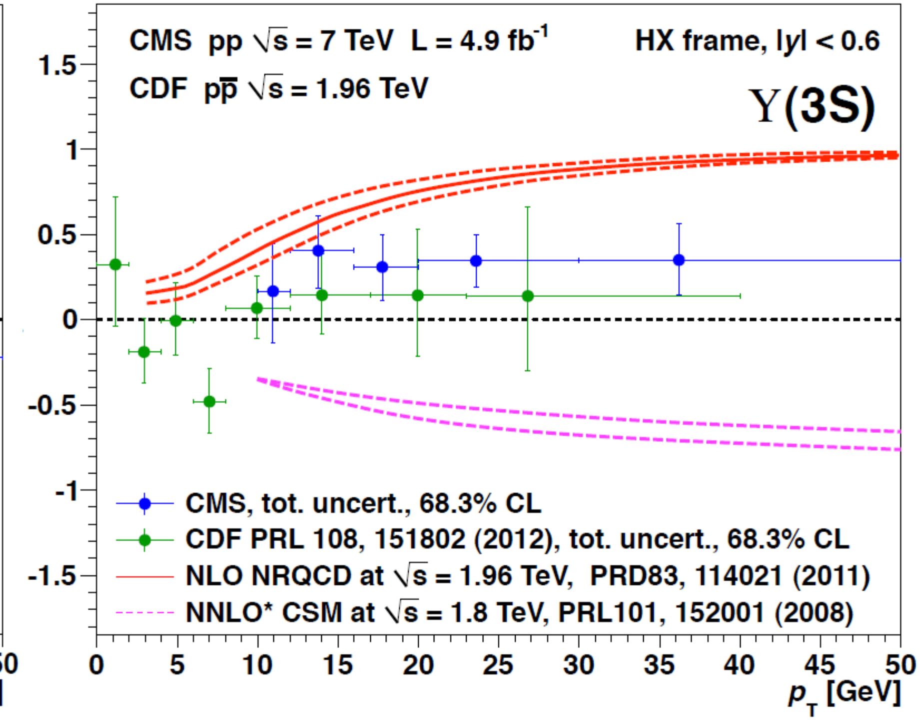


- **CDF** vs **D0**

Meanwhile…

- Improved results from **CDF** and the new measurements from the LHC (**CMS**, LHCb, ALICE) have finally been measuring all parameters in several frames





small polarizations (all parameters / frames) **theory challenged more and more**

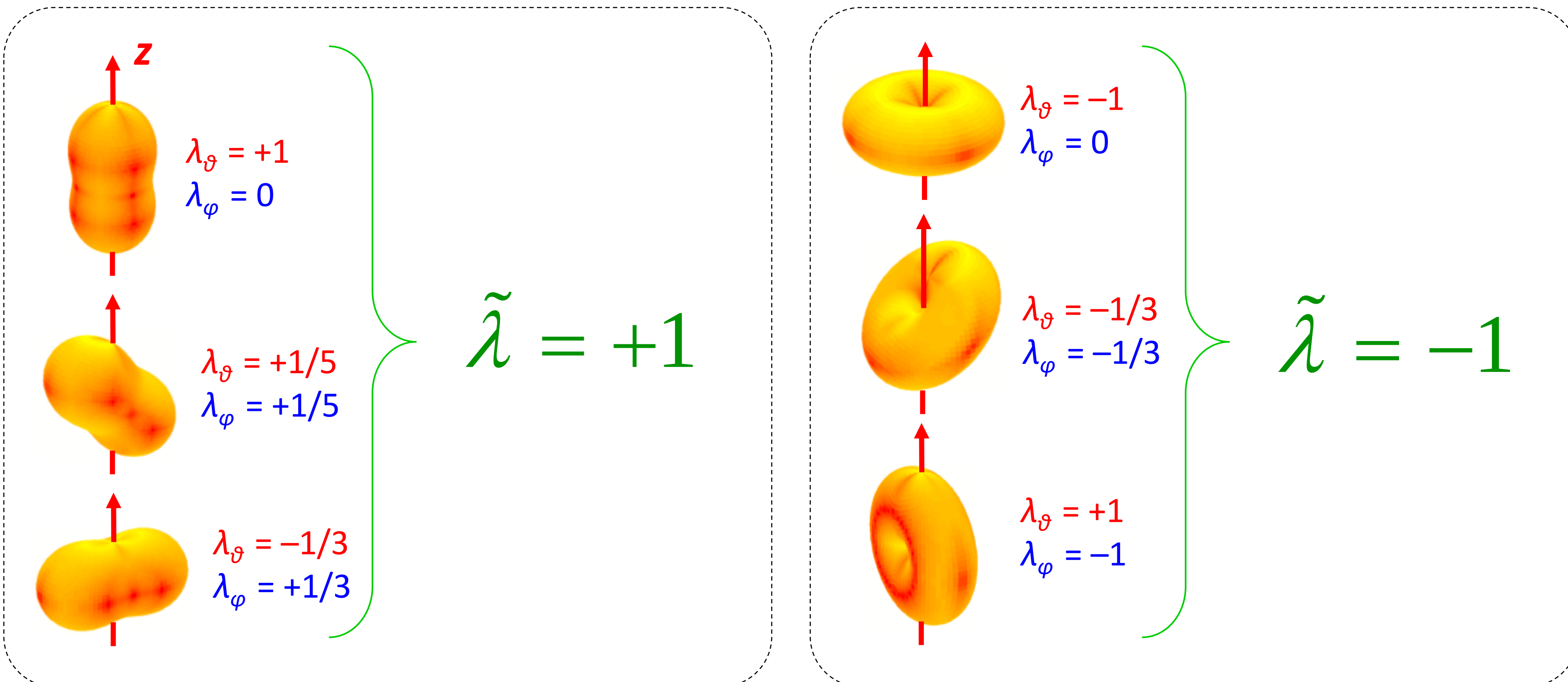
Results reaffirm quarkonium puzzles eliminating limits/ambiguities of previous analyses

A complementary approach: frame-independent polarization

The *shape* of the distribution is (obviously) frame-invariant (= invariant by rotation)

→ it can be characterized by (at least one) frame-independent parameter:

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$



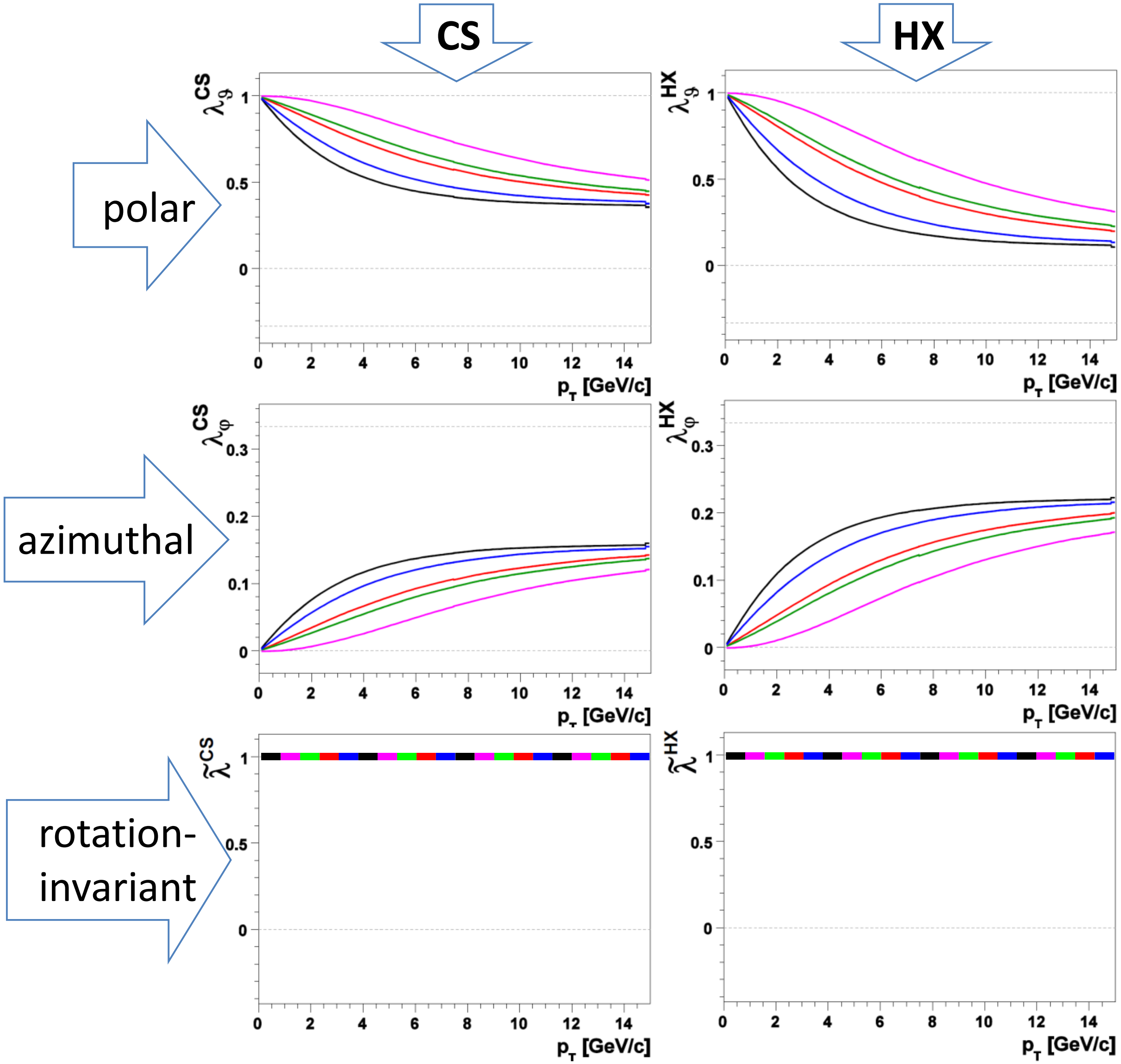
rotations *in the production plane*

Reduces acceptance dependence

Gedankenscenario: vector state produced in this subprocess admixture:

- **60%** processes with natural **transverse** polarization in the **CS** frame
- **40%** processes with natural **transverse** polarization in the **HX** frame

assumed indep. of kinematics, for simplicity



M = 10 GeV/c^2

CDF	**|y| < 0.6**
D0	**|y| < 1.8**
ATLAS/CMS	**|y| < 2.5**
ALICE e^+e^-	**|y| < 0.9**
ALICE $\mu^+\mu^-$	**2.5 < y < 4**
LHCb	**2 < y < 4.5**

- Immune to "extrinsic" kinematic dependencies

→ *less acceptance-dependent*

→ *facilitates comparisons*

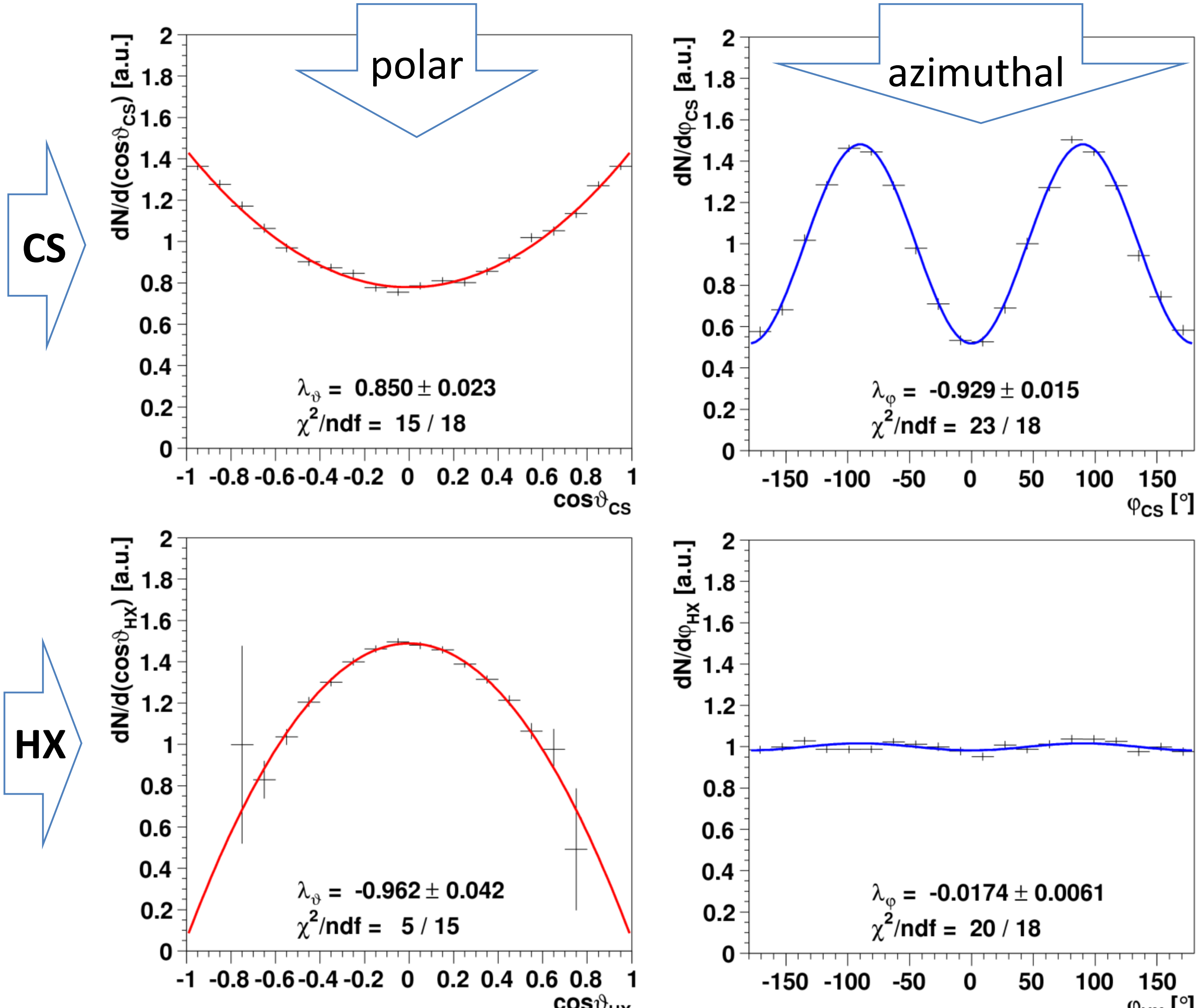
- *useful as closure test*

Can be used to spot analysis mistakes

Same 1D analysis discussed before, with 1D “acceptance” correction.

Using an iteratively reweighted MC (with a carefully chosen starting step!) we can correct the mistake

Looking at the azimutal dimension and, at the same time, at the results in the HX frame we can spot the mistake by calculating $\tilde{\lambda}$:



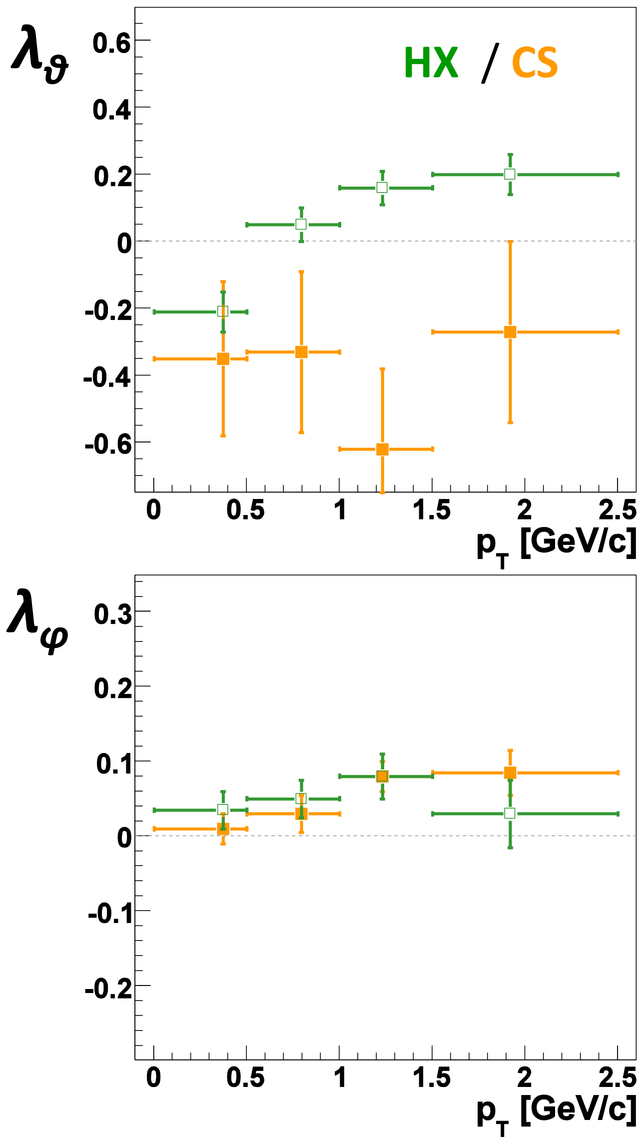
$\tilde{\lambda}_{CS} = -1.00$ / -0.32

correct!

$\tilde{\lambda}_{HX} = -1.00$ / -0.93

A real example

Preliminary J/ψ result, before evaluation of systematic errors



Is this a self-consistent pattern?

→ check quantitatively by calculating the average invariant polarization

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

$\tilde{\lambda}$(HX) – $\tilde{\lambda}$(CS) = **0.49** [± 0.13]

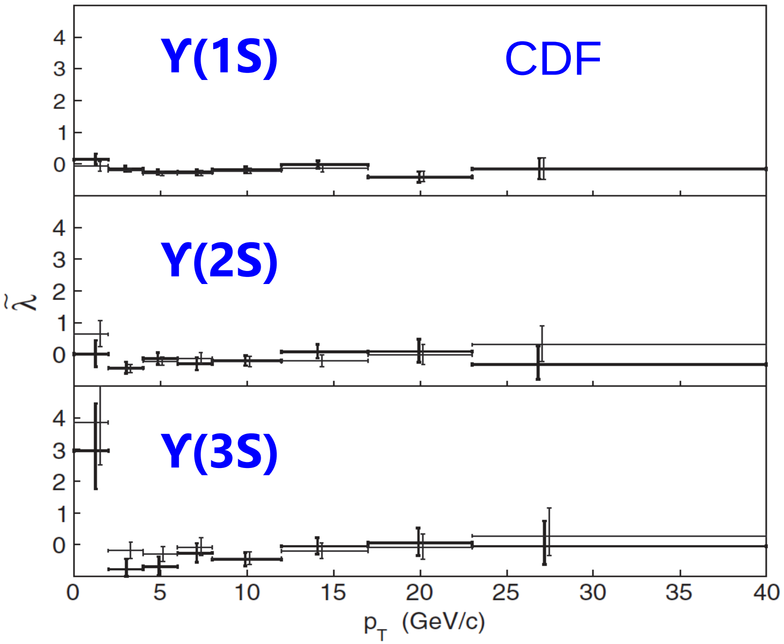
[CS and HX data fully statistically correlated]

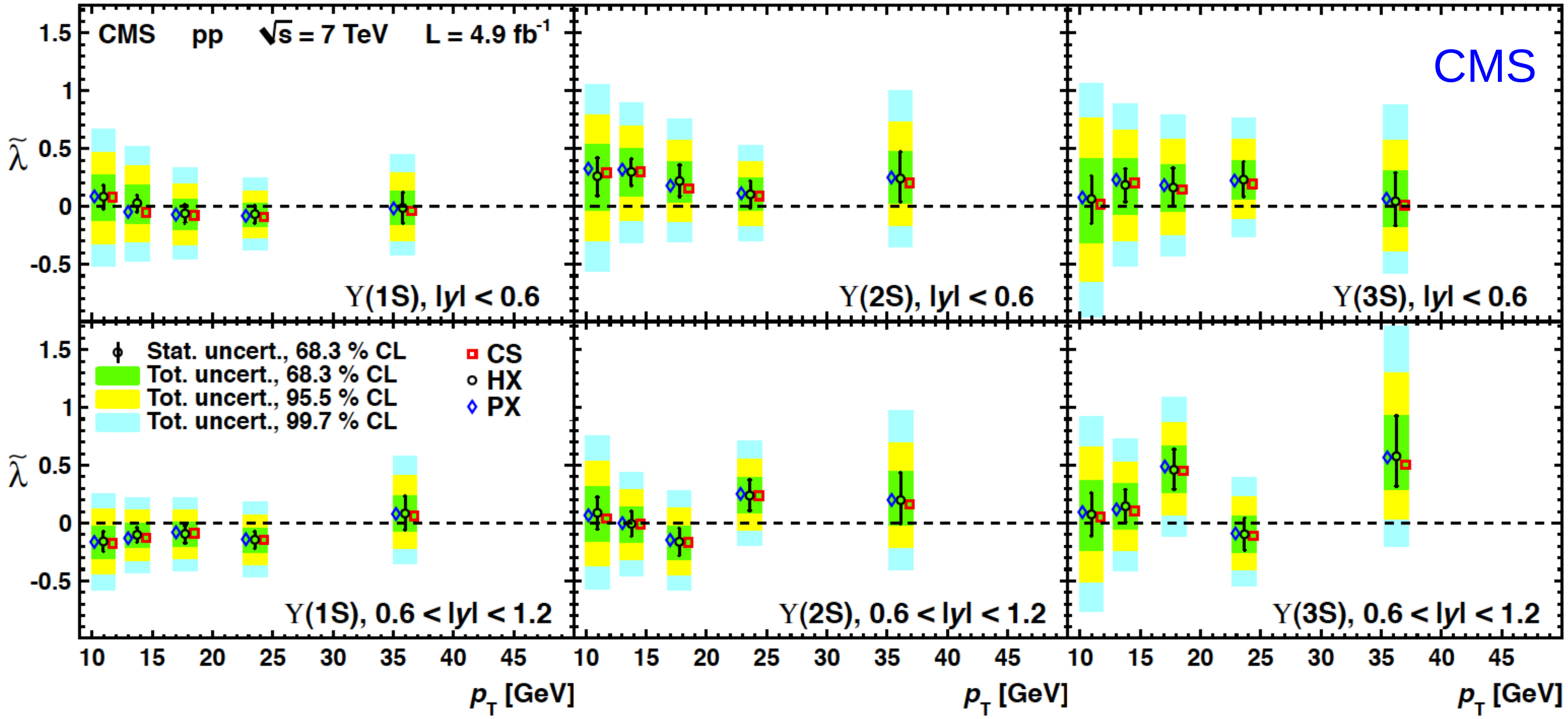
order of magnitude of the expected systematic error on the anisotropy parameters

"Modern" measurements

Improved results from **CDF** and new measurements from the **LHC** (CMS, LHCb, ALICE) now include frame-invariant observables

Results in all reference frames are consistent
→ No evidence of unaccounted systematic effects



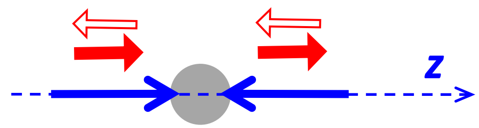


CDF: PRL 108 (2012) 15180
CMS: PRL 110 (2013) 081802

Frames for Drell-Yan, *Z* and *W* polarizations

- polarization is *always fully* ***transverse***...

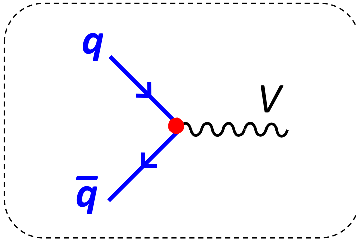
$V = \gamma^*, Z, W$



Due to helicity conservation at the q-$\bar{q}$-V (q-q^*-V) vertex,
$J_z = \pm 1$ along the q-$\bar{q}$ (q-q^*) scattering direction z

- ...but with respect to a ***subprocess-dependent quantization axis***

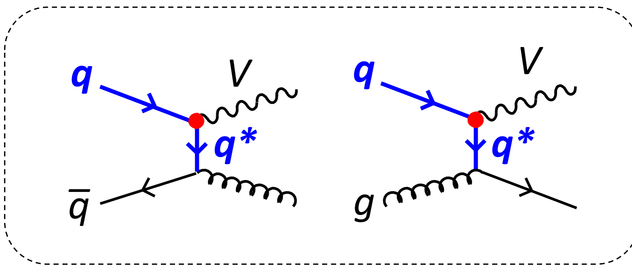
$O(\alpha_S^0)$



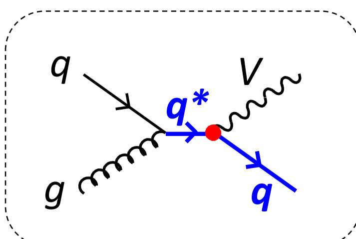
z = relative dir. of incoming q and $q$bar
(~ **Collins-Soper frame**)

important only up to $p_T = \mathcal{O}$(parton k_T)

$O(\alpha_S^1)$
QCD
corrections



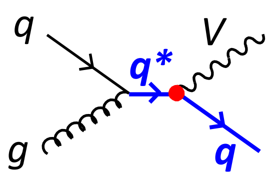
z = dir. of *one* incoming quark
(~ **Gottfried-Jackson frame**)



z = dir. of outgoing q
(= **parton-cms-helicity** ≈ **lab-cms-helicity**)

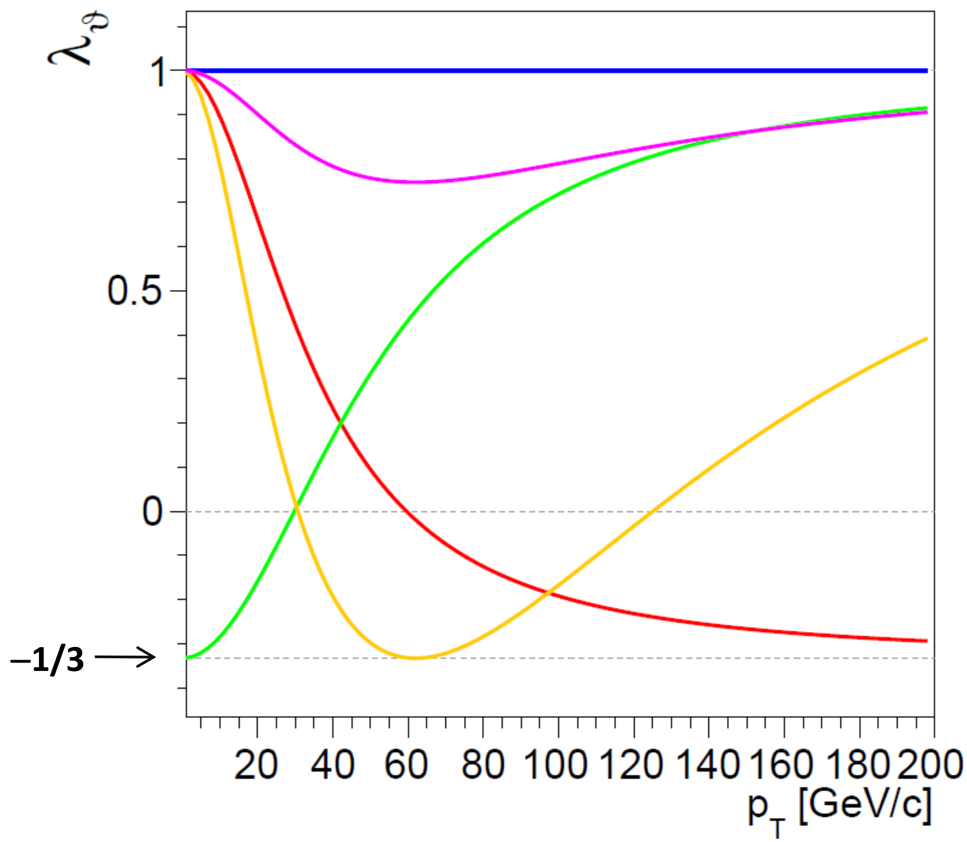
“Optimal” frames for Drell-Yan, *Z* and *W* polarizations

Different subprocesses have different “natural” quantization axes



For ***s*-channel processes** the natural axis is the direction of the outgoing quark (= direction of dilepton momentum)

→ optimal frame (= maximizing polar anisotropy): **HX** (neglecting parton-parton-cms vs proton-proton-cms difference!)

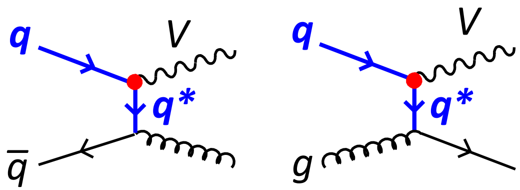


HX
CS
PX
GJ1 (negative beam)
GJ2 (positive beam)

example: Z
$y = +0.5$

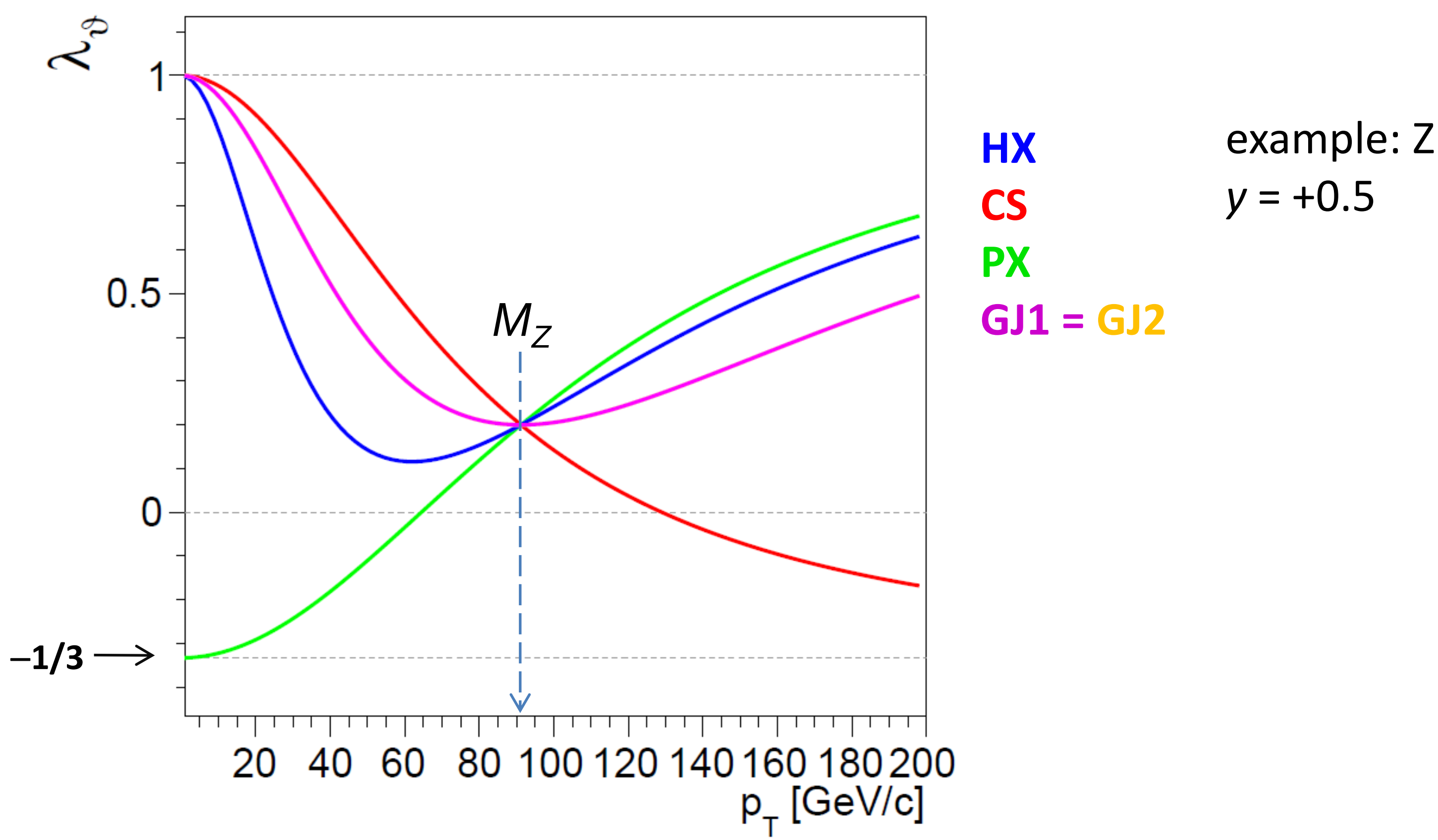
"Optimal" frames for Drell-Yan, *Z* and *W* polarizations

Different subprocesses have different "natural" quantization axes



For ***t*- and *u*-channel processes** the natural axis is the direction of either one or the other incoming parton (~ "Gottfried-Jackson" axes)

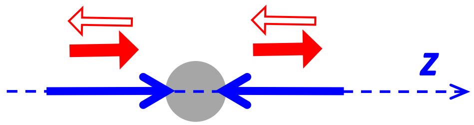
→ optimal frame: geometrical average of GJ1 and GJ2 axes = **CS ($p_T < M$)** and **PX ($p_T > M$)**



Rotation-invariant Drell-Yan, *Z* and *W* polarizations

- polarization is *always fully* ***transverse***...

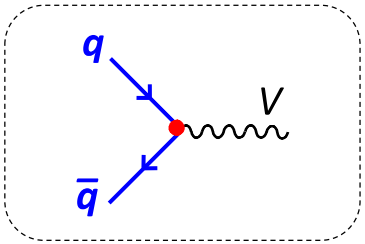
$V = \gamma^*, Z, W$



Due to helicity conservation at the q-$\bar{q}$-V (q-q^*-V) vertex, $J_z = \pm 1$ along the q-$\bar{q}$ (q-q^*) scattering direction z

- ...but with respect to a ***subprocess-dependent quantization axis***

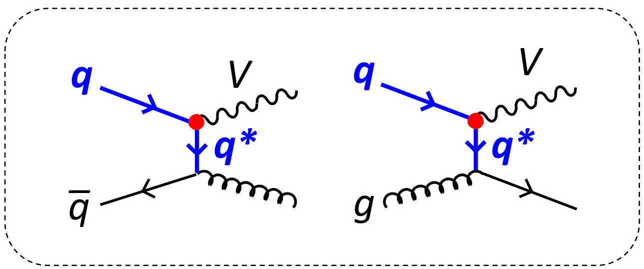
$O(\alpha_S^0)$ →



"natural" z = relative dir. of *q* and *q*bar
→ λ_ϑ("CS") = +1

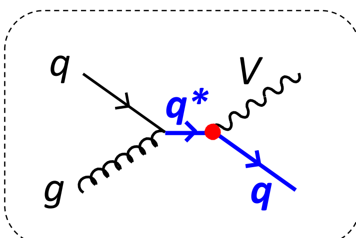
wrt ***any*** axis: $\tilde{\lambda} = +1$

$O(\alpha_S^1)$ (LO) QCD corrections



z = dir. of *one* incoming quark
→ λ_ϑ("GJ") = +1

$\tilde{\lambda} = +1$



z = dir. of outgoing *q*
→ λ_ϑ("HX") = +1

$\tilde{\lambda} = +1$

N.B.: $\tilde{\lambda} = +1$ in both pp-HX and qg-HX frames!

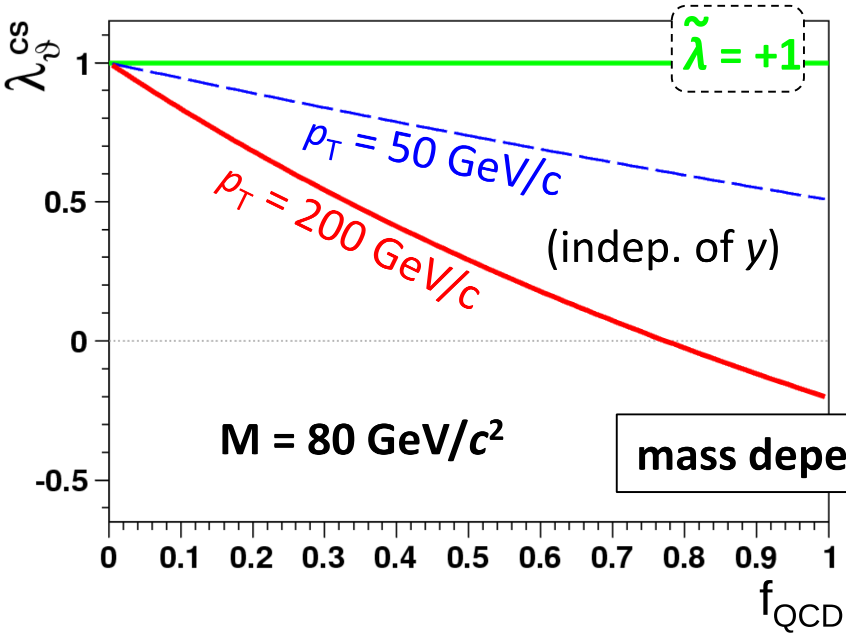
$\tilde{\lambda} = +1$ any frame

In all these cases the *q*-*q*-*V* lines are in the production plane ("planar" processes);
The CS, GJ, pp-HX and qg-HX axes only differ by a rotation in the production plane

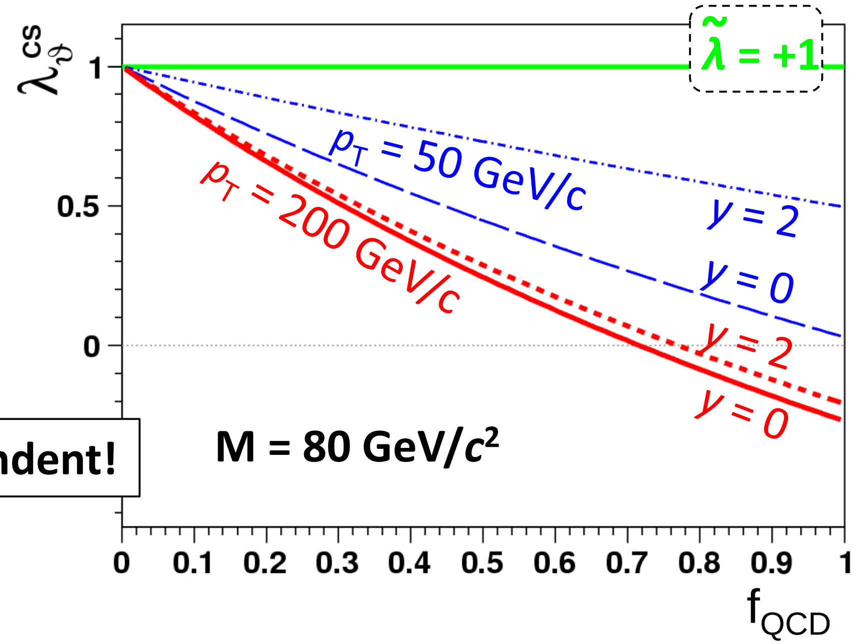
λ_ϑ vs $\tilde{\lambda}$

Example: ***Z/γ*/W* polarization** (CS frame) as a function of contribution of LO QCD corrections:

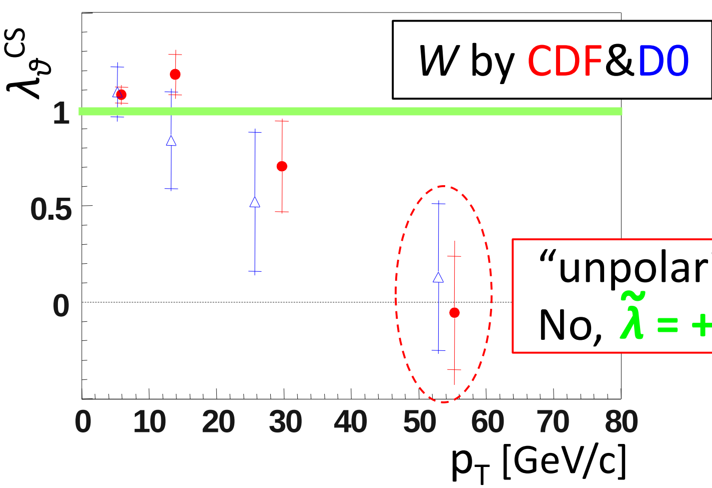
Case 1: dominating ***q-qbar*** QCD corrections



Case 2: dominating ***q-g*** QCD corrections



mass dependent!



"unpolarized"?
No, $\tilde{\lambda}$ = +1 !

λ_ϑ
- depends on p_T , y and mass
  → by integrating we lose significance
- is far from being maximal
- depends on process admixture
  → need pQCD and PDFs

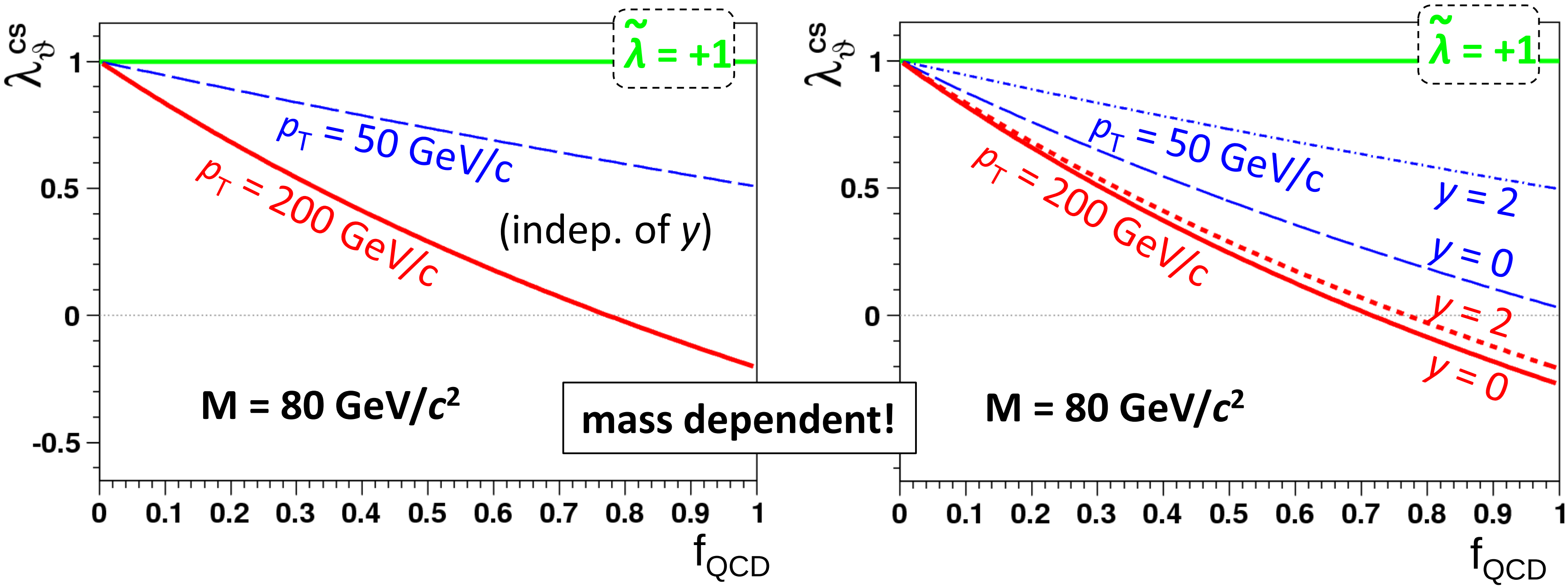
$\tilde{\lambda}$ is constant, maximal and independent of process admixture

λ_ϑ vs $\tilde{\lambda}$

Example: ***Z/γ*/W* polarization** (CS frame) as a function of contribution of LO QCD corrections:

Case 1: dominating ***q-qbar*** QCD corrections

Case 2: dominating ***q-g*** QCD corrections



On the other hand, $\tilde{\lambda}$ forgets about the direction of the quantization axis.
This information is crucial if we want to **disentangle the *qg* contribution**,
the only one resulting in a ***rapidity-dependent*** $\boldsymbol{\lambda_\vartheta}$

Measuring λ_ϑ(CS) *as a function of rapidity* gives information on the gluon content of the proton

The Lam-Tung relation

PHYSICAL REVIEW D VOLUME 21, NUMBER 9 1 MAY 1980

Parton-model relation without quantum-chromodynamic modifications in lepton pair production

C. S. Lam
Wu-Ki Tung

...ch more to the quark...
...QCD modifications in LPP than jus...
...egrated Drell-Yan cross-section formula. ...lepton angular distributions are controlled by structure functions which obey parton-model relations[3,4] similar to those between F_1 and F_2 in deep-inelastic scattering (DIS). How are these relations affected by perturbative QCD corrections? The answer to this question is quite surprising: At least one of these relations—the exact counterpart of the Callan-Gross[5] relations—is not modified at all by first-order QCD corrections, although individual terms in this relation ...y be subject to large corrections. In the re... ...note, we spell out explicitly the pa... ...as the contrast betw...

...cross-section formula [essentially W^{μ}_{μ}, c... Eq. (2)]. This appears to be a rather remarkable result; we are not aware of any other parton-model result which is not affected by QCD corrections. For this reason, we sketch in the ...endix a derivation of Eq. (5) from the dia... ...which is more di...

...erms of helicity structure fu... ...lation takes the form $W_L = 2W_{\Delta\Delta}$, Eq. (7). ...though for LPP, the helicity structure functions depend on the choice of coordinate axes[4] (e.g., Gottfried-Jackson, Collins-Soper, etc.), *this relation remains frame independent*—i.e., if the QCD-quark-parton model is correct, the two structure functions W_L and $W_{\Delta\Delta}$ must be related by Eq. (7), for *any* choice of axes in the lepton-pair center-of-mass frame. This strong result again demonstrates the significance of this relation.

We know the angular distribution of the lepton...

The Lam-Tung relation

PHYSICAL REVIEW D **76**, 074006 (2007)

Transverse momentum dependence of the angular distribution of the Drell-Yan process

Edmond L. Berger,[1,*] Jian-Wei Qiu,[1,2,†] and Ricardo A. Rodriguez-Pedraza[2,‡]

We calculate the transverse momentum $Q_\perp$ dependence of the helicity structure functions for the hadroproduction of a massive pair of leptons with pair invariant mass Q. These structure functions determine the angular distribution of the leptons in the pair rest frame. Unphysical behavior in the region $Q_\perp \to 0$ is seen in the results of calculations done at fixed order in QCD perturbation theory. We use current conservation to demonstrate that the unphysical inverse-power and $\ln(Q/Q_\perp)$ logarithmic divergences in three of the four independent helicity structure functions share the same origin as the divergent terms in fixed-order calculations of the angular-integrated cross section. We show that the resummation of these divergences to all orders in the strong coupling strength α_s can be reduced to the solved problem of the resummation of the divergences in the angular-integrated cross section, resulting in well-behaved predictions in the small $Q_\perp$ region. Among other results, we show the resummed part of the helicity structure functions preserves the Lam-Tung relation between the longitudinal and double spin-flip structure functions as a function of $Q_\perp$ to all orders in α_s.

The Lam-Tung relation

A fundamental result of the theory of vector-boson polarizations (Drell-Yan, directly produced *Z* and *W*) is that, at leading order in perturbative QCD,

$\lambda_\vartheta + 4\lambda_\varphi = 1$ independently of the polarization frame

Lam-Tung relation, Pysical Review D 18, 2447 (1978)

This identity was considered as a surprising result of cancellations in the calculations

Today we know that it is only a *special* case of general frame-independent polarization relations, corresponding to a *transverse* intrinsic polarization:

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi} = +1 \quad \Rightarrow \lambda_\vartheta + 4\lambda_\varphi = 1$$

It is, therefore, not a “QCD” relation, but a consequence of

1) rotational invariance

2) properties of the **quark-photon/Z/W couplings** (helicity conservation)

Beyond the Lam-Tung relation

Even when the Lam-Tung relation is violated,
$\tilde{\lambda}$ can always be defined and is always frame-independent

$\tilde{\lambda} = +1$ → Lam-Tung. New interpretation: only ***vector boson – quark – quark*** couplings (in planar processes) $\rightarrow$ automatically verified in DY at QED & LO QCD levels and in several higher-order QCD contributions

$$\tilde{\lambda} = +1 - \mathcal{O}(0.1)$$

$$\rightarrow +1 \text{ for } p_T \rightarrow 0$$

→ vector-boson – quark – quark couplings in ***non-planar*** **processes** (higher-order contributions)

$\tilde{\lambda}$ □ $+1$
$\tilde{\lambda} > +1$

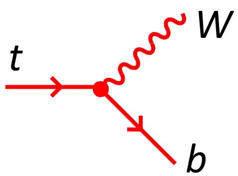
→ contribution of ***different/new couplings or processes***
(e.g.: *Z* from Higgs, *W* from top, triple *ZZ*γ coupling,
higher-twist effects in DY production, etc…)

Polarization can be used to distinguish
between different kinds of physics signals,
or between “signal” and “background” processes
($\rightarrow$improve significance of new-physics searches)

Example: *W* from top ↔ *W* from *q*-*q*bar and *q*-*g*

longitudinally polarized:

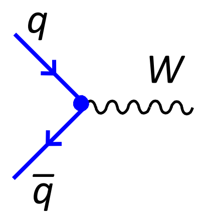
$\lambda_{\vartheta}^{SM} \cong -0.65$ wrt *W direction in*
$\lambda_{\varphi}^{SM} \cong 0$ *the top rest frame*
(top-frame helicity)



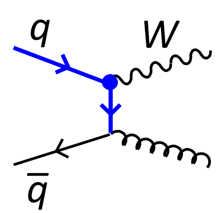
independently of top production mechanism

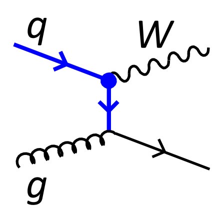
The top quark decays almost always to *W*+*b*
→ the longitudinal polarization of the W is a signature of the top

transversely polarized,
$\lambda_{\vartheta} = +1$ & $\lambda_{\varphi} = 0$ *wrt 3 different axes:*

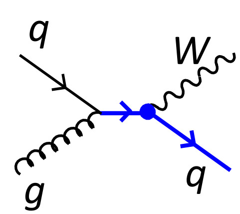


relative direction of *q* and *q*bar ("Collins-Soper")





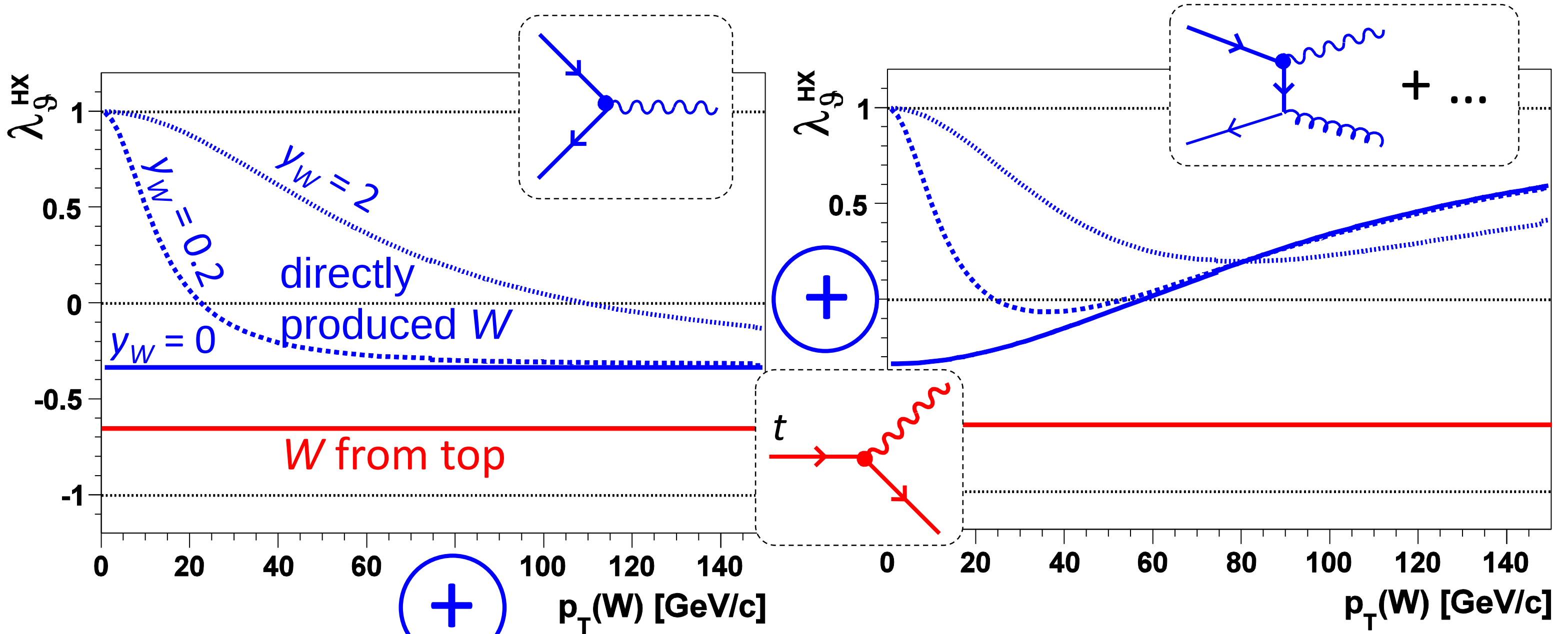
direction of *q* or *q*bar ("Gottfried-Jackson")

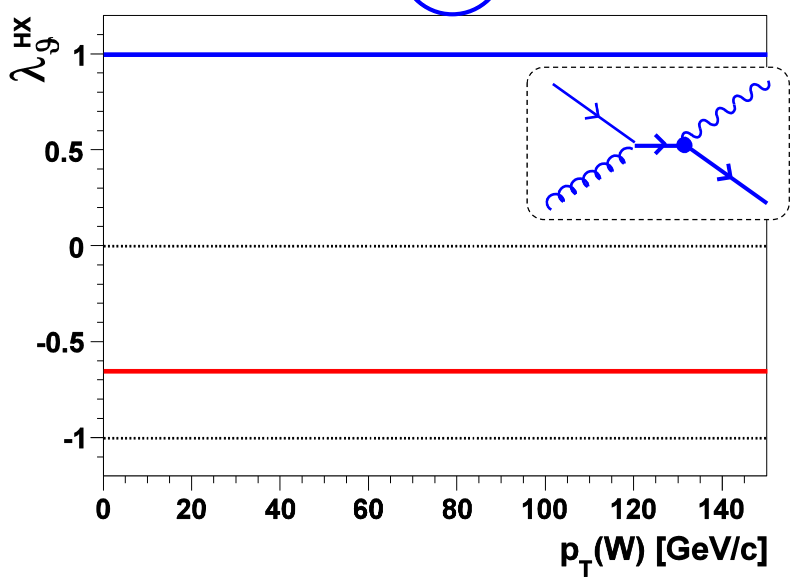


direction of outgoing *q* (cms-helicity)

a) Frame-dependent approach

We measure λ_ϑ choosing the helicity axis

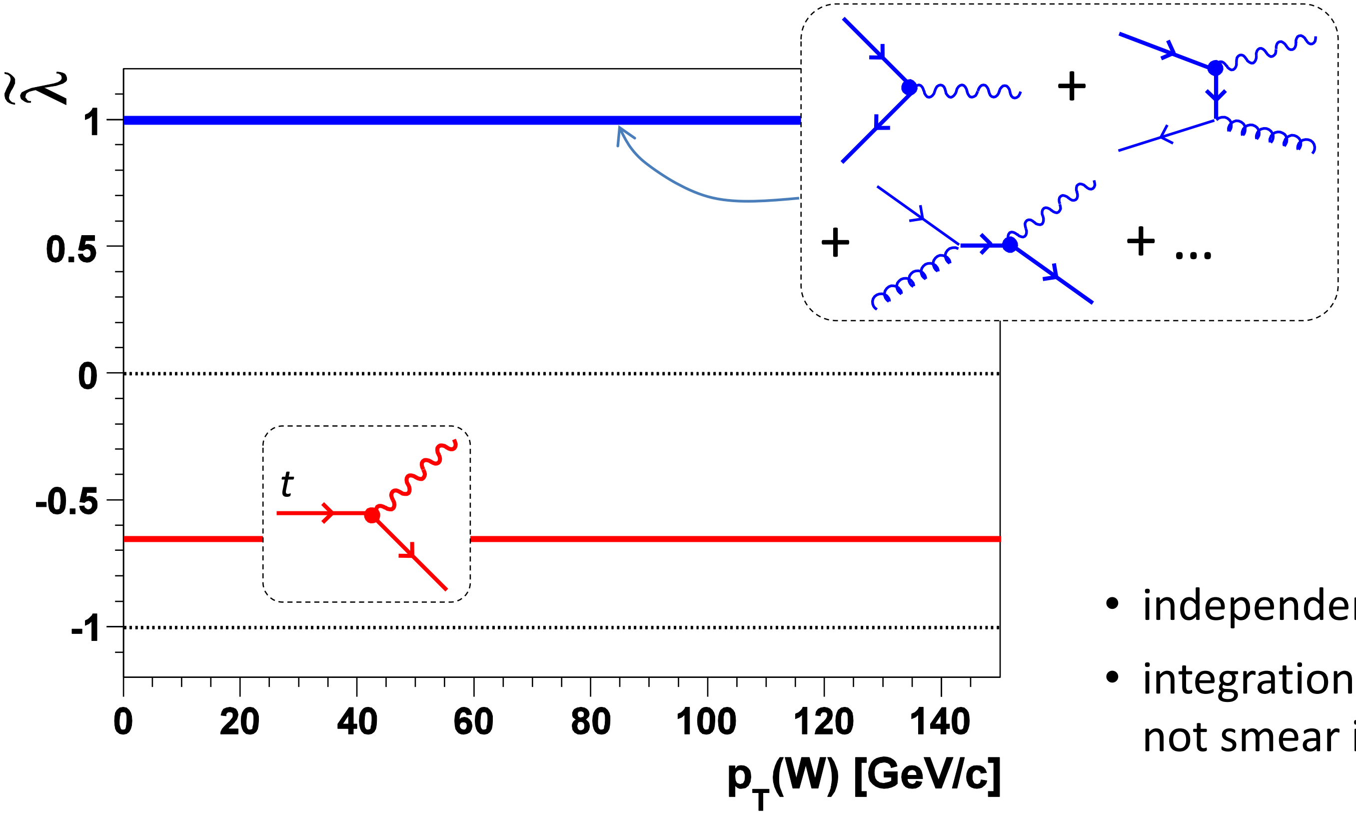




The polarization of *W* from *q-qbar / q-g*

- is generally far from being maximal
- depends on p_T and y
  $\rightarrow$ integration in p_T and y degrades significance
- depends on the actual mixture of processes
  $\rightarrow$ we need pQCD and PDFs to evaluate it

b) Rotation-invariant approach



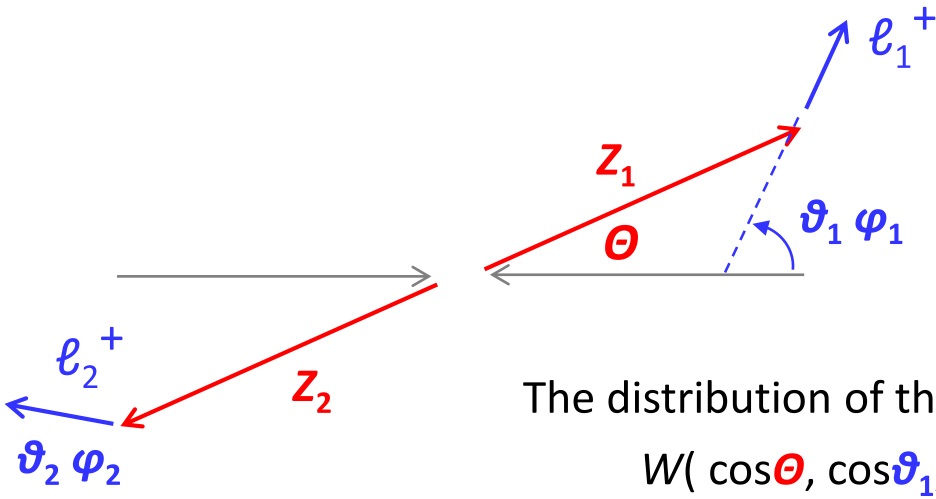
The *invariant* polarization of *W* from *q-qbar* / *q-g* is **constant** and fully **transverse**

- independent of PDFs
- integration over kinematics does not smear it

Example: the *q*-*q*bar → *ZZ* continuum background

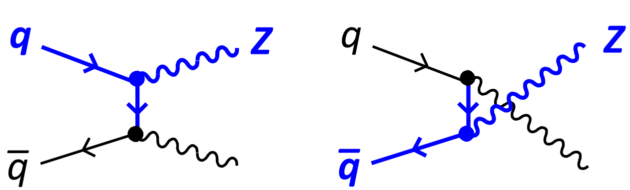
dominant Standard Model background for new-signal searches
in the $ZZ \to 4\ell$ channel with $m(ZZ) > 200$ GeV/c^2

The new Higgs-like resonance was discovered also thanks to these techniques



The distribution of the **5 angles** depends on the **kinematics**

$$W(\cos\Theta, \cos\vartheta_1, \varphi_1, \cos\vartheta_2, \varphi_2 \mid M_{ZZ}, \vec{p}(Z_1), \vec{p}(Z_2))$$

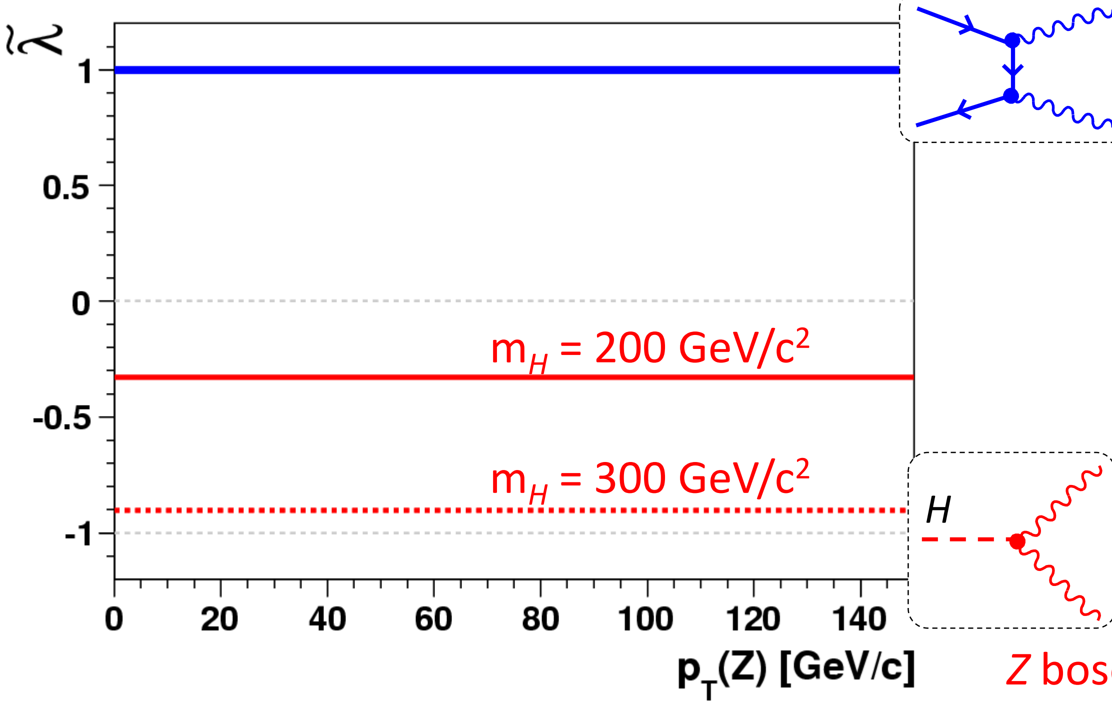


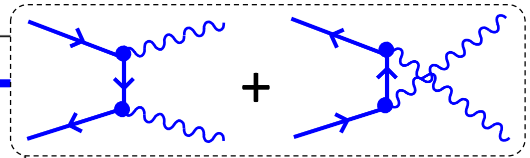
t-channel u-channel

- for helicity conservation each of the two *Z's* is transverse along the direction of one or the other incoming quark
- t-channel and u-channel amplitudes are proportional to $\frac{1}{1-\cos\Theta}$ and $\frac{1}{1+\cos\Theta}$ for $M_Z/M_{ZZ} \to 0$

Z Z from Higgs ↔ *Z Z* from *q-q*bar

Discriminant nº1: ***Z* polarization**



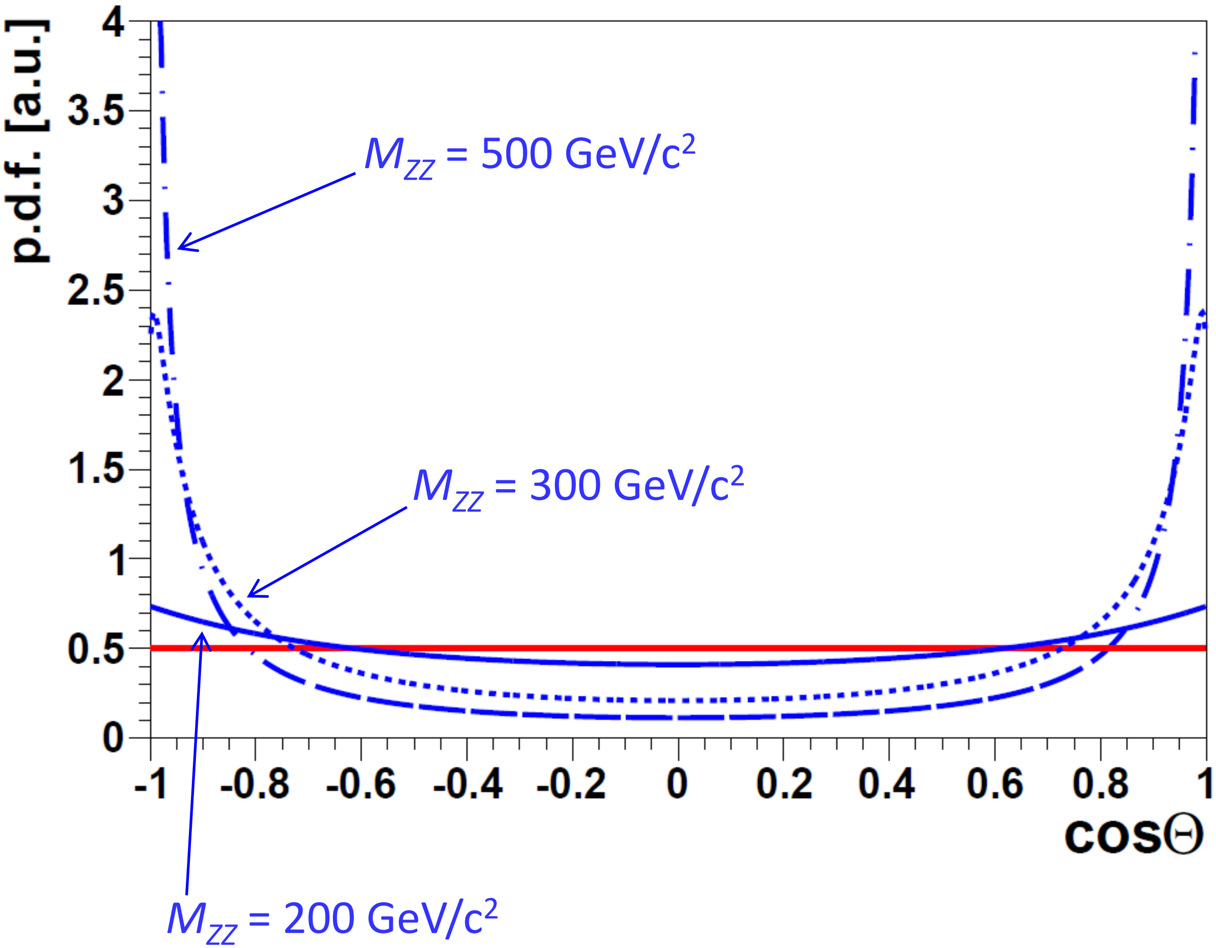


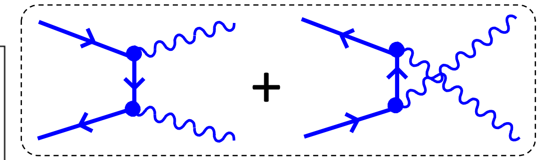
The *invariant* polarization of *Z* from *q-q*bar is fully **transverse**

Z bosons from $H \rightarrow ZZ$ are **longitudinally** polarized (stronger polarization for heavier *H*)

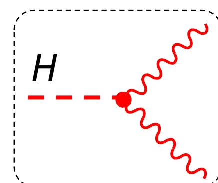
Z Z from Higgs ↔ Z Z from *q*-*q*bar

Discriminant nº2: ***Z* emission direction**





Z from *q*-*q*bar is emitted mainly close to the beam if M_{ZZ}/M_Z is large



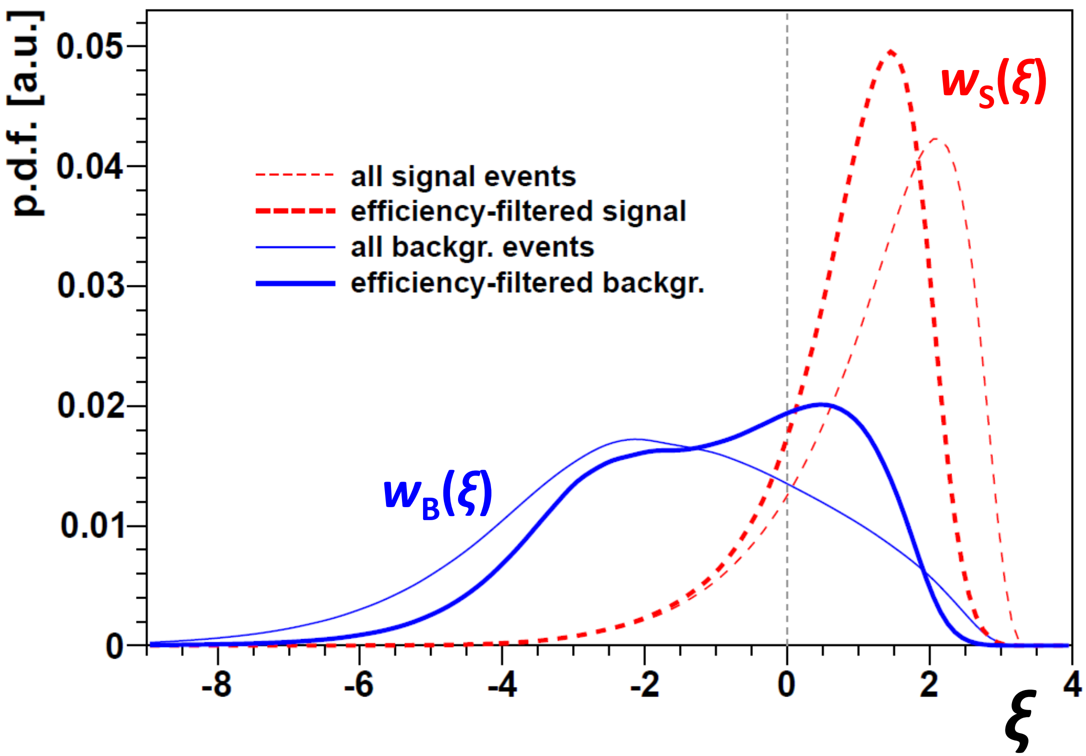
Z bosons from *H* decay are emitted isotropically

Putting everything together

5 angles (Θ, ϑ_1, φ_1, ϑ_2, φ_2), with distribution depending on
5 kinematic variables (M_{ZZ}, $p_T(Z_1)$, $y(Z_1)$, $p_T(Z_2)$, $y(Z_2)$)

1 shape discriminant: $\xi = \ln \dfrac{\mathcal{P}_{H\to ZZ}}{\mathcal{P}_{q\bar{q}\to ZZ}}$

event probabilities, including detector acceptance and efficiency effects



$\sqrt{s}$ = 14 TeV
500 < M_{ZZ} < 900 GeV/c^2
M_H = 700 GeV/c^2
$|y_{ZZ}|$ < 2.5

lepton selection:
p_T > 15 GeV/c
$|\eta|$ < 2.5

Further reading

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