Polarization measurements at the LHC: from quarkonia to gauge bosons

- Basics: dilepton decay distributions of vector particles
- A paradigm measurement: quarkonium polarization — theoretical puzzles and experimental pitfalls
- Vector-boson polarizations: Lam-Tung relation and its generalization
- Polarization of vector bosons as a discriminant of new physics signals

Pietro Faccioli

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Polarization of vector particles

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

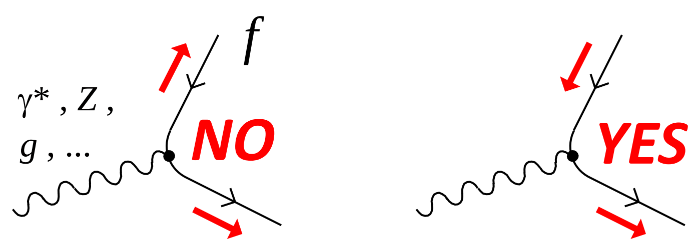
Measure polarization = measure (average) angular momentum composition

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

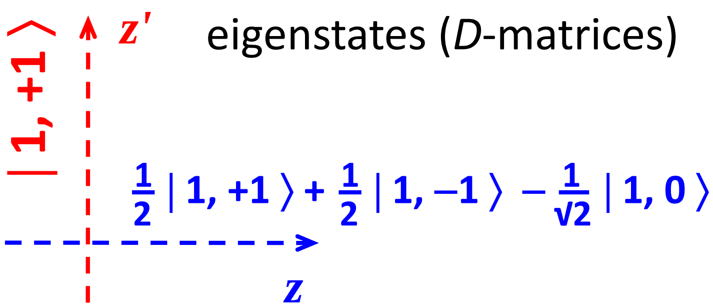
The decay **into fermion-antifermion pair** is an especially clean case to be studied

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

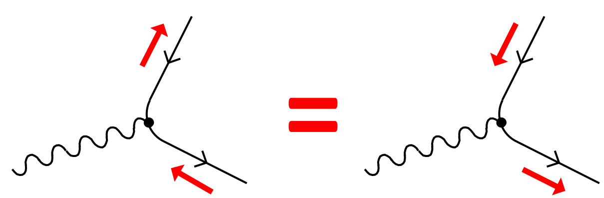
1) "helicity conservation"



2) rotational covariance of angular momentum eigenstates (*D*-matrices)

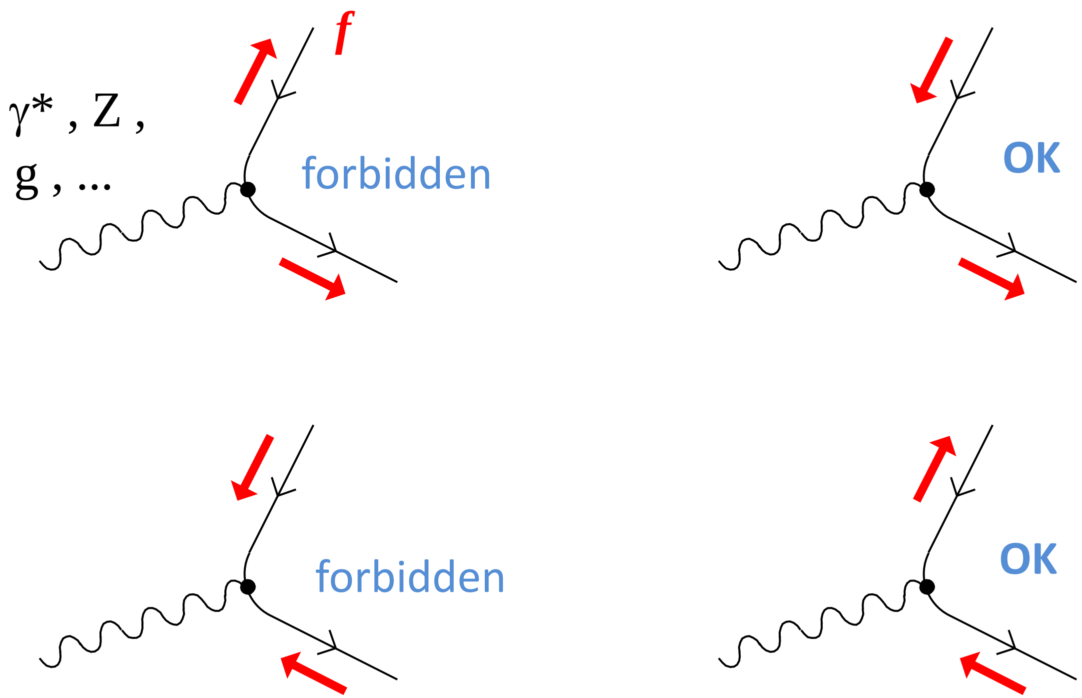


3) parity properties

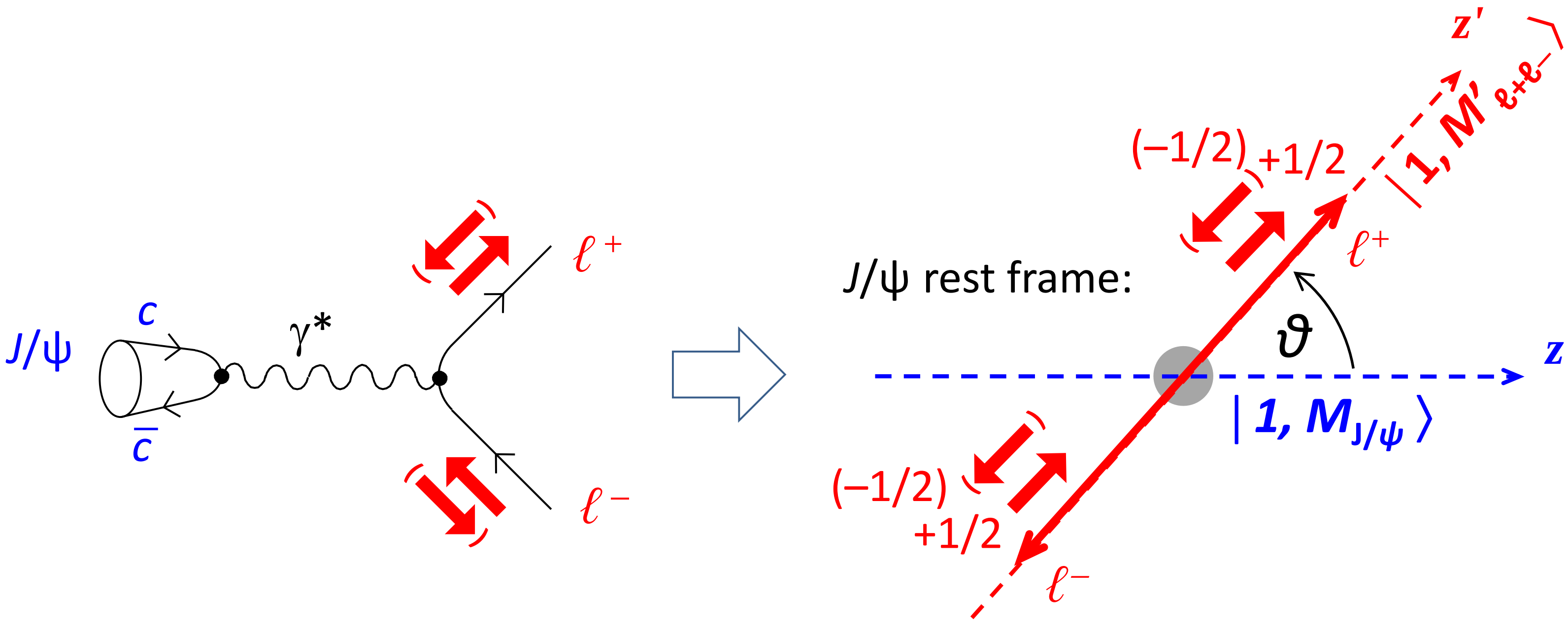


1: helicity conservation

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*:**

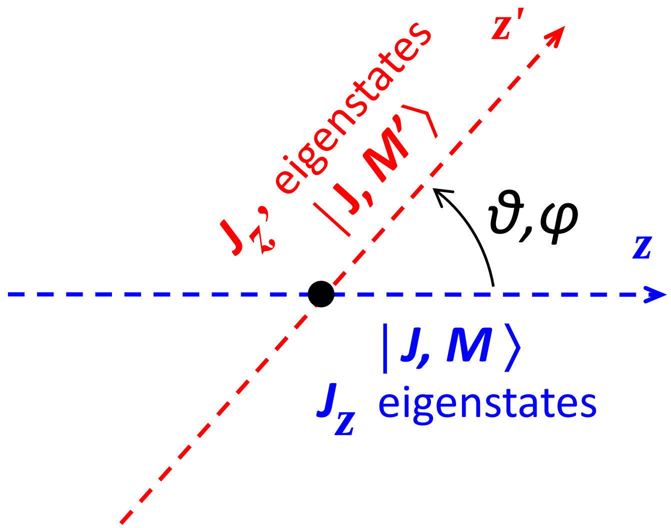
$\boldsymbol{M_{J/\psi}}$ **= -1, 0, +1** (determined by *production mechanism*)

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

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

0 forbidden

2: rotation of angular momentum eigenstates



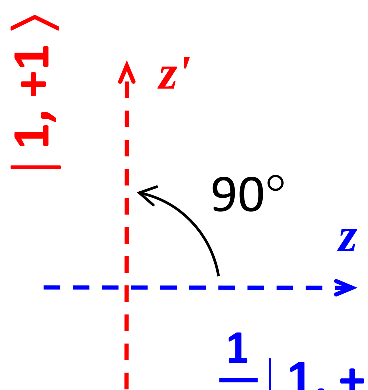
change of quantization frame:

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

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

Wigner D-matrices
(in angular momentum textbooks)

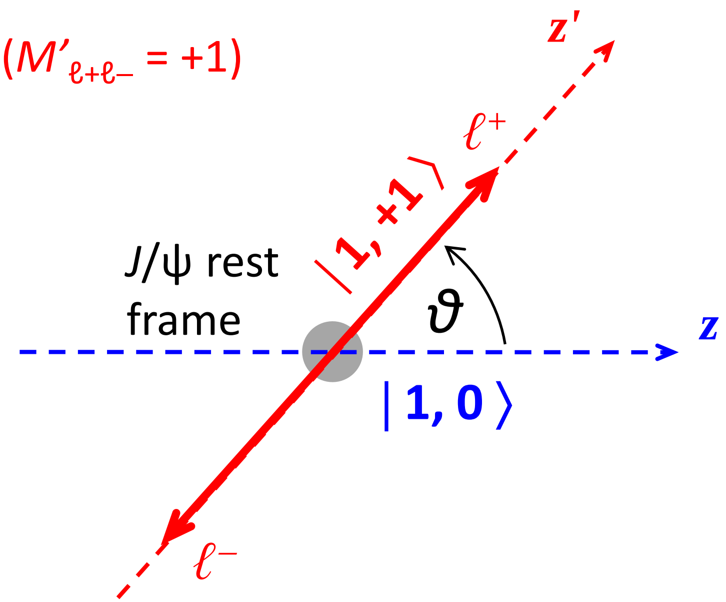
Example:



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

(example: M = 0)

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

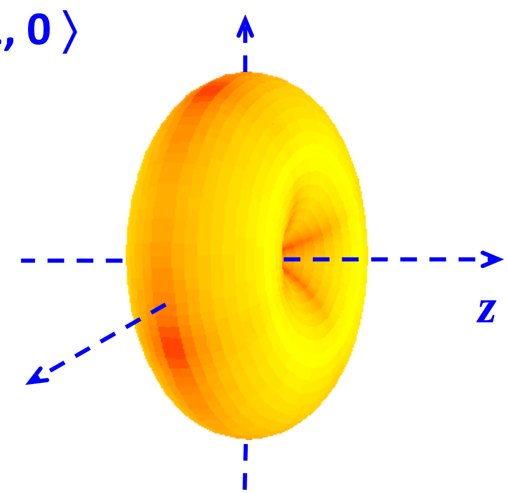


$$|\,\mathbf{1,+1}\,\rangle \;=\; D^{1}_{-1,+1}(\vartheta,\varphi)\ |\,\mathbf{1,-1}\,\rangle \;+\; D^{1}_{0,+1}(\vartheta,\varphi)\ |\,\mathbf{1,0}\,\rangle \;+\; D^{1}_{+1,+1}(\vartheta,\varphi)\ |\,\mathbf{1,+1}\,\rangle$$

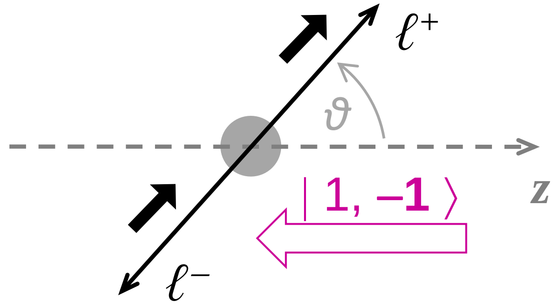
→ the $J_{z'}$ eigenstate $|\,\mathbf{1,+1}\,\rangle$ "contains" the J_z eigenstate $|\,\mathbf{1,0}\,\rangle$ with component amplitude $D^{1}_{0,+1}(\vartheta,\varphi)$

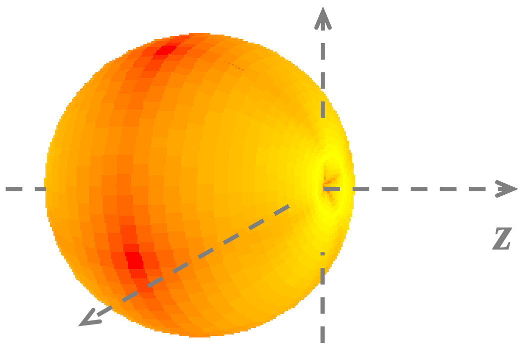
→ the decay distribution is

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



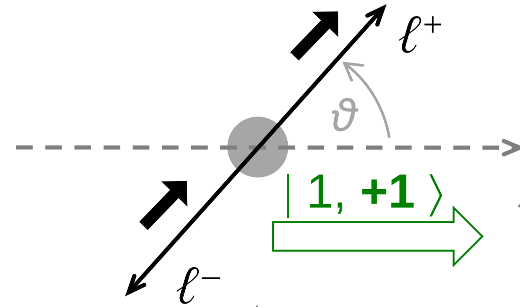
3: parity

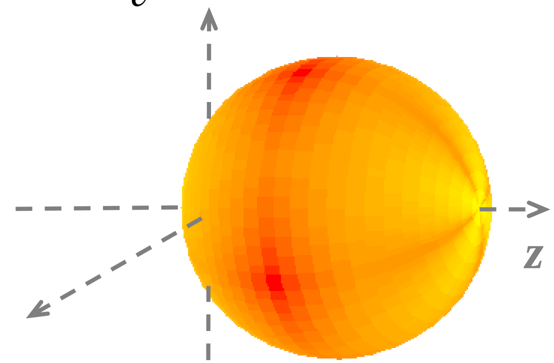




$$\frac{dN}{d\Omega} \propto |D_{-1,+1}(\vartheta,\varphi)|^2 \propto 1 + \cos^2\vartheta - \mathbf{2\cos\vartheta}$$

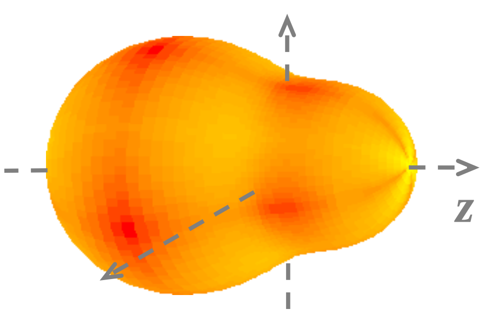
| 1, –1 ⟩ and | 1, +1 ⟩ distributions are mirror reflections of one another



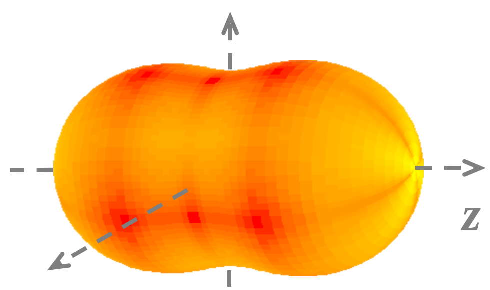


$$\frac{dN}{d\Omega} \propto |D_{+1,+1}(\vartheta,\varphi)|^2 \propto 1 + \cos^2\vartheta + \mathbf{2\cos\vartheta}$$

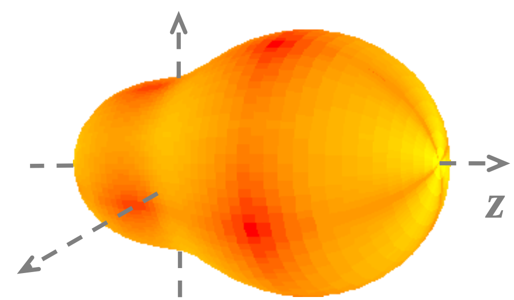
Are they equally probable?



$\mathcal{P}(-1) > \mathcal{P}(+1)$



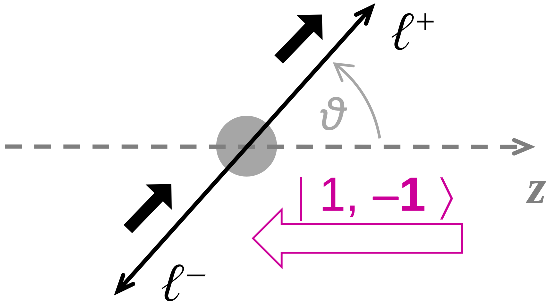
$\mathcal{P}(-1) = \mathcal{P}(+1)$

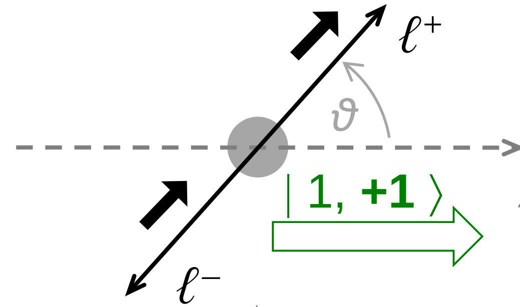


$\mathcal{P}(-1) < \mathcal{P}(+1)$

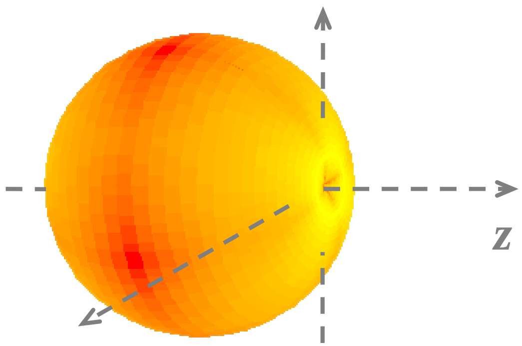
$$\frac{dN}{d\Omega} \propto \mathbf{1 + \cos^2\vartheta + 2[\mathcal{P}(+1) - \mathcal{P}(-1)]\cos\vartheta}$$

3: parity

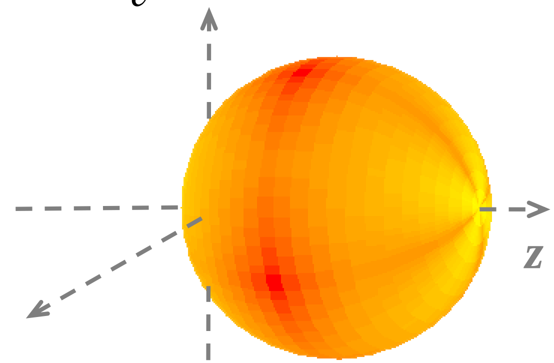




$|\,1, -1\,\rangle$ and $|\,1, +1\,\rangle$
distributions
are mirror reflections
of one another

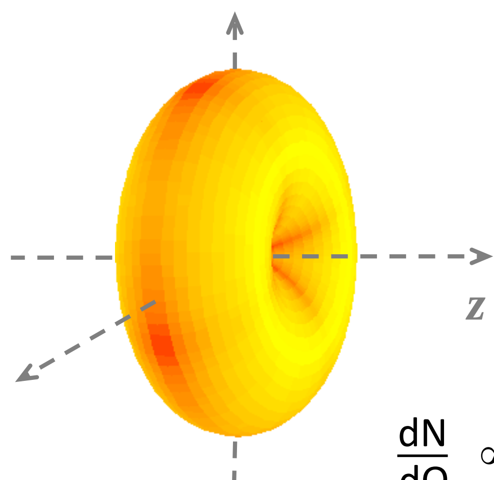


$$\frac{dN}{d\Omega} \propto |D_{-1,+1}(\vartheta,\varphi)|^2 \propto 1 + \cos^2\vartheta - \mathbf{2\cos\vartheta}$$



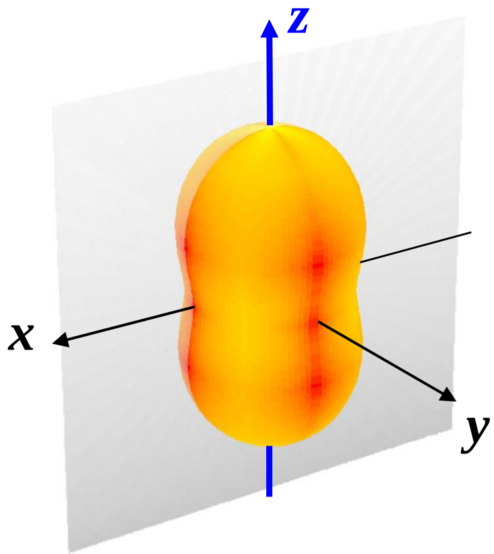
$$\frac{dN}{d\Omega} \propto |D_{+1,+1}(\vartheta,\varphi)|^2 \propto 1 + \cos^2\vartheta + \mathbf{2\cos\vartheta}$$

Decay distribution of $|\,1, \mathbf{0}\,\rangle$ state is always parity-symmetric:



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

"Transverse" and "longitudinal"

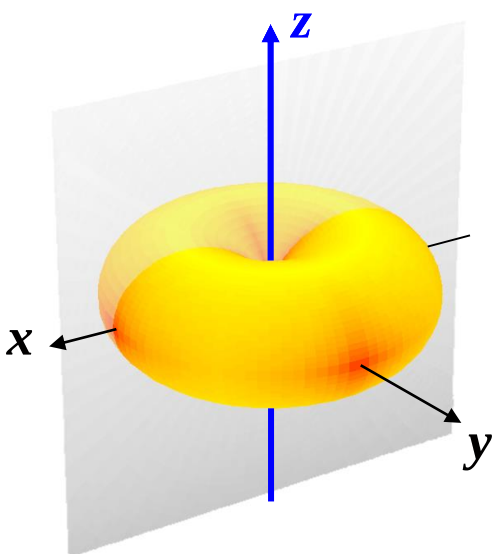


$$|J/\psi\rangle = |1, +1\rangle$$
$$\text{or } |1, -1\rangle$$

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

(parity-conserving case)

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



$$|J/\psi\rangle = |1, 0\rangle$$

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

"Longitudinal" polarization

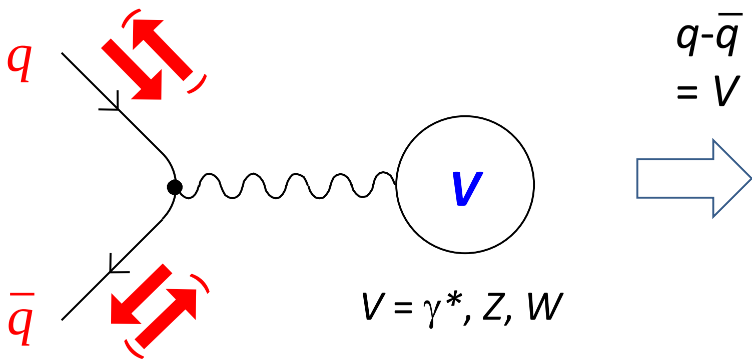
Transverse and longitudinal processes can be mixed together:

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

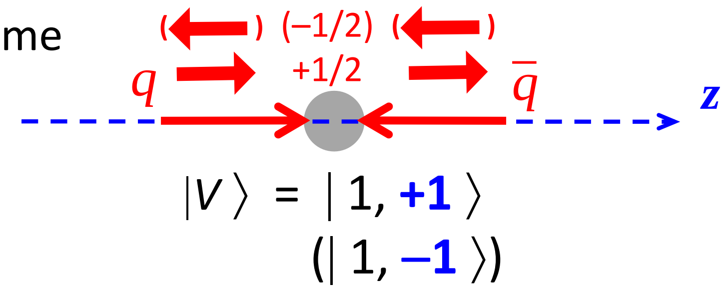
$$-1 < \lambda_\vartheta < +1$$

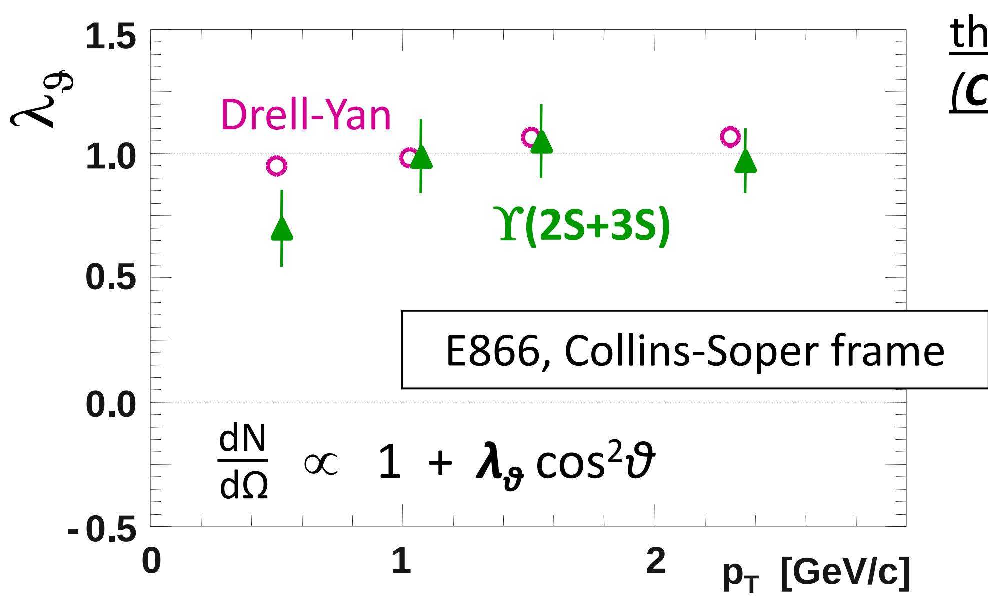
Why "photon-like" polarizations are common

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





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

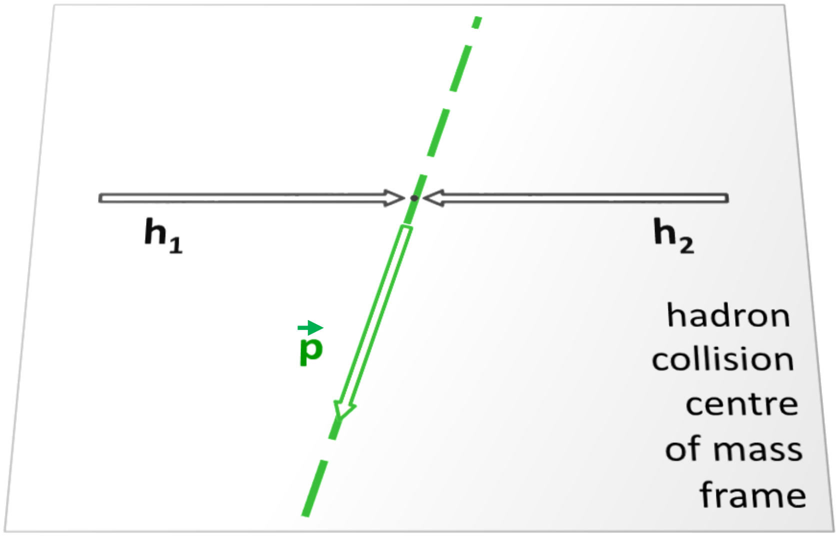
Polarization frames

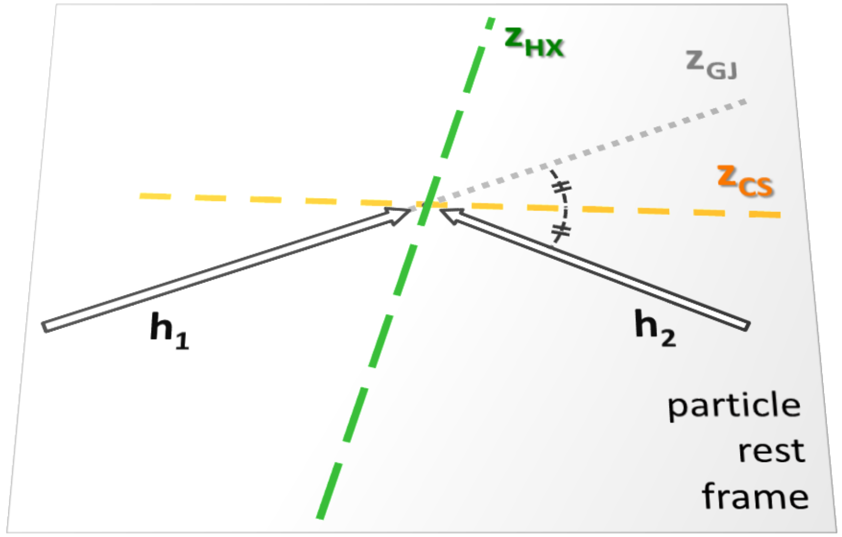
Helicity axis (HX): quarkonium momentum direction

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

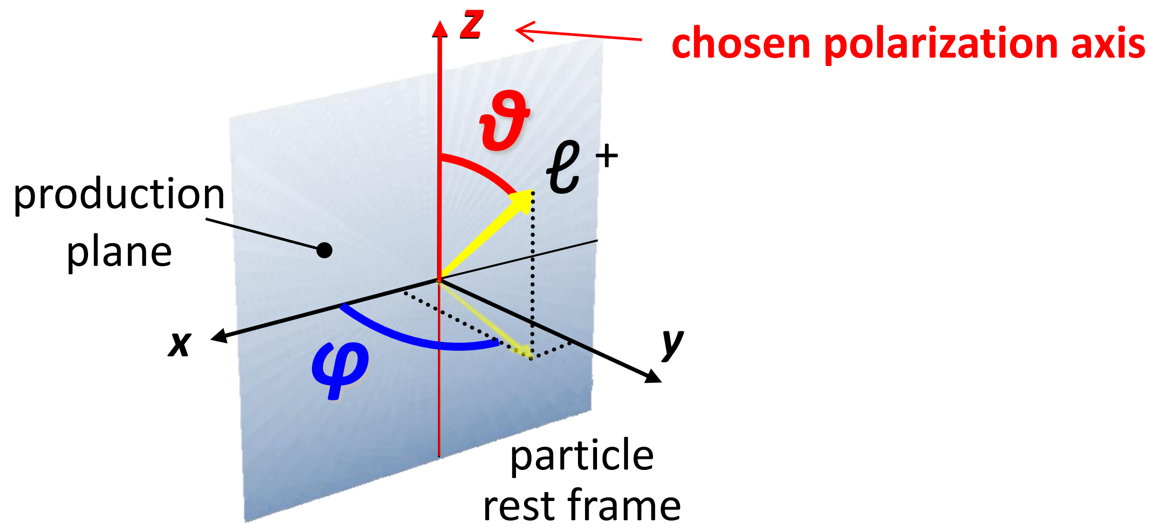
Collins-Soper axis (CS): average of the two beam directions

production plane





The most general distribution



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

$$+ \lambda_\varphi^\perp \sin^2\theta \sin 2\varphi + \lambda_{\theta\varphi}^\perp \sin 2\theta \sin\varphi$$

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

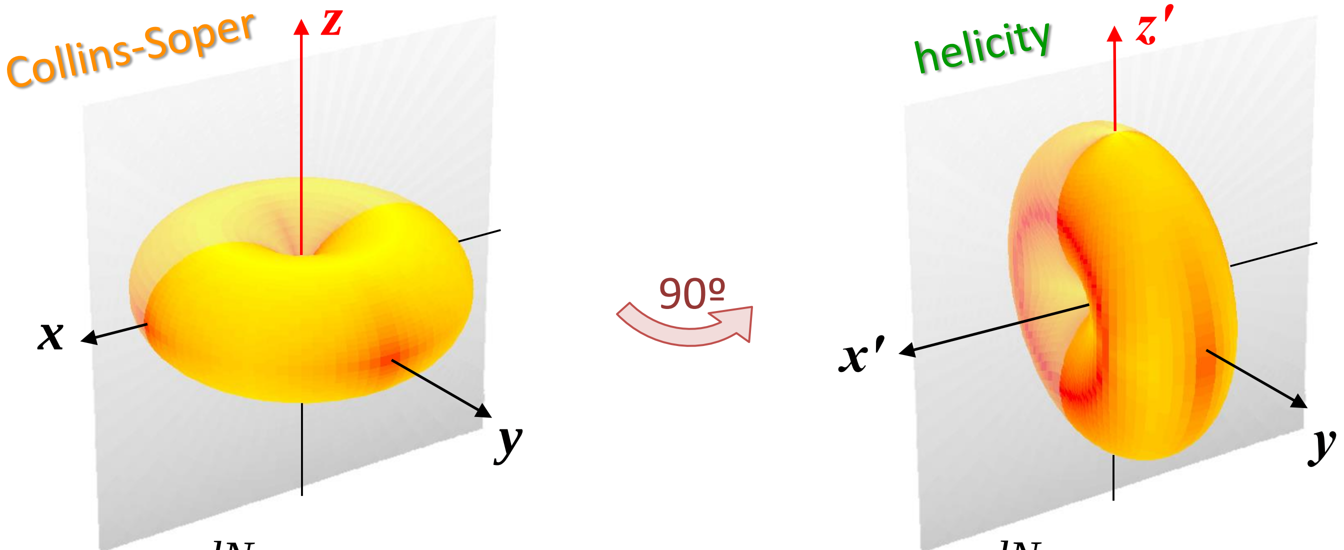
violate parity

asymmetric by reflection about the production plane

- vanish (in the event average) in the parity-conserving case
- small in the parity-violating case, especially in pp

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"

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

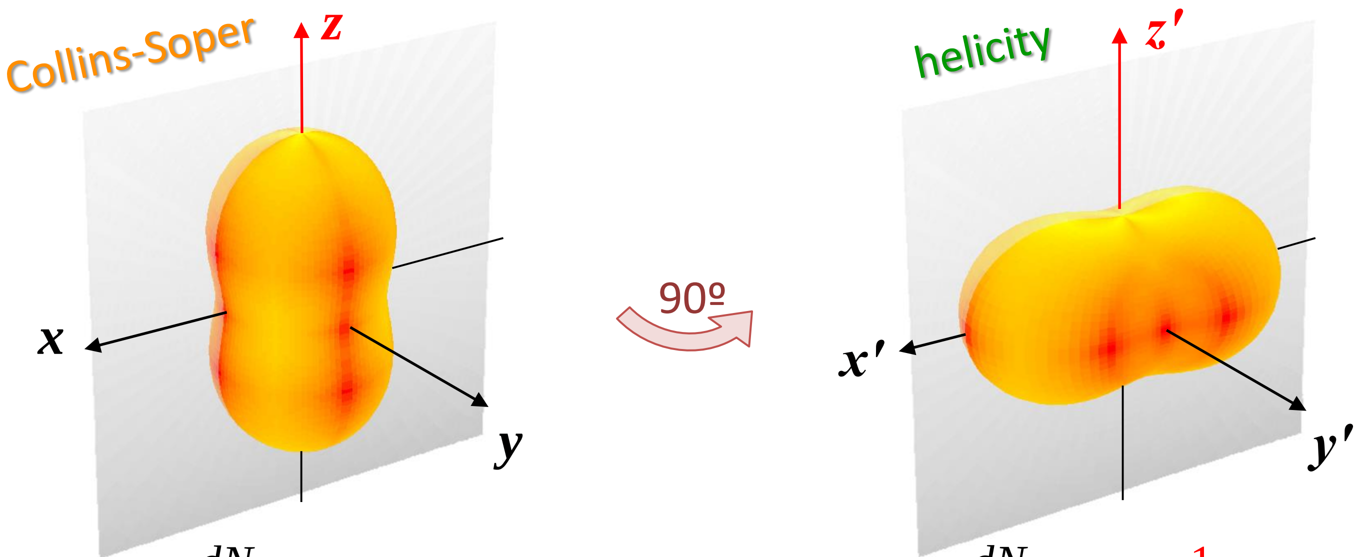
(pure state)

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

(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



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

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)

Reference frames are not all equally good

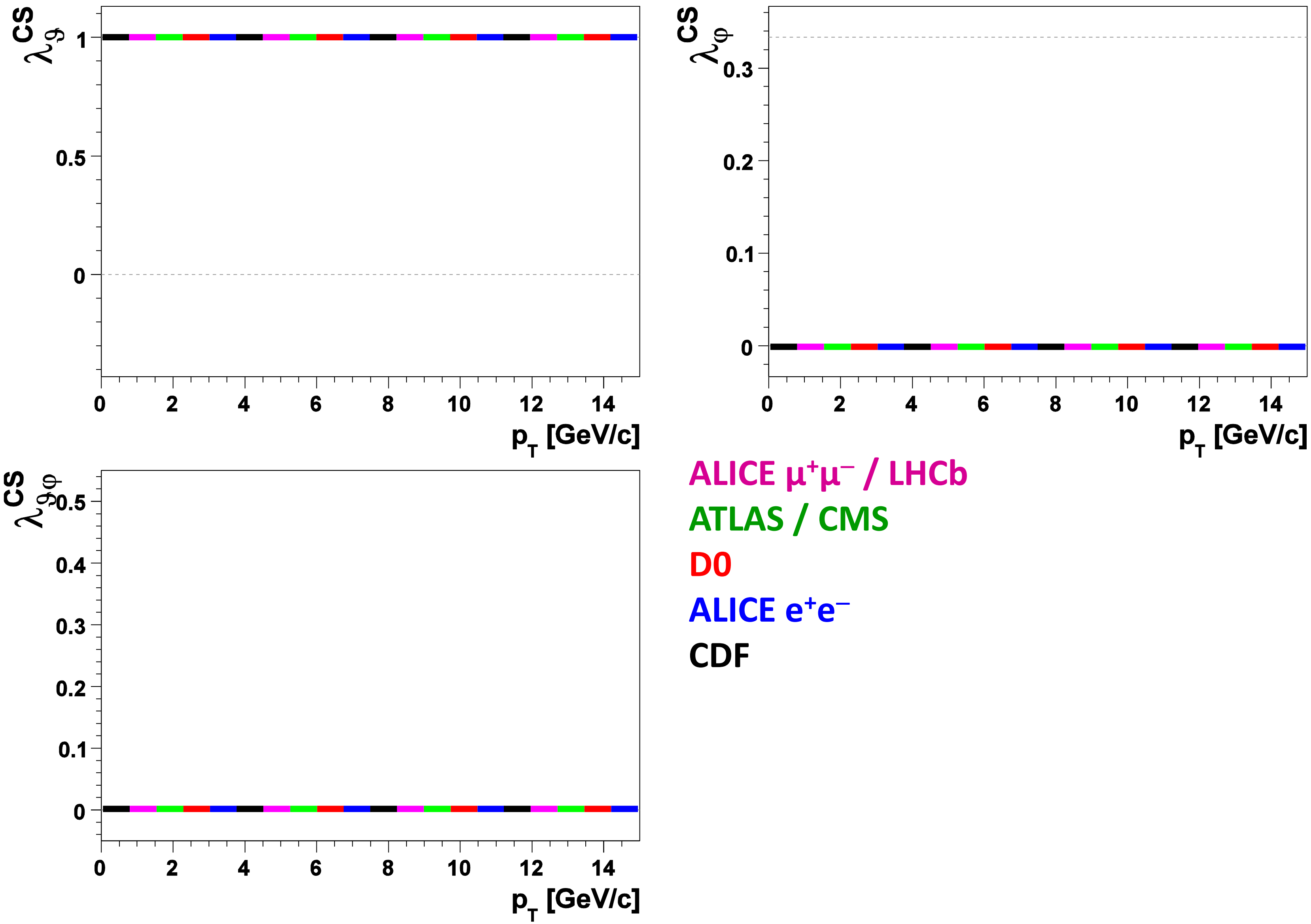
Gedankenscenario:
how would different detectors observe a Drell-Yan-like decay distribution
[“naturally” of the kind **$1 + \cos^2\vartheta$** in the Collins-Soper frame]
with an arbitrary choice of the reference frame?

Example:
Υ(1S) dilepton decay distribution,
as measured by 6 detectors with different dilepton acceptances:

CDF	$\lvert y\rvert < 0.6$
D0	$\lvert y\rvert < 1.8$
ATLAS & CMS	$\lvert y\rvert < 2.5$
ALICE e^+e^-	$\lvert y\rvert < 0.9$
ALICE $\mu^+\mu^-$	$2.5 < \lvert y\rvert < 4$
LHCb	$2 < \lvert y\rvert < 5$

The lucky frame choice

(CS in this case)



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

ATLAS / CMS

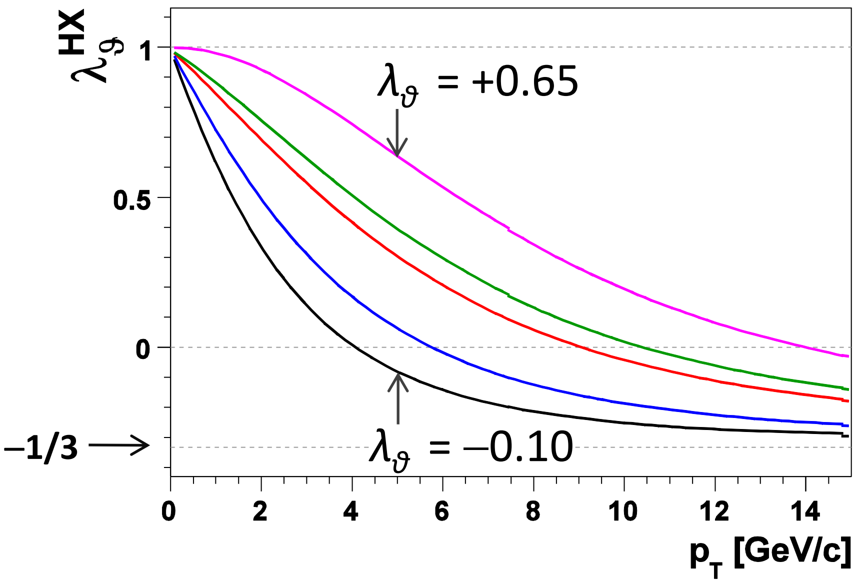
D0

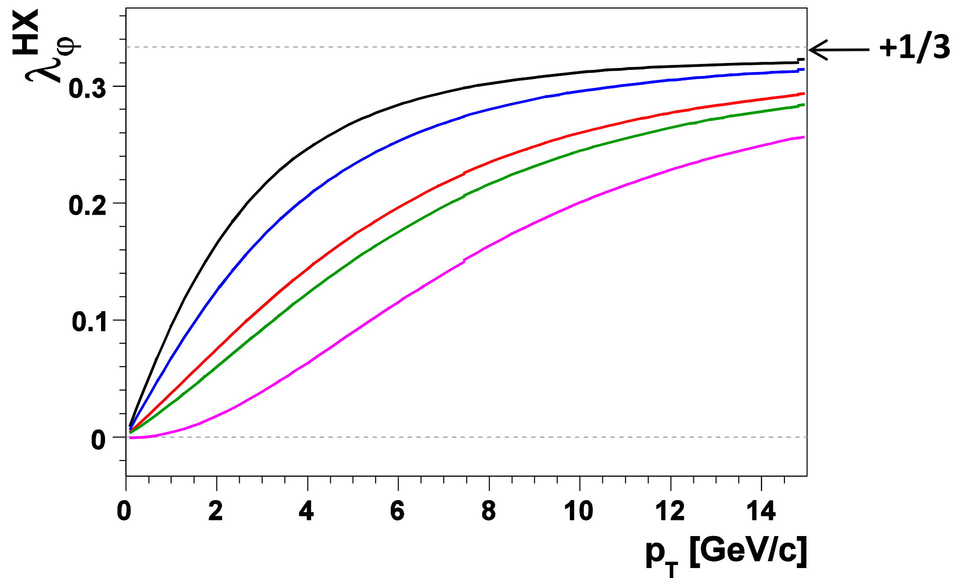
ALICE e^+e^-

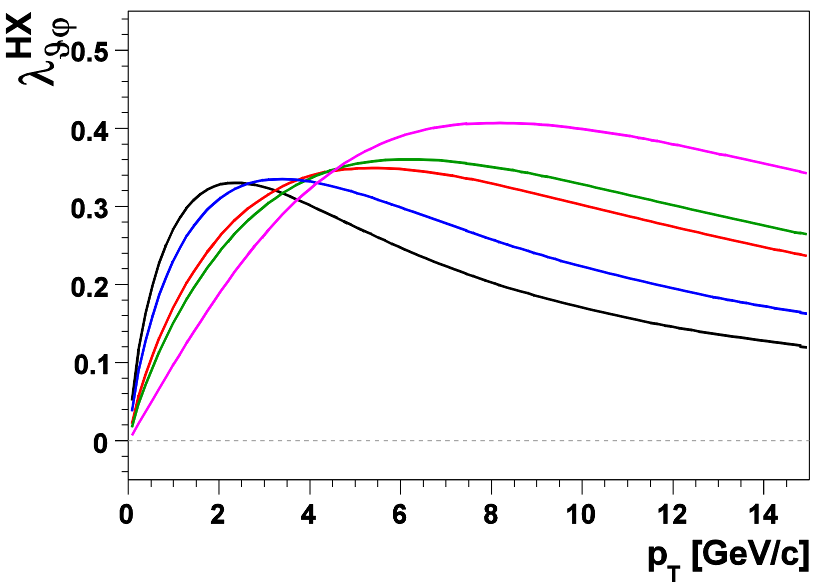
CDF

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!

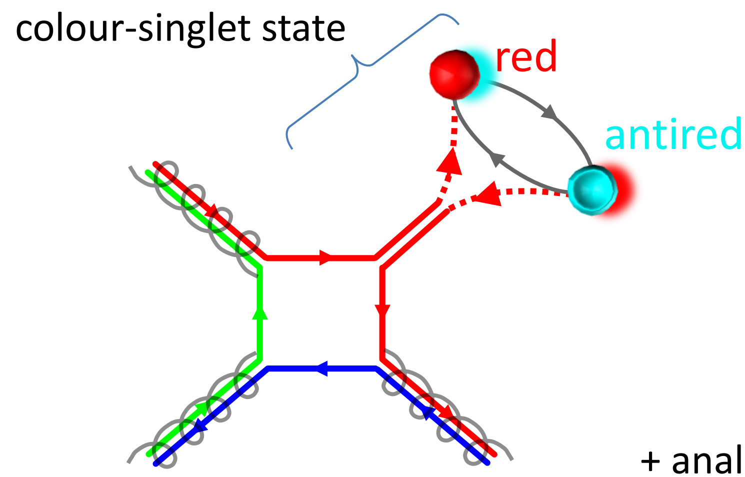
Why to measure polarization?

- The decay distribution offers a much closer insight into the quality/topology of the production processes wrt to decay-averaged production cross sections
- Polarization analyses allow us to:
  - understand still unexplained production mechanisms [J/ψ, χ_c, ψ', Υ, χ_b]
  - test QCD calculations [***Z/W*** decay distributions, ***t*-tbar** spin correlations]
  - constrain Standard Model couplings [$\sin\theta_W$ from $Z+\gamma^*$ decays]
  - constrain universal quantities [**proton PDFs** from Z/W decays]
  - measure P violation [**F/B and charge asymm.** in $Z+\gamma^*$, W decays] and CP violation [$B_s \rightarrow J/\psi\ \phi$]
  - search for anomalous couplings revealing existence of new particles [$H \rightarrow WW$ / ZZ / ***t*-tbar**, $t \rightarrow H^+ b$...]
  - characterize the spin of newly discovered resonances [$\rightarrow$ ***X*(3872)**, Higgs, Z', graviton, ...]

The quarkonium production dilemma: a matter of colour

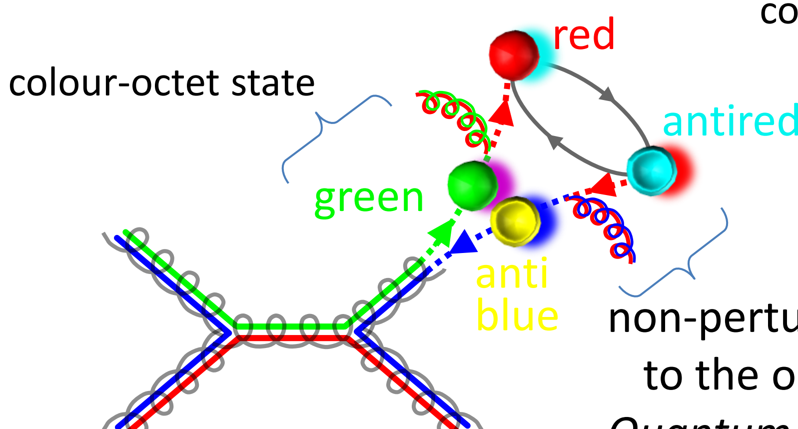
- Quarkonium production mechanisms are not understood
- How/when do the observed *Q*-*Q*bar bound states acquire their final quantum numbers?

  - **Colour Singlet Model**: quarkonia always produced directly as observable ***colour-neutral*** *Q*-*Q*bar pairs



+ analogous colour combinations

  - **NRQCD factorization**: quarkonia are also produced through ***coloured*** *Q*-*Q*bar pairs *of any possible quantum numbers*

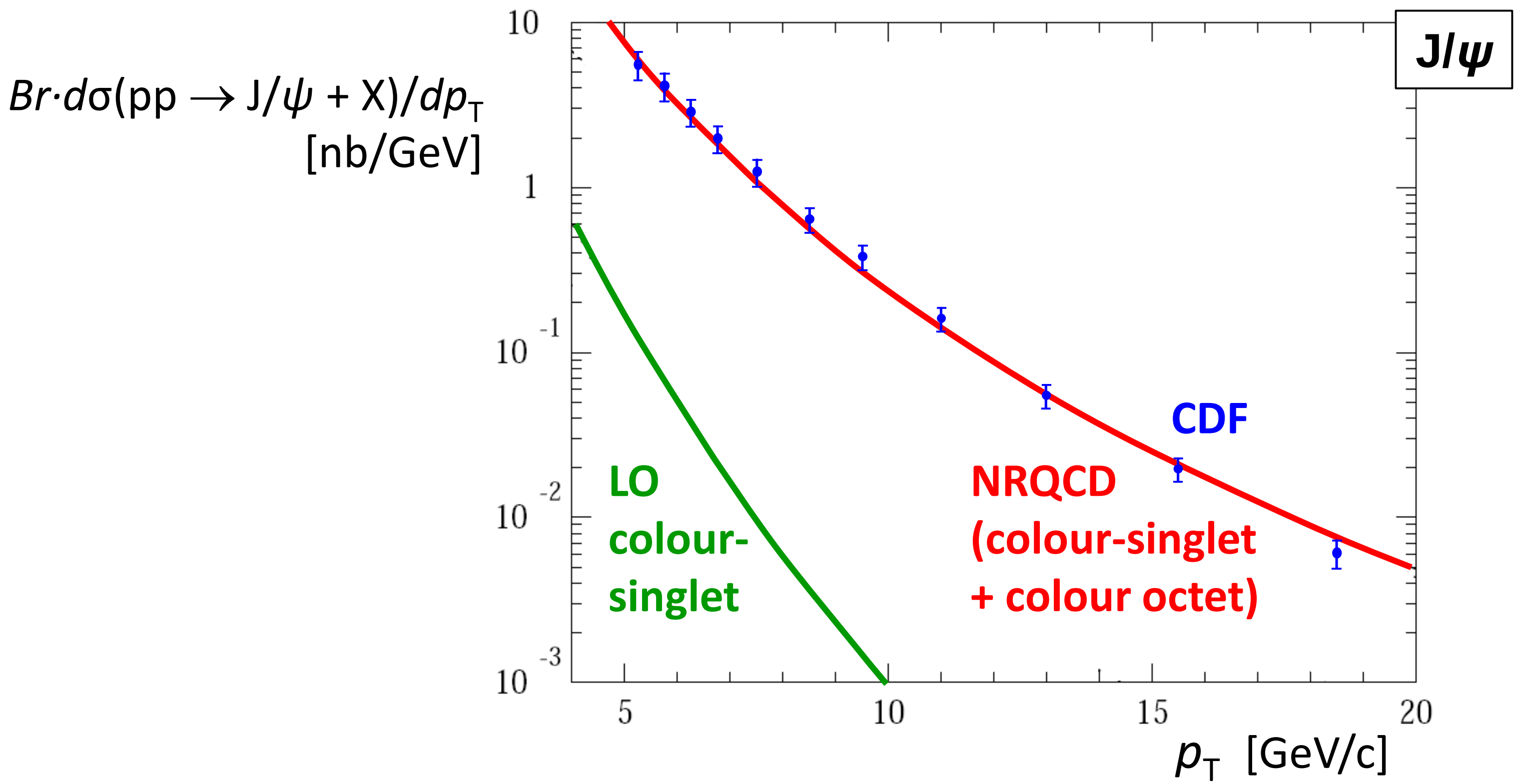


non-perturbative transition to the observable state. *Quantum numbers change!*

Factorization: transition to observed state described by universal matrix elements

Non-**R**elativistic: $\boldsymbol{\beta_Q \ll 1}$ → neglect transition matrix elements < $\mathcal{O}[(\beta_Q)^N]$

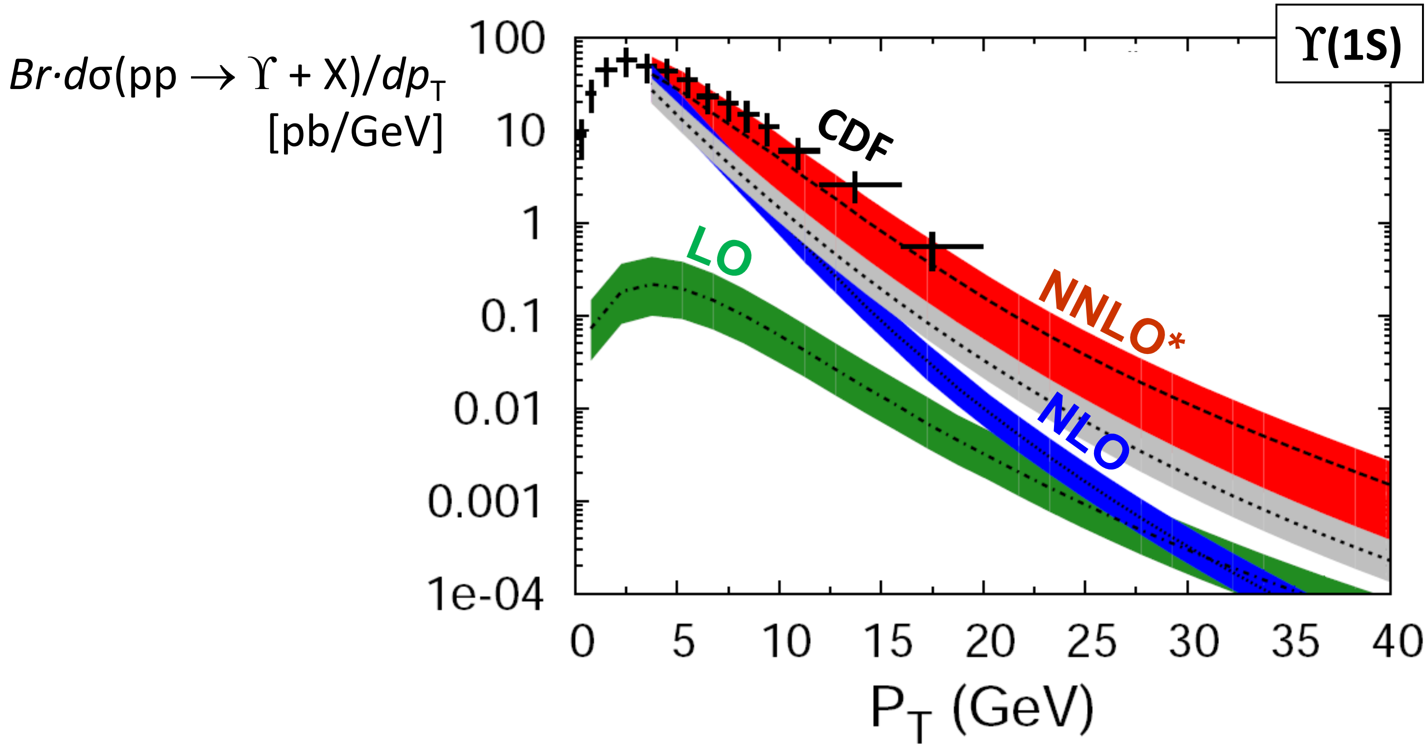
The seeming success of NRQCD



In 1995, **CDF** observed J/ψ (and ψ') direct production cross sections ~50 times larger than existing calculations based on **leading-order colour-singlet production**

The **NRQCD framework** apparently solved the problem… by freely *adjusting* long distance colour-octet matrix elements to describe the measurements

A rebirth of the colour-singlet model?



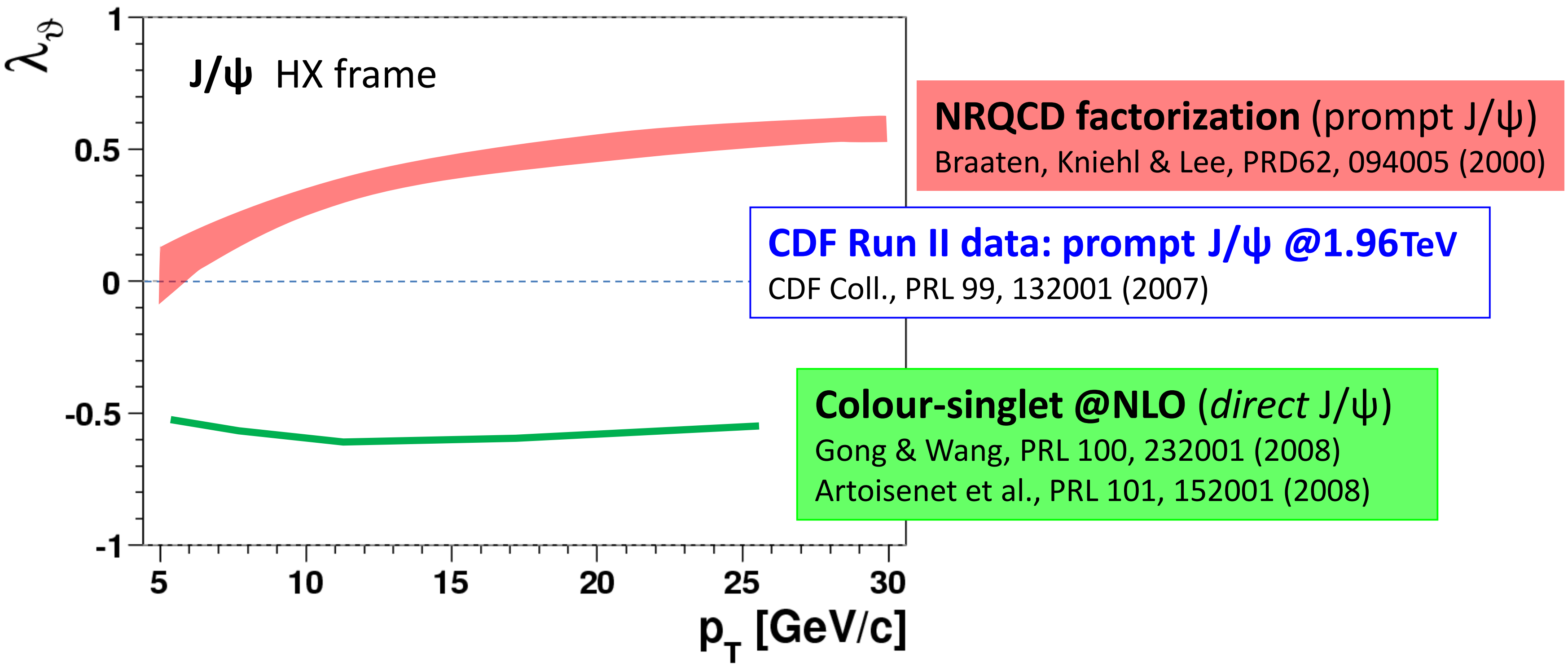
(parameter-free predictions)

Recent higher-order colour-singlet-model calculations almost fill the gap! (at least for the Upsilon)

The data no longer point to a dominant colour-octet component

→ Differential cross sections are insufficient information to ensure progress in our understanding of quarkonium production

The crucial J/ψ polarization measurements
Is the J/ψ polarized?
The “J/ψ polarization puzzle”



$$\frac{dN}{d\cos\vartheta} \propto 1 + \lambda_\vartheta (\cos\vartheta)^2$$

ϑ = angle between lepton direction
(in the J/ψ rest frame)
and J/ψ lab direction (helicity axis)

$\lambda_\vartheta > 0$: transverse (= photon-like)
$\lambda_\vartheta < 0$: longitudinal

"Unpolarized" means very special!

J=1 states are intrinsically "polarized"

Single elementary subprocess: $|\psi\rangle = a_{-1}\,|1,\mathbf{-1}\rangle + a_0\,|1,\mathbf{0}\rangle + a_{+1}\,|1,\mathbf{+1}\rangle$

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

$$\lambda_\theta = \frac{1-3|a_0|^2}{1+|a_0|^2} \qquad \lambda_\varphi = \frac{2\,\mathrm{Re}\,a_{+1}^* a_{-1}}{1+|a_0|^2} \qquad \lambda_{\theta\varphi} = \frac{\sqrt{2}\,\mathrm{Re}[a_0^*(a_{+1}-a_{-1})]}{1+|a_0|^2}$$

There is no combination of a_0, a_{+1} *and* a_{-1} *such that* $\lambda_\vartheta = \lambda_\varphi = \lambda_{\vartheta\varphi} = 0$

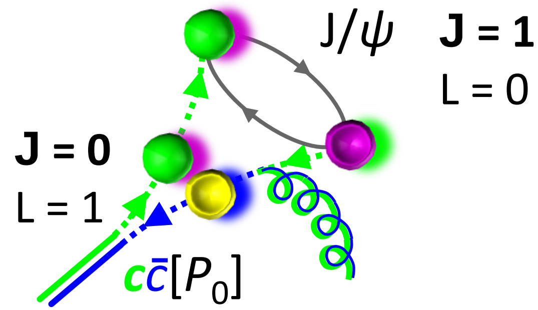
The angular distribution is never intrinsically *isotropic*

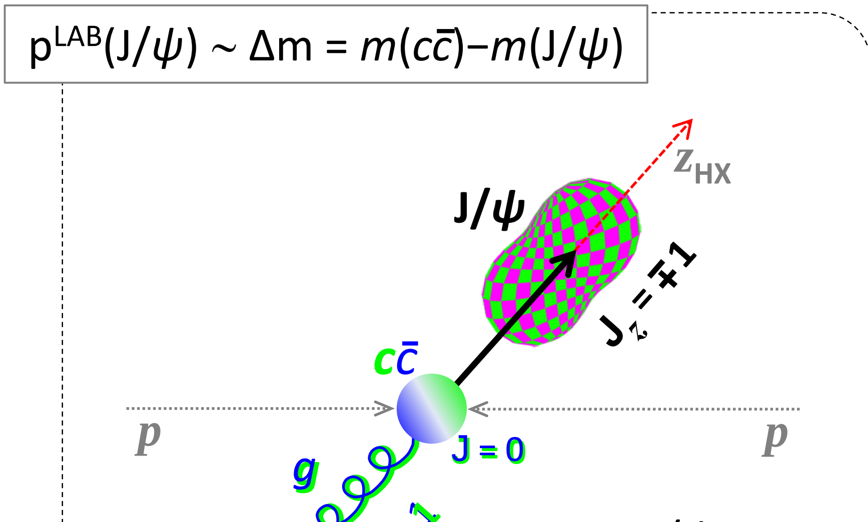
- Polarization is a distinctive and crucial property of quarkonium
  - Only a "fortunate" ***mixture of subprocesses*** or randomization/smearing effects can lead to a cancellation of ***all three*** observable parameters
    - To measure **zero polarization** would be an exceptionally interesting result...

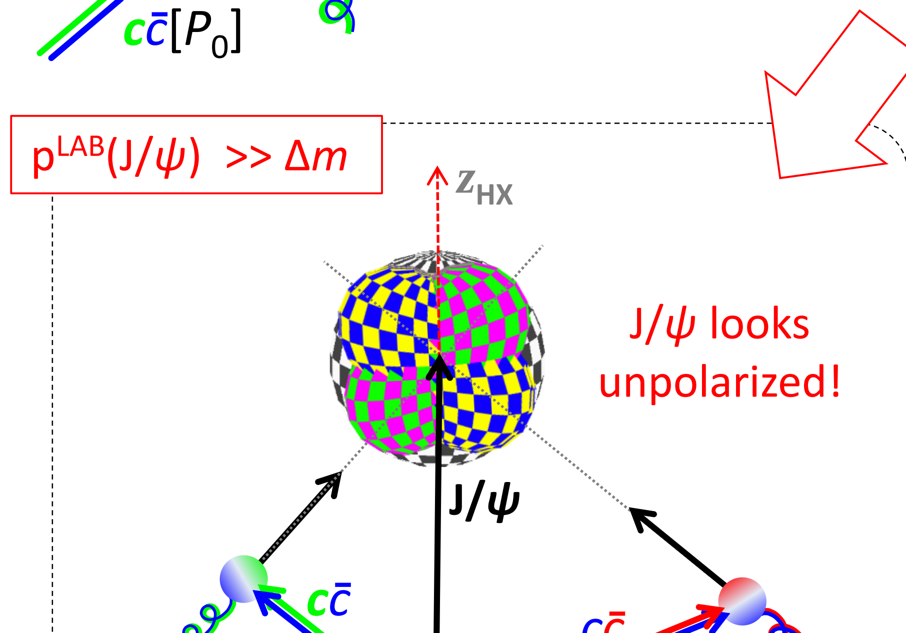
But what would it mean?

Straightforward explanation:
J/ψ evolves from **J = 0** $c\bar{c}$ state

E.g.: $c\bar{c}[P_0] \rightarrow J/\psi\ g$







Eventual implications:

- quarkonium would acquire its characteristic quantum numbers only while evolving to its final bound-state configuration, losing memory of its embryo partonic state
- colour singlet model would be ruled out
- NRQCD β_Q-scaling rules (now favouring J =1 $\rightarrow$ J =1) should be reconsidered
- (strong constraint on quarkonium nuclear absorption models...)

Polarization measurements are complex

Example: how to test the “unpolarized” quarkonium scenario?

1) is the distribution really isotropic?

   → measure the **full** decay distribution (not only its polar projection)

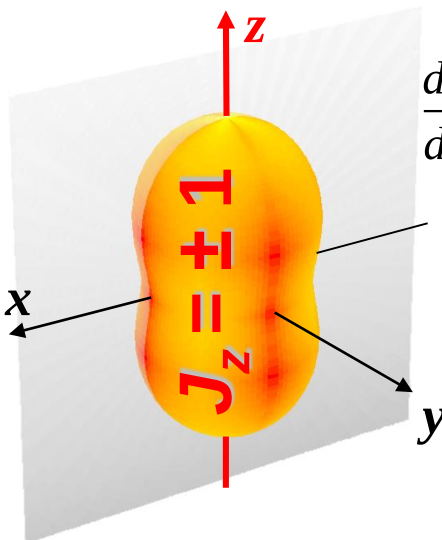
2) is there a mutual cancellation between different processes?

   → isolate different production mechanisms as much as possible

The azimuthal anisotropy is not a detail

Most existing measurements ignore the azimuthal component of the distribution. This is a mutilation of the measurement!

Case 1: natural transverse polarization

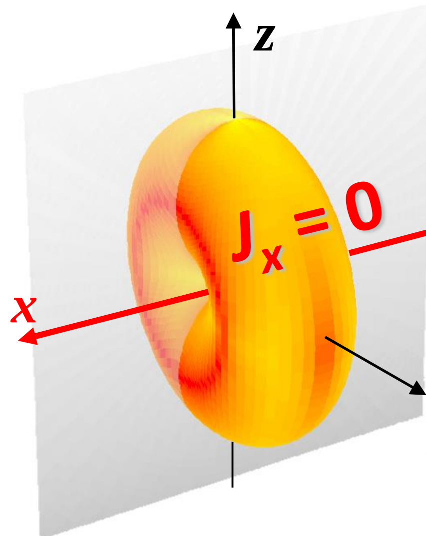


$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta$$

$\lambda_\vartheta = +1$

$\boldsymbol{\lambda_\varphi = 0}$

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



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

$\lambda_\vartheta = +1$

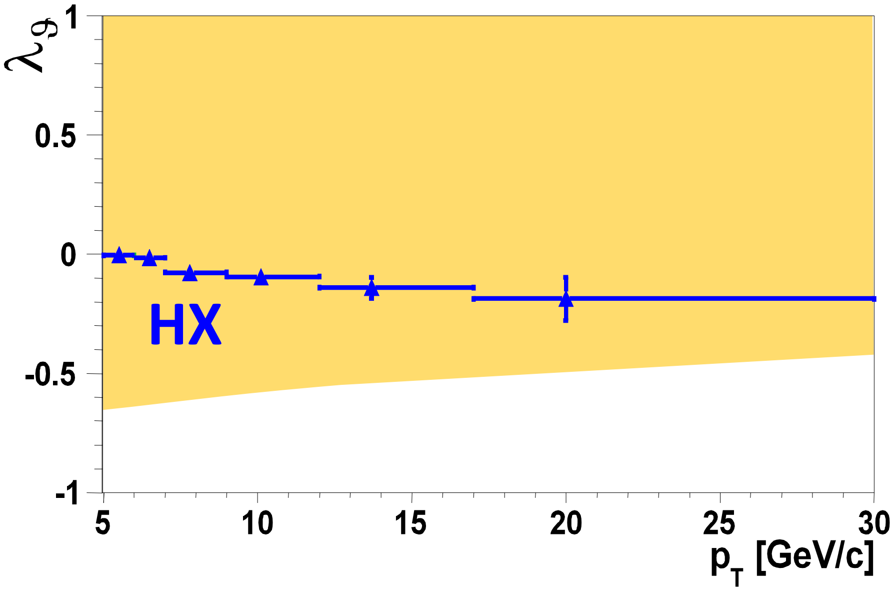
$\boldsymbol{\lambda_\varphi = -1}$

- Two very different (opposite) physical cases, with same $\boldsymbol{\lambda_\vartheta}$
- distinguishable only by measuring $\boldsymbol{\lambda_\varphi}$ (no integration over $\boldsymbol{\varphi}$!)

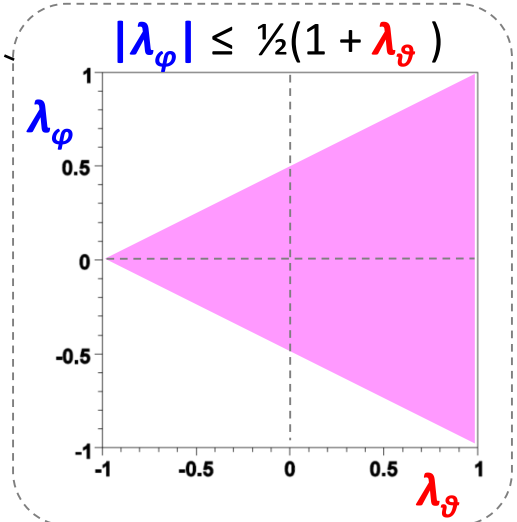
"One-dimensional" analyses give ambiguous results

Has CDF really measured almost unpolarized J/ψ polarization?

For example, what would have they measured in the CS frame ?



CS, for all possible hypotheses on λ_φ^{HX}



The reported weakly *"**longitudinal**"* polarization in the HX frame is perfectly compatible even with a *fully "**transverse**"* polarization in the CS frame !

Without measuring λ_φ we do not fully constrain the polarization state in which the J/ψ is produced

Several very different polarization scenarios can reproduce the CDF measurement, but would be distinguishable in the φ dimension and/or in the CS frame

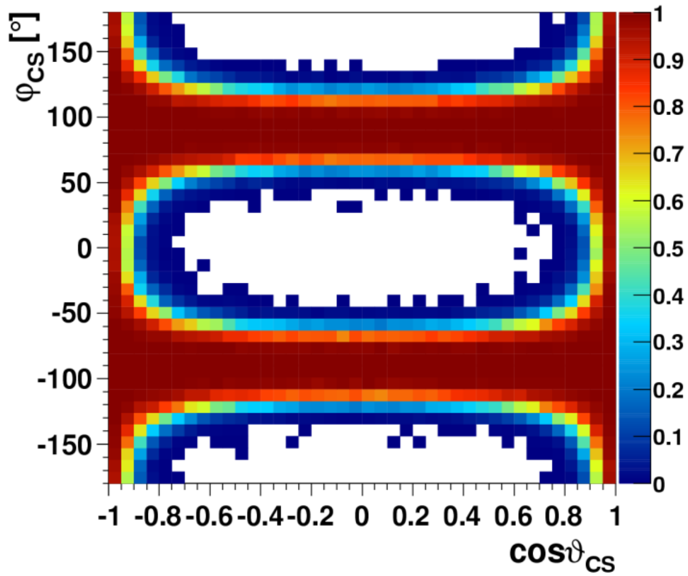
One-dimensional analyses can give *wrong* results

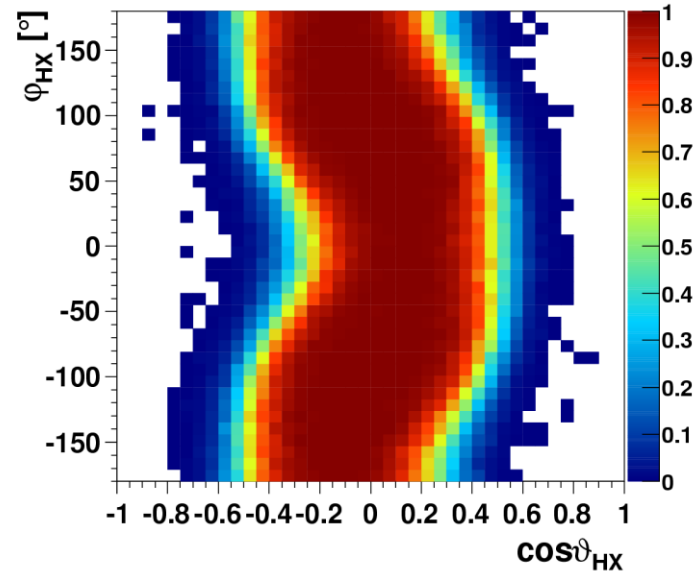
Ignoring the azimuthal dimension is an analysis mistake!

Usually cosϑ and φ "acceptances" are strongly intercorrelated
(CMS case: correlation in the CS frame; experiments with forward spectrometers show an inverted behaviour):

CMS-like toy MC
for 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)

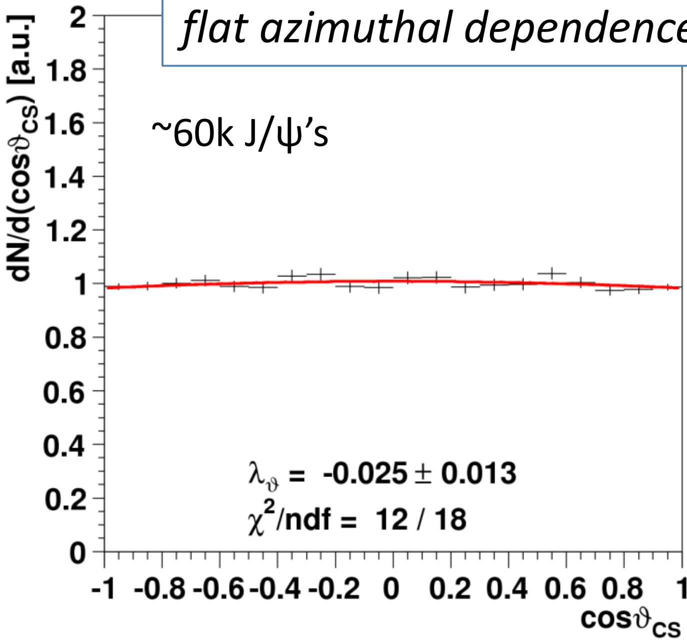
If the φ dimension is integrated out and ignored, the λ_ϑ measurement is strongly dependent on the specific "prior hypothesis" (implicitly) made for the angular distribution (e.g.: flat azimuthal dependence)

One-dimensional analyses can give *wrong* results

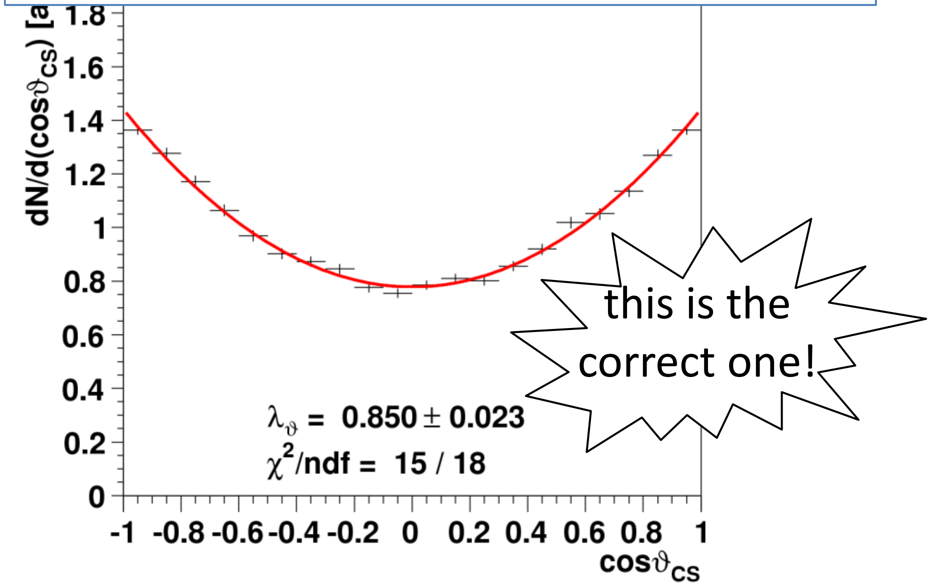
Example scenario:

- *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*



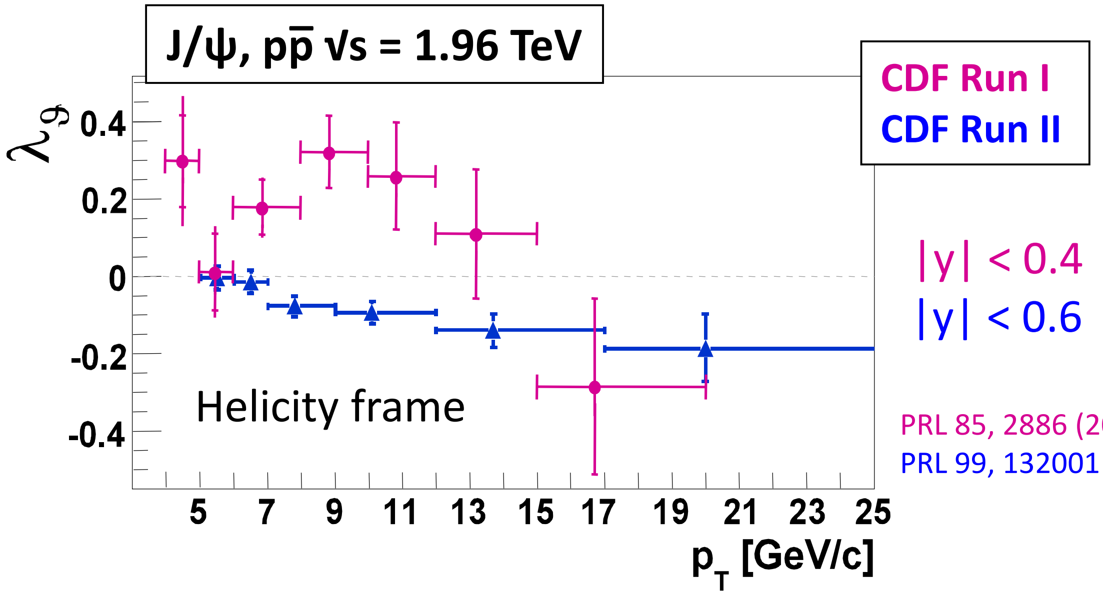
MC *reweighted* to the "true" polarization (a 2D ingredient!), or event-by-event multi-dimensional efficiency correction



If we can / want to only measure a 1D projected distribution, the efficiency description *must*, nevertheless, be maintained multi-dimensional!

Avoid 1D cosϑ "acceptance" corrections or 1D "template" fits, unless the MC is iteratively re-generated with the *correct* φ distribution!

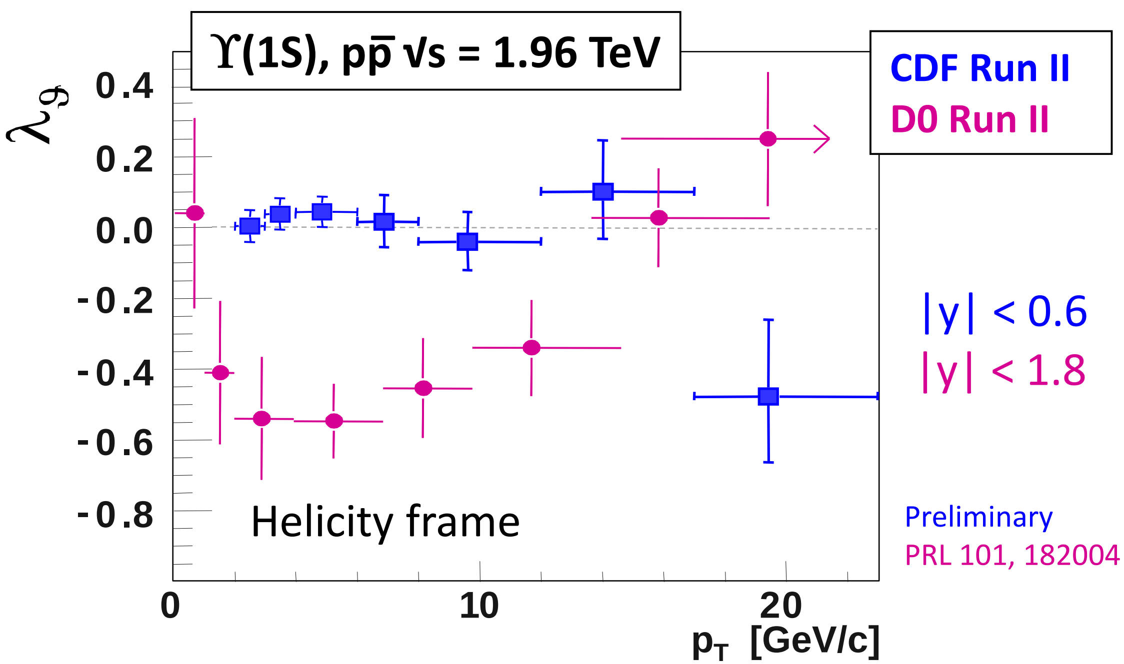
One-dimensional analyses gave *puzzling* results…



|y| < 0.4
|y| < 0.6

PRL 85, 2886 (2000)
PRL 99, 132001 (2007)

- CDF II vs CDF I



|y| < 0.6
|y| < 1.8

Preliminary
PRL 101, 182004 (2008)

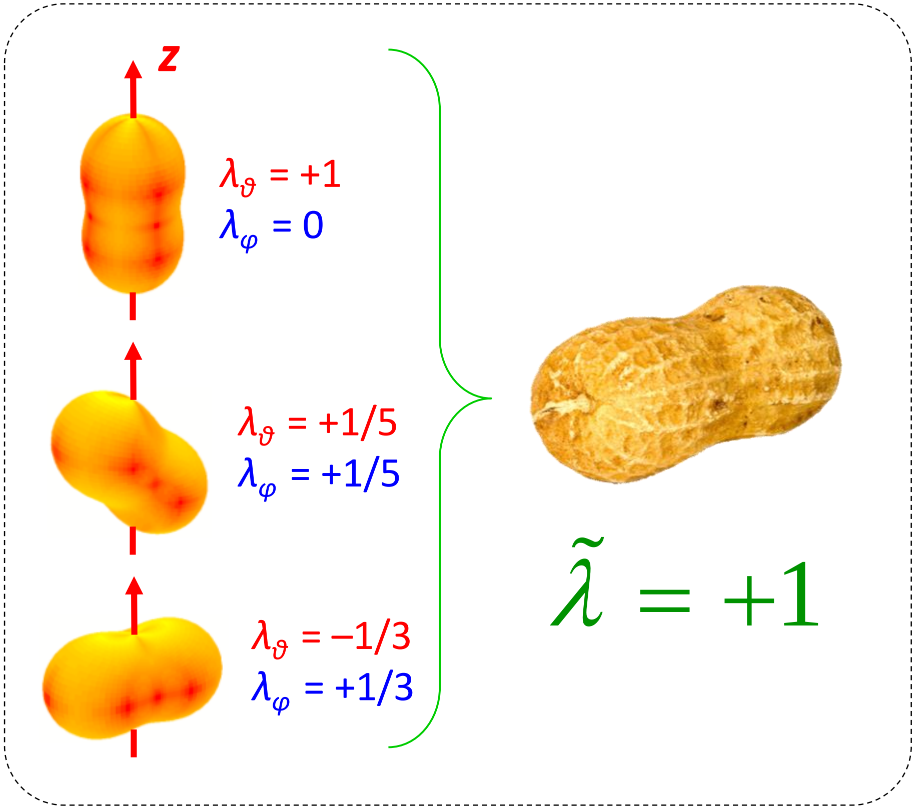
- CDF vs D0

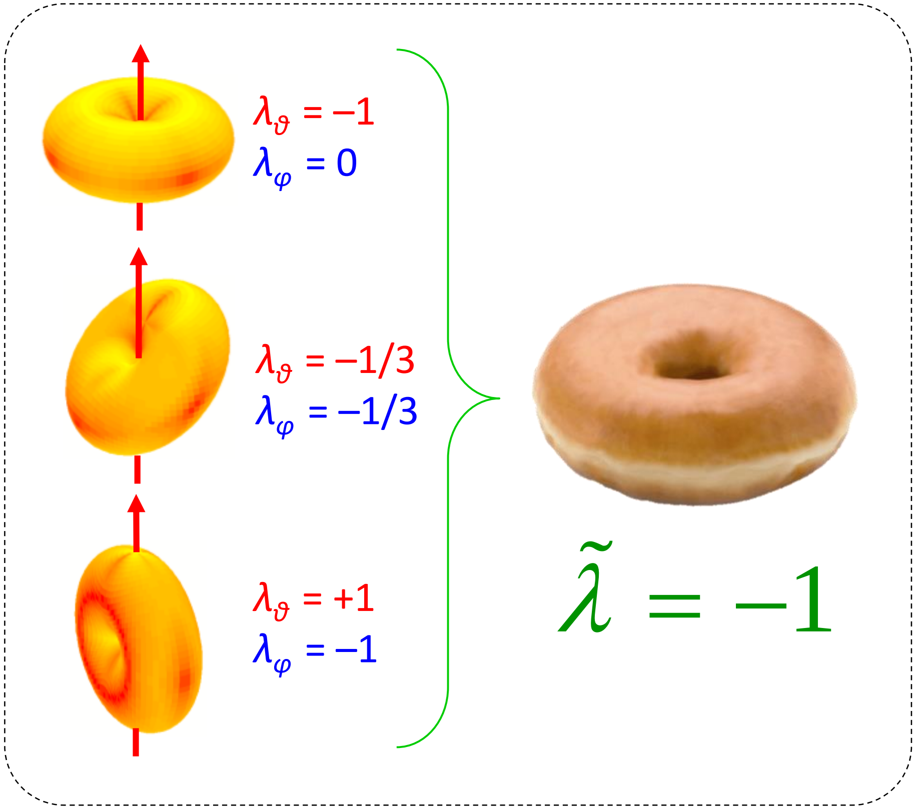
A complementary approach: frame-independent polarization

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

→ it can be characterized by two different frame-independent parameters:

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi} \qquad \lambda^* = \frac{\lambda_\vartheta - 3\Lambda^*}{1 + \Lambda^*} \qquad \text{with } \Lambda^* = \frac{1}{4}\left\{\lambda_\vartheta - \lambda_\varphi \pm \sqrt{\left(\lambda_\vartheta - \lambda_\varphi\right)^2 + 4\lambda_{\vartheta\varphi}^2}\right\}$$



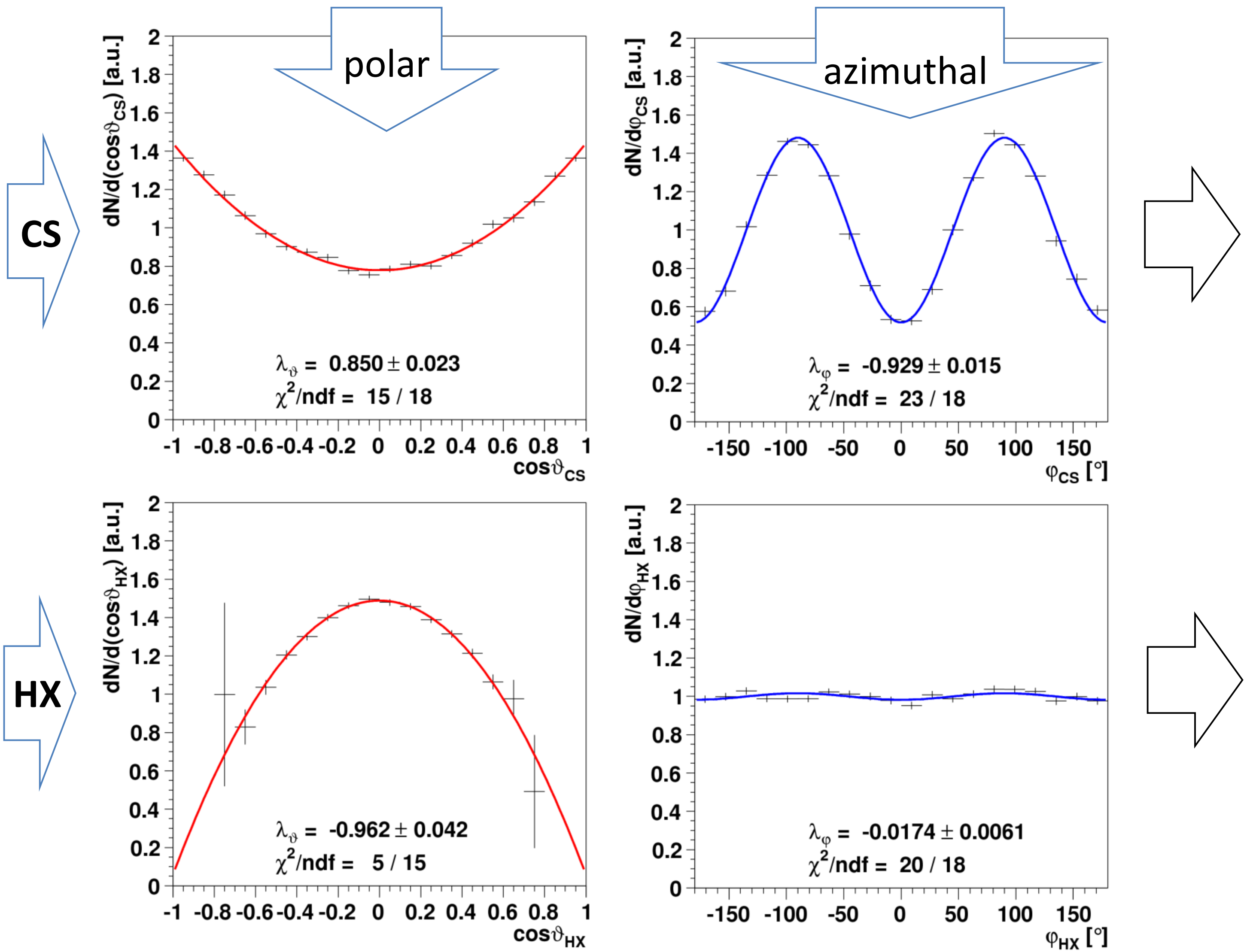


[PRL 105, 061601; PRD 82, 096002; PRD 83, 056008]

Can be used to spot analysis mistakes

Same 1D analysis discussed before, with 1D "acceptance" correction.
Looking at the azimutal dimension and, at the same time, at the results in the HX frame we can spot the mistake by calculating $\tilde{\lambda}$:

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

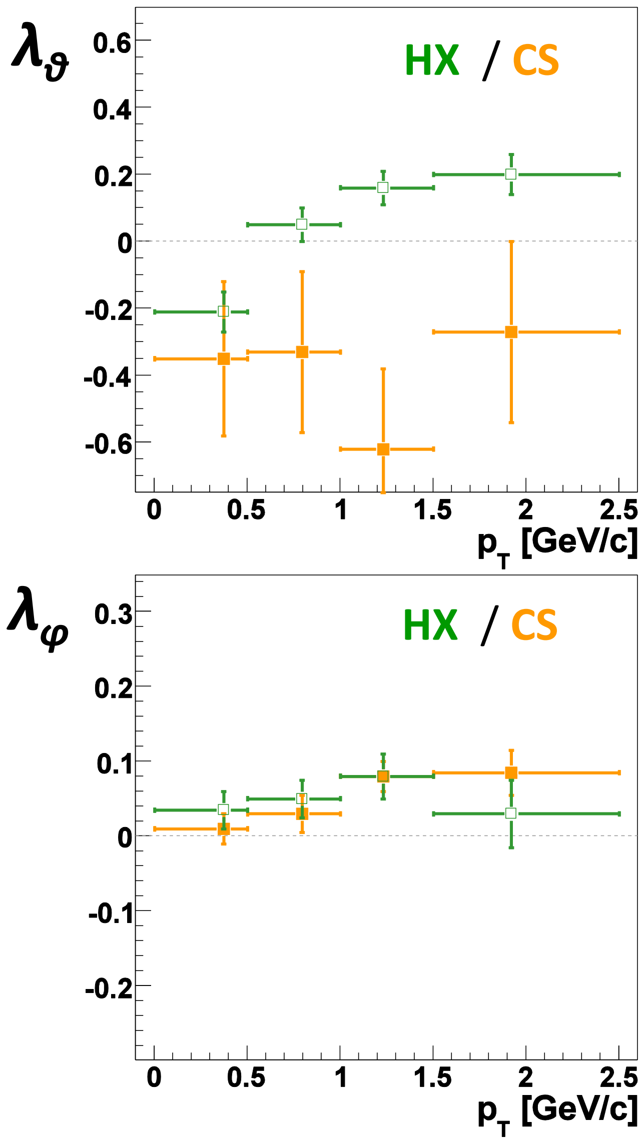


$\tilde{\lambda}_{CS} = -10.032$

correct!

$\tilde{\lambda}_{HX} = -10.093$

Enables cross-checks of experimental results



Experiment XYZ presented at conferences J/ψ polarizations results in two frames

At that time (< 2010) the frame-invariant relations were not known...

Today we can ask ourselves:
is this a self-consistent pattern?

$\tilde{\lambda}$(HX) – $\tilde{\lambda}$(CS) = **0.49** on average

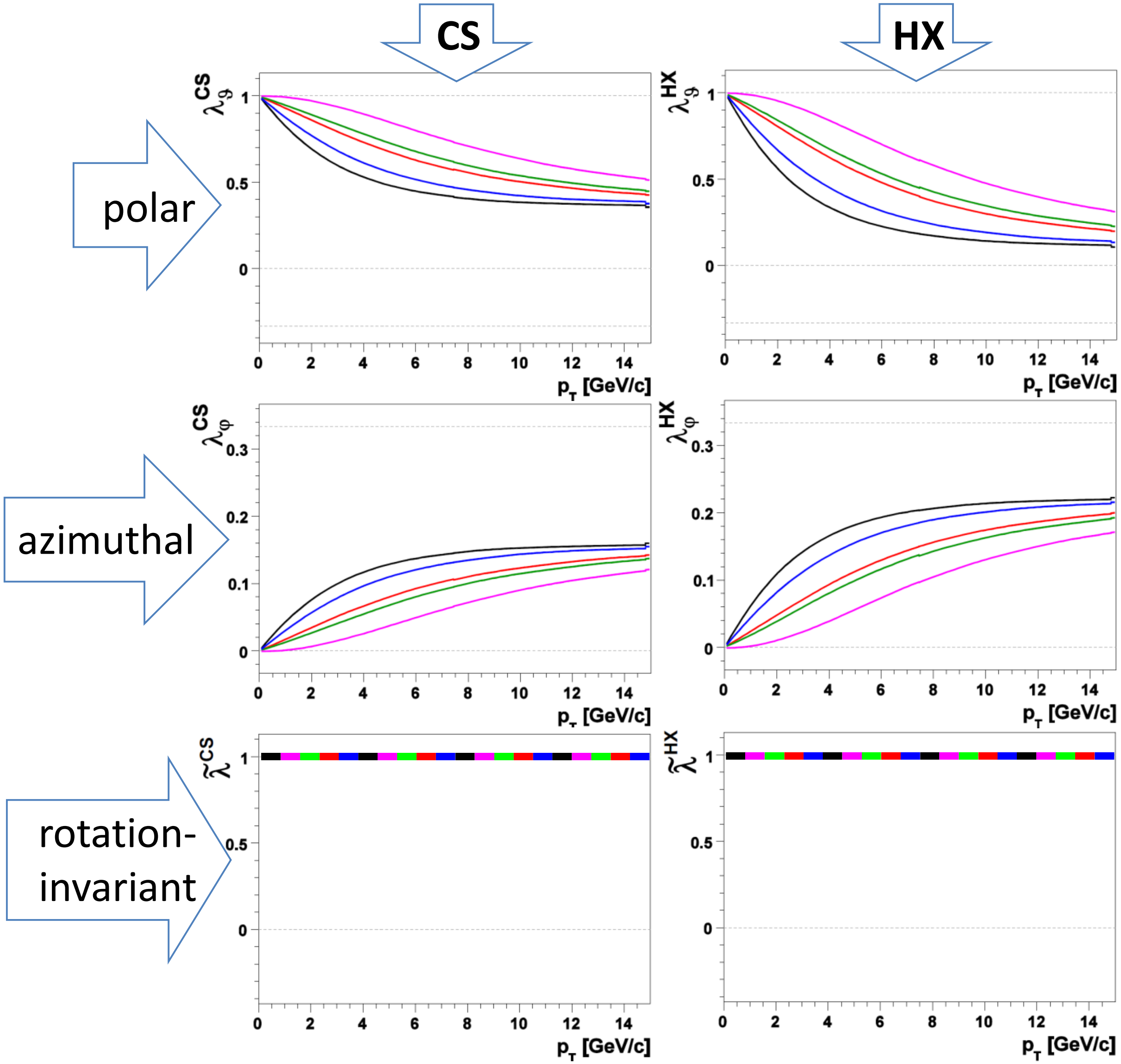
→ unaccounted systematic error of at least this magnitude...

Minimizes 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	$\lvert y \rvert < 0.6$
D0	$\lvert y \rvert < 1.8$
ATLAS/CMS	$\lvert y \rvert < 2.5$
ALICE e^+e^-	$\lvert y \rvert < 0.9$
ALICE $\mu^+\mu^-$	$-4 < y < -2.5$
LHCb	$2 < y < 5$

- Immune to “extrinsic” kinematic dependencies

→ *less acceptance-dependent*

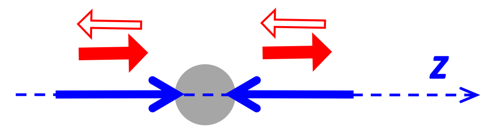
→ *facilitates comparisons*

- *useful as closure test*

Physical example: Drell-Yan, *Z* and *W* polarizations

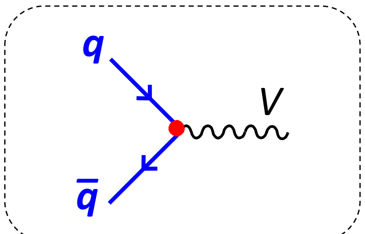
- *always fully* ***transverse*** polarization
- but with respect to a *subprocess-dependent quantization axis*

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



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

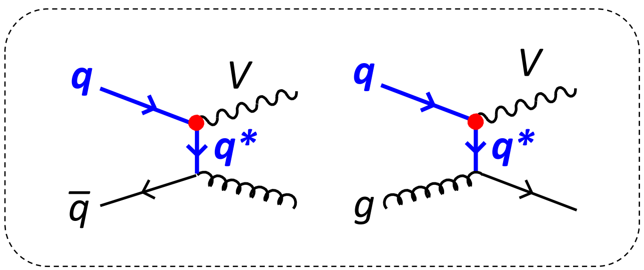
$O(\alpha_S^0)$



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

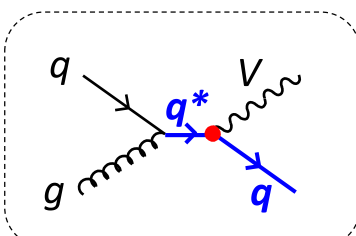
$\tilde{\lambda} = +1$

$O(\alpha_S^1)$
QCD corrections



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

$\tilde{\lambda} = +1$



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

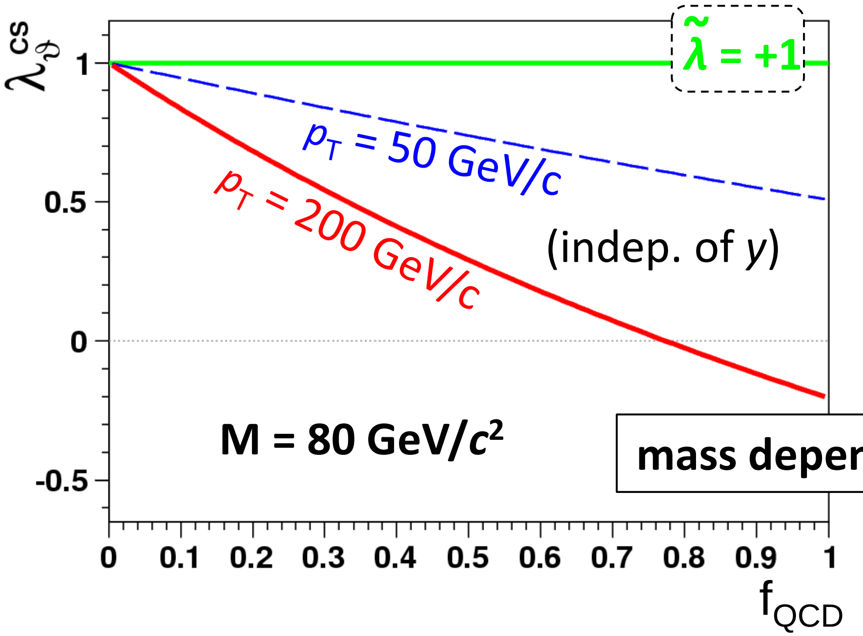
$\tilde{\lambda} = +1$

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

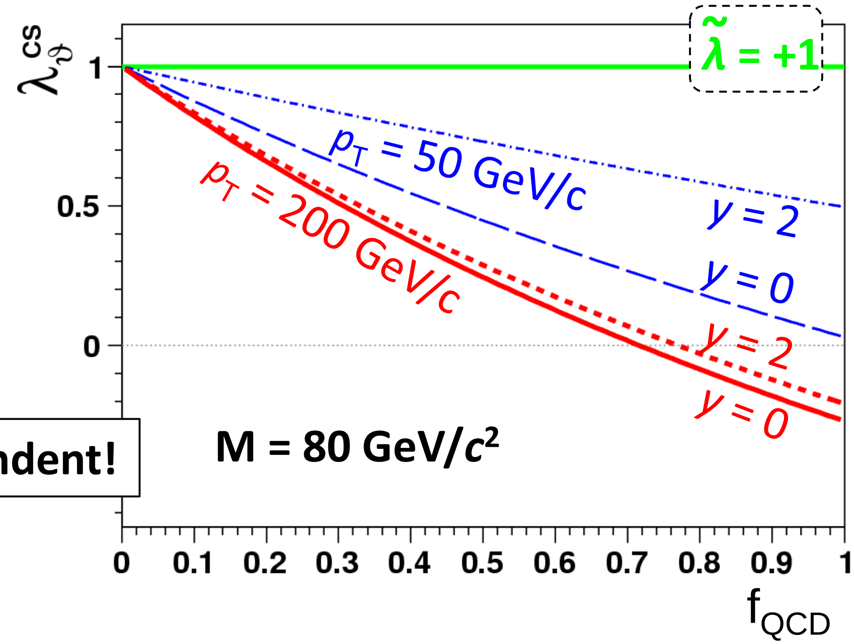
λ_ϑ vs $\tilde{\lambda}$

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

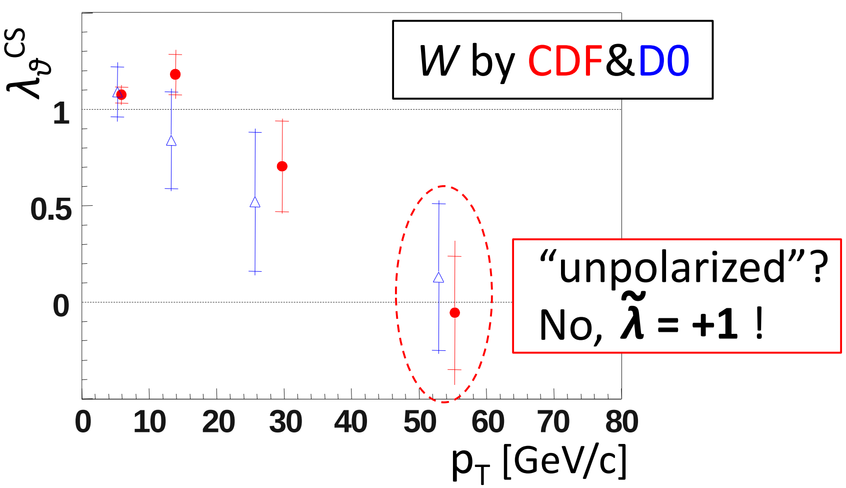
Case 1: dominating ***q-qbar*** QCD corrections



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



mass dependent!



λ_ϑ

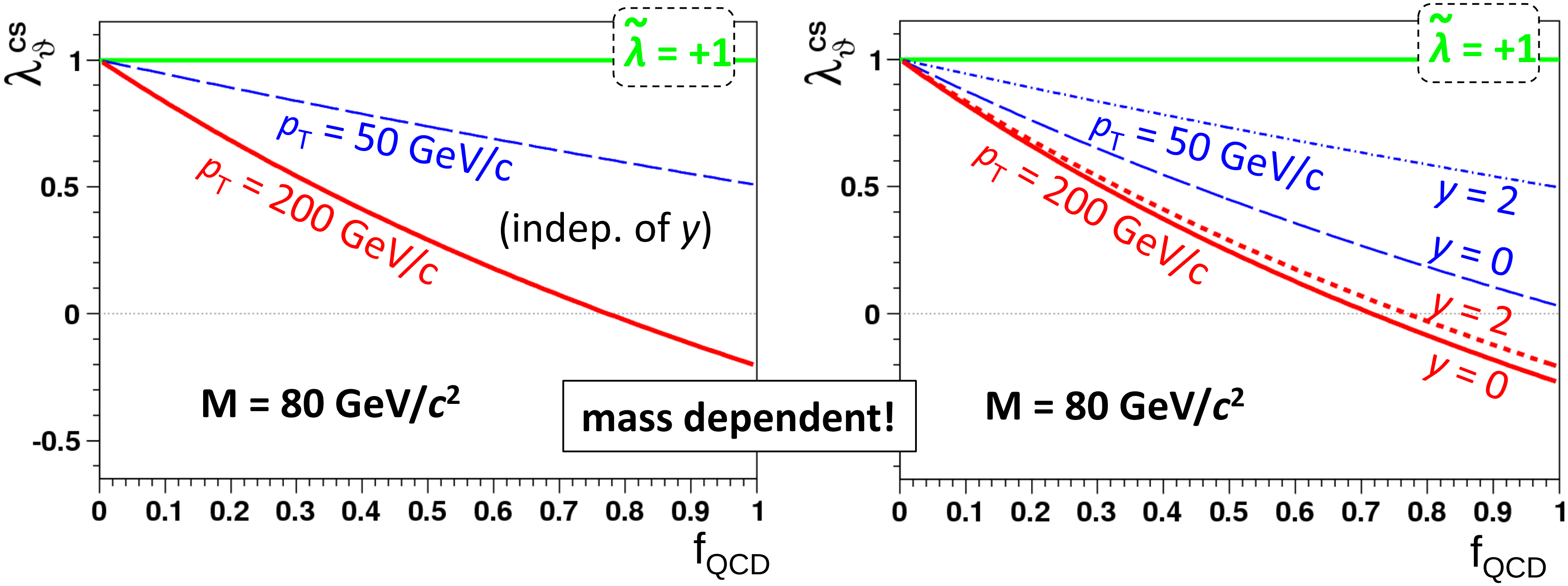
- depends on p_T , y and mass
  $\rightarrow$ by integrating we lose significance
- is far from being maximal
- depends on process admixture
  $\rightarrow$ need pQCD and PDFs

$\tilde{\lambda}$ 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.
In this case, this information is crucial if we want to **disentangle the *qg* contribution**, the only one giving maximum spin-alignment along the boson momentum, resulting in a ***rapidity-dependent λ_ϑ***

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

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, PRD 18, 2447 (1978)

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

Today we know that it is only a special case of general frame-independent polarization relations (LIP, 2010), when the intrinsic polarization is transverse:

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

The Lam-Tung relation is simply a consequence of

1) rotational invariance

2) specific properties of fundamental couplings (vector boson – quark – quark vertices)

Beyond the Lam-Tung relation

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

$$\left.\begin{array}{l} \tilde{\lambda} \ll +1 \\ \tilde{\lambda} > +1 \end{array}\right\}$$

→ contribution of ***different/new couplings or processes***

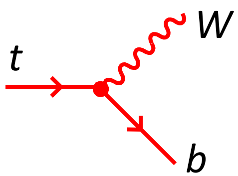
(e.g.: *Z* from Higgs, *W* from top, triple *ZZ*γ coupling, higher-twist effects in DY production, etc…)

e.g.: *W* from top ↔ *W* from *q*-*q*bar and *q*-*g*

longitudinally polarized:

$\lambda_{\vartheta}^{\mathrm{SM}} \cong -0.65$
$\lambda_{\varphi}^{\mathrm{SM}} \cong 0$

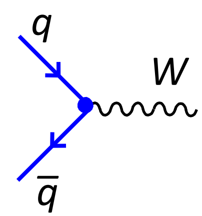
wrt *W direction in the top rest frame* (top-frame helicity)



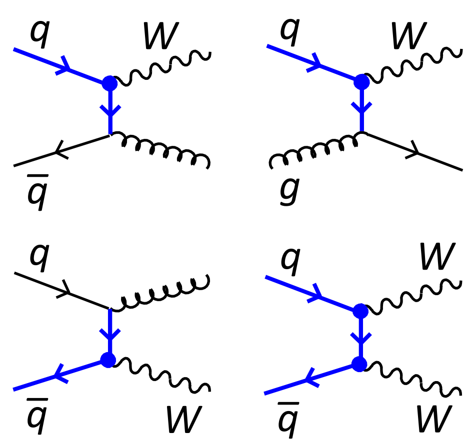
independently of top production mechanism

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

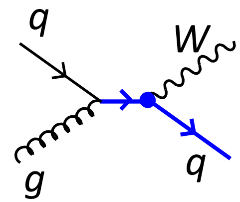
transversely polarized,
$\lambda_{\vartheta} = +1$ & $\lambda_{\varphi} = 0$ *wrt 3 different axes:*



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



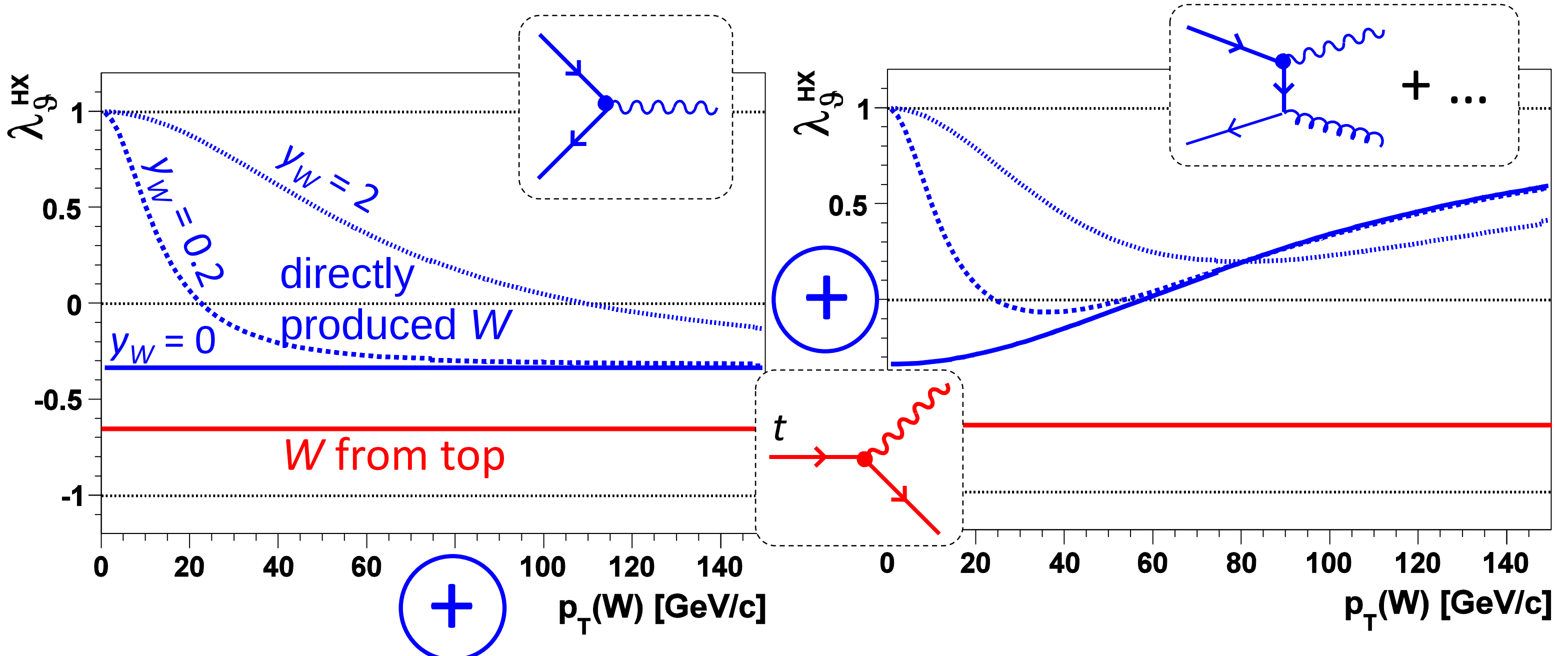
direction of *q* or *q*bar (Gottfried-Jackson)

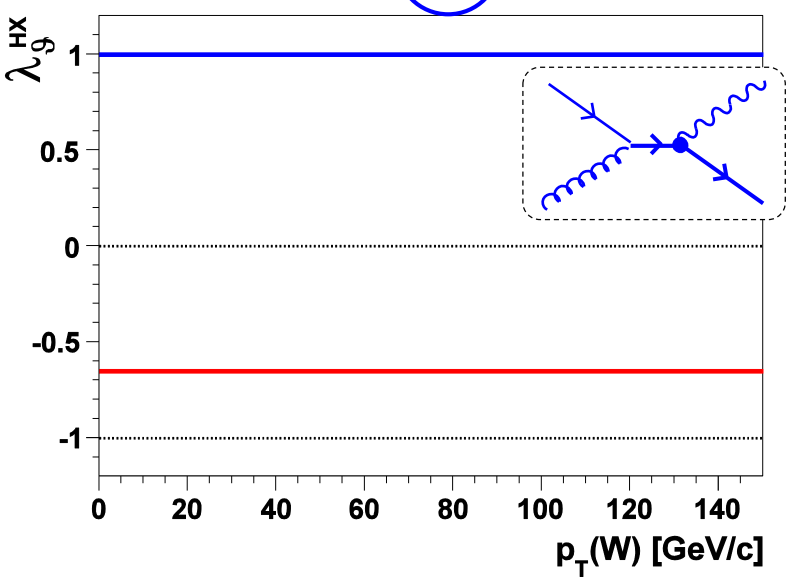


direction of outgoing *q* (cms-helicity)

a) Frame-dependent approach

We measure λ_ϑ choosing the helicity axis defined wrt the top rest frame

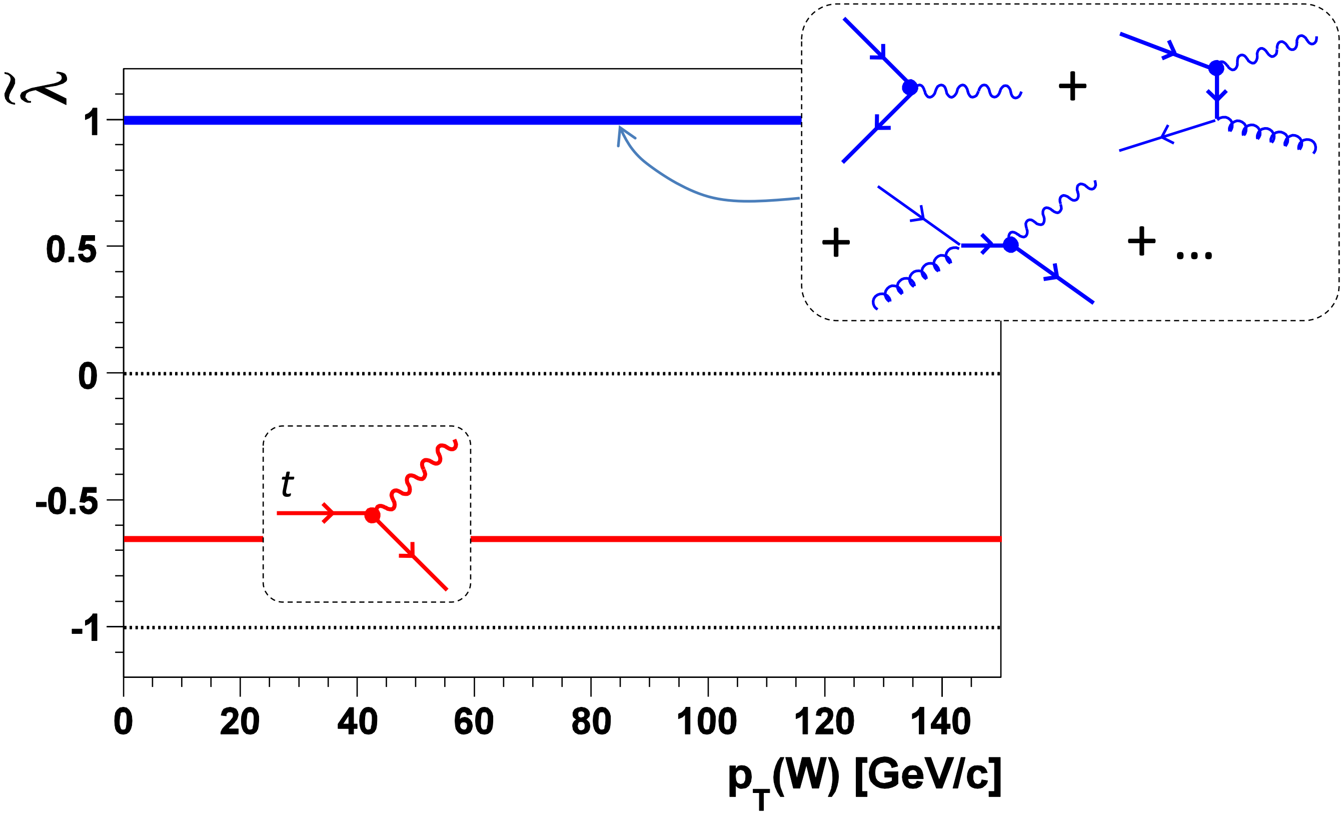




The polarization of *W from q-qbar / q-g*

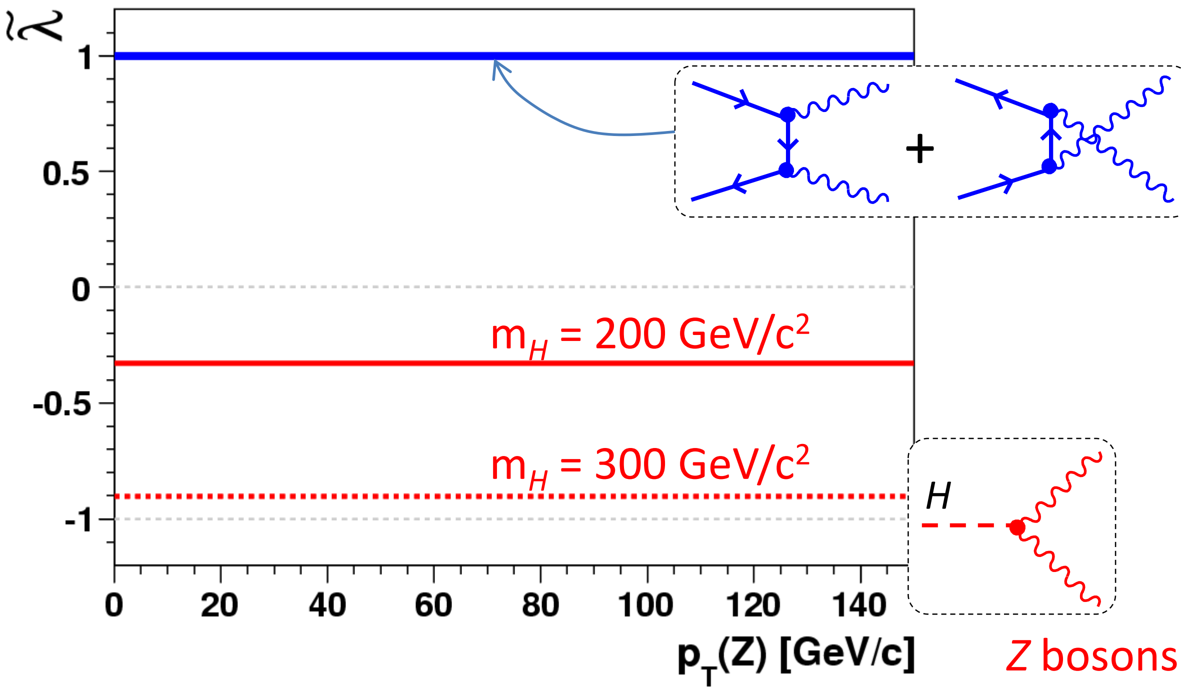
- depends on the actual mixture of processes
  $\rightarrow$ we need pQCD and PDFs to evaluate it
- depends on p_T and y
- is generally far from being maximal
  $\rightarrow$ significant λ_φ

b) Rotation-invariant approach



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

e.g.: *Z* from Higgs ↔ *Z* from *q*-*q*bar and *q*-*g*



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

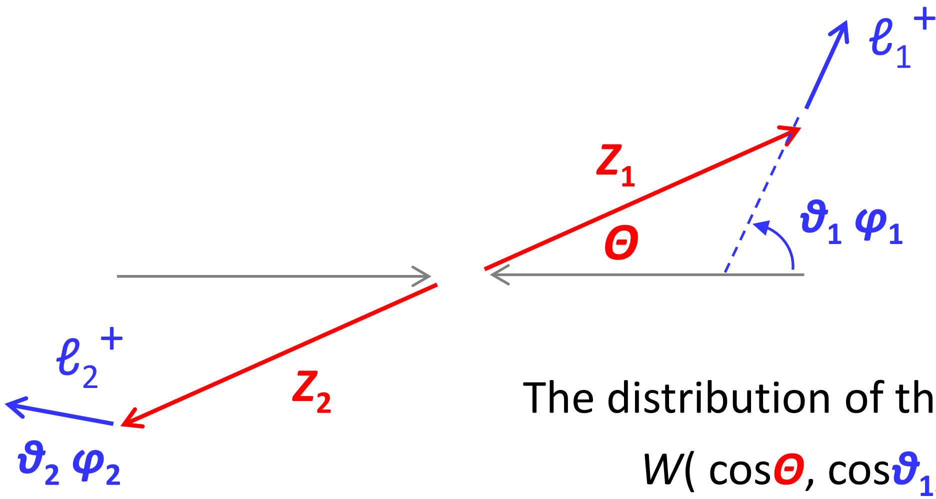
Z bosons from $H \to ZZ$ are **longitudinally** polarized (stronger polarization for heavier *H*)

Using polarization to identify processes

The polarization reflects directly the production mechanism
→ in certain situations it can be used to distinguish “signal” and “background” processes

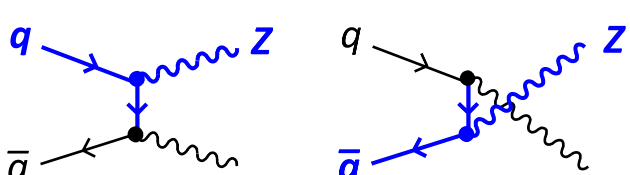
Example: polarization discriminants of *ZZ* from *q*-*q*bar

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



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

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

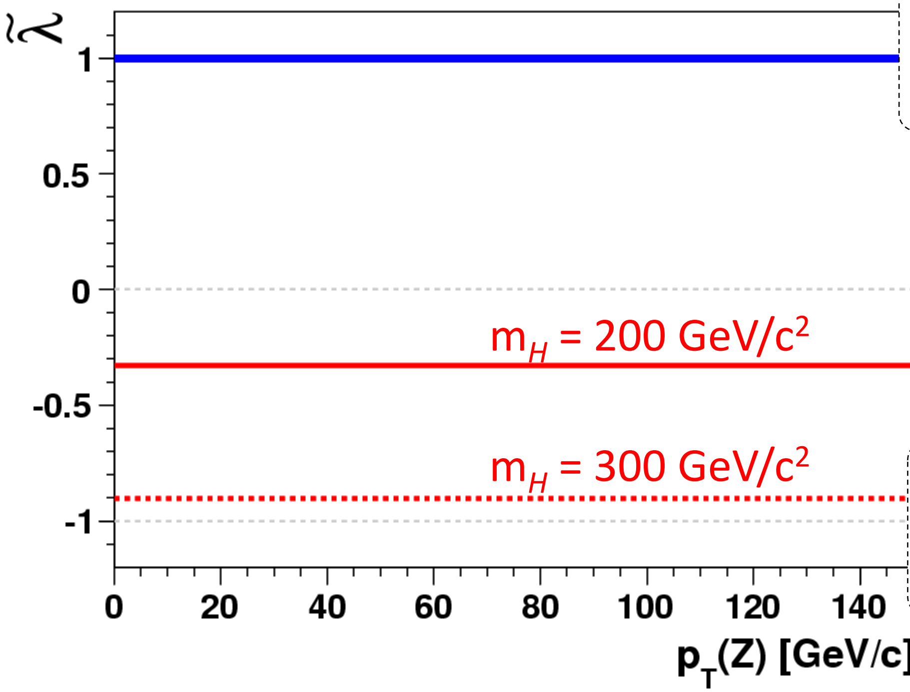


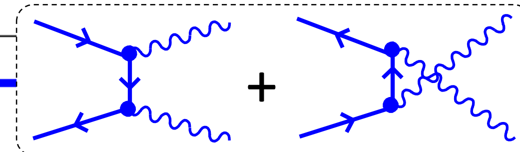
t-channel u-channel

- for helicity conservation each of the two *Z's* is transverse along 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 $M_Z/M_{ZZ} \to 0$

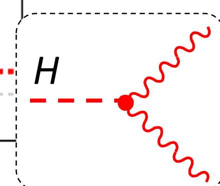
ZZ from Higgs ↔ ZZ from q-$q$bar

Discriminant nº1: ***Z* polarization**





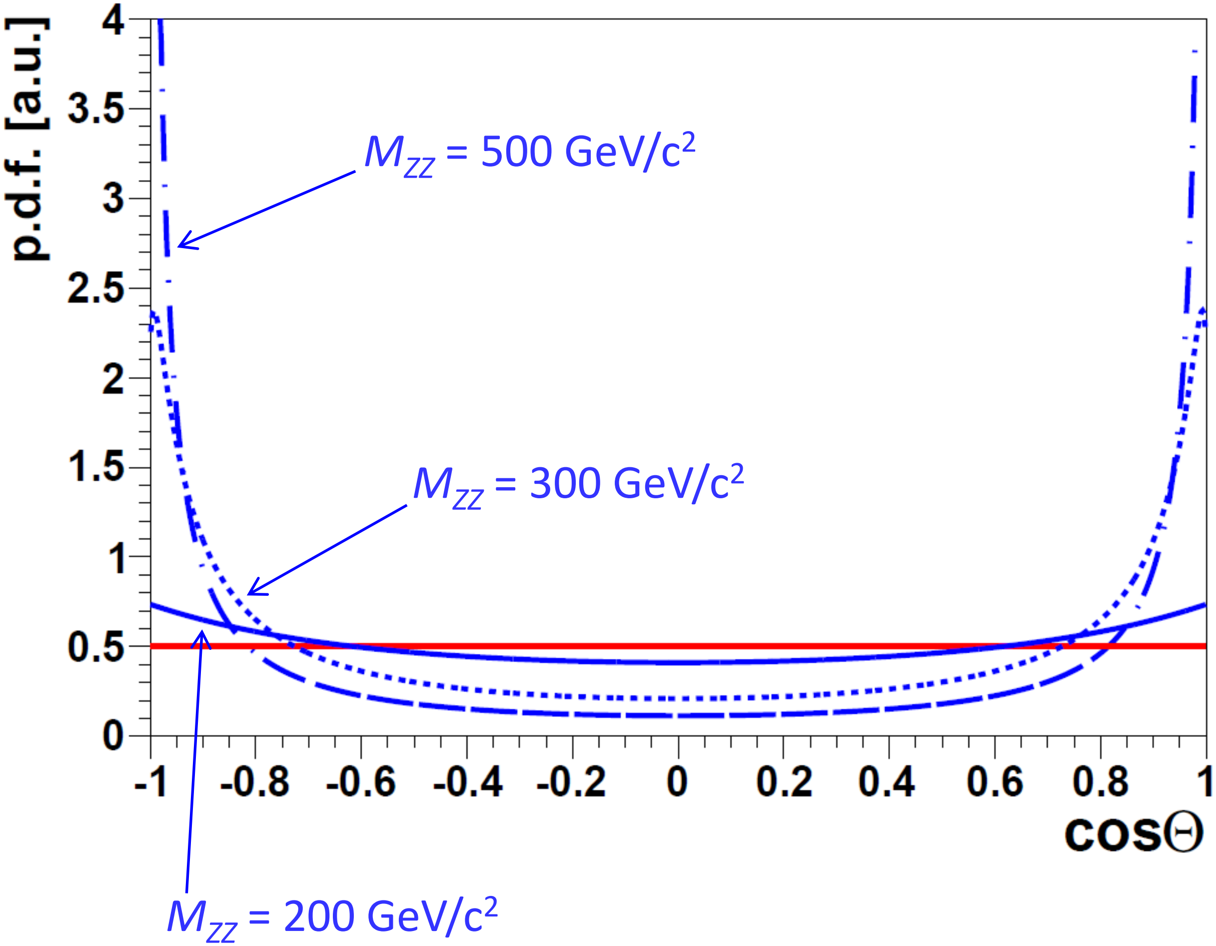
The *invariant* polarization of *Z* from *q*-*q*bar is fully **transverse**

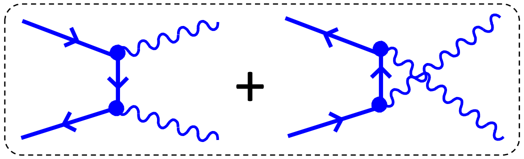


Z bosons from *H* → *ZZ* are **longitudinally** polarized (stronger polarization for heavier *H*)

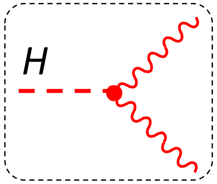
Z Z from Higgs ↔ Z Z from q-qbar

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

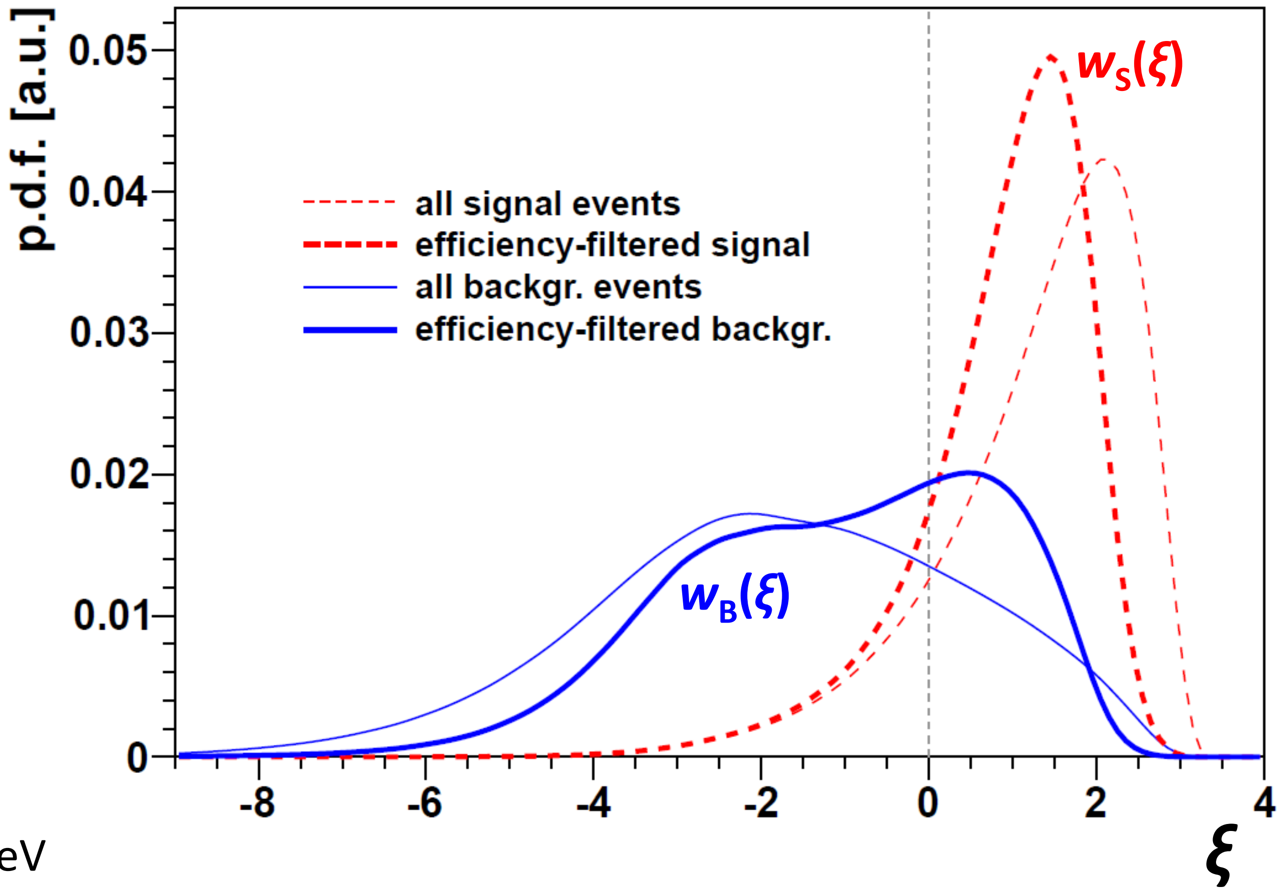
5 angles (Θ, ϑ_1, φ_1, ϑ_2, φ_2), with distribution depending on
5 kinematic variables (M_{ZZ}, $p_T(Z_1)$, $y(Z_1)$, $p_T(Z_2)$, $y(Z_2)$)

$$\Downarrow$$

1 shape discriminant:

$$\xi = \ln\left(\frac{W_{H\to ZZ} \times (A\varepsilon)_{H\to ZZ}}{W_{q\bar{q}\to ZZ} \times (A\varepsilon)_{q\bar{q}\to ZZ}} \times \underbrace{\frac{\int W_{q\bar{q}\to ZZ} \times (A\varepsilon)_{q\bar{q}\to ZZ}\, d\vec{p}(Z_1)d\vec{p}(Z_2)}{\int W_{H\to ZZ} \times (A\varepsilon)_{H\to ZZ}\, d\vec{p}(Z_1)d\vec{p}(Z_2)}}_{\text{normalization factor (optional)}} \right)$$

ξ distribution for signal and background



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

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

Likelihood definitions

μ_B = avg. number of BG events expected for the given luminosity

μ_S = avg. number of Higgs events expected for the given luminosity

β = ratio of observed / expected signal events

N = total number of events in the sample

1) $$\mathcal{L}_{\text{BGnorm}}(\beta) \propto \frac{e^{-(\mu_B + \beta\,\mu_S)}\,(\mu_B + \beta\,\mu_S)^N}{N!}$$

usual "counting experiment" constraint

signal = excess
wrt expected BG events

2) $$\mathcal{L}_{\text{angular}}(\beta) = \prod_{i=1}^{N} \left(\frac{\mu_B}{\mu_B + \beta\,\mu_S} w_B(\xi_i) + \frac{\beta\,\mu_S}{\mu_B + \beta\,\mu_S} w_S(\xi_i) \right)$$

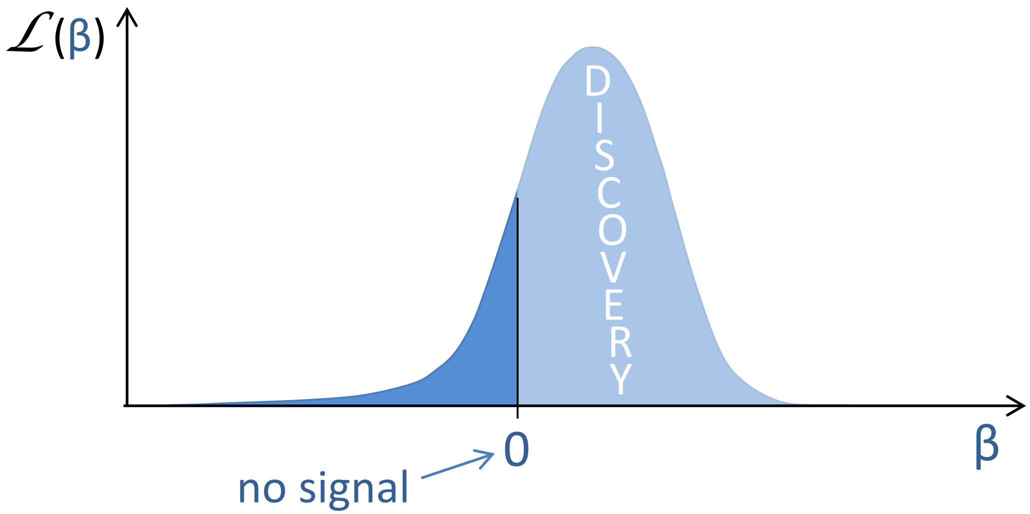
constraint from
angular distribution

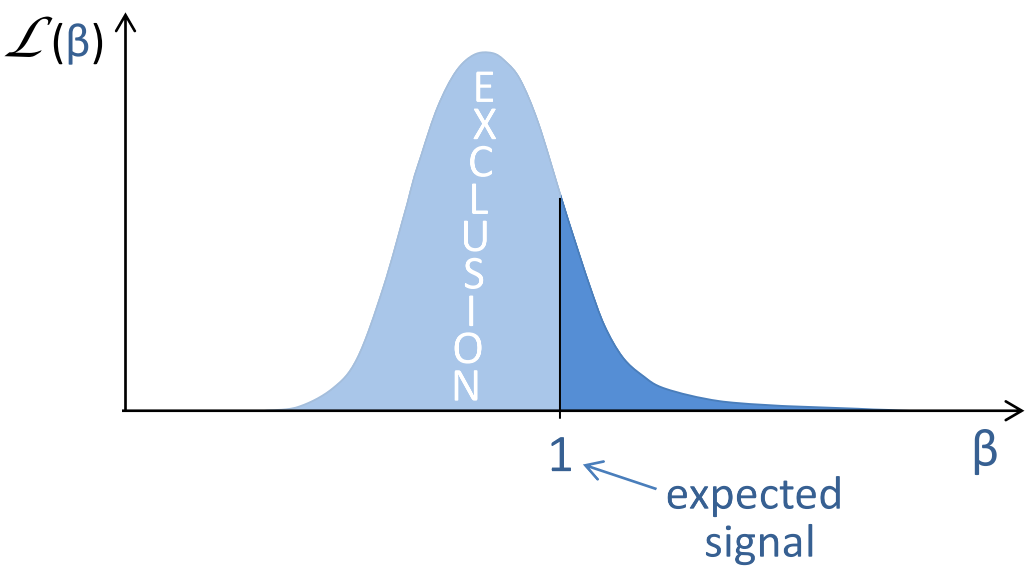
signal = deviation from the *shape* of the BG angular distribution.
Constraint independent of luminosity and cross-section uncertainties
and reasonably immune from look-elsewhere effect

3) $$\mathcal{L}_{\text{tot}}(\beta) = \mathcal{L}_{\text{angular}}(\beta) \times \mathcal{L}_{\text{BGnorm}}(\beta)$$

combination of the two

Confidence levels

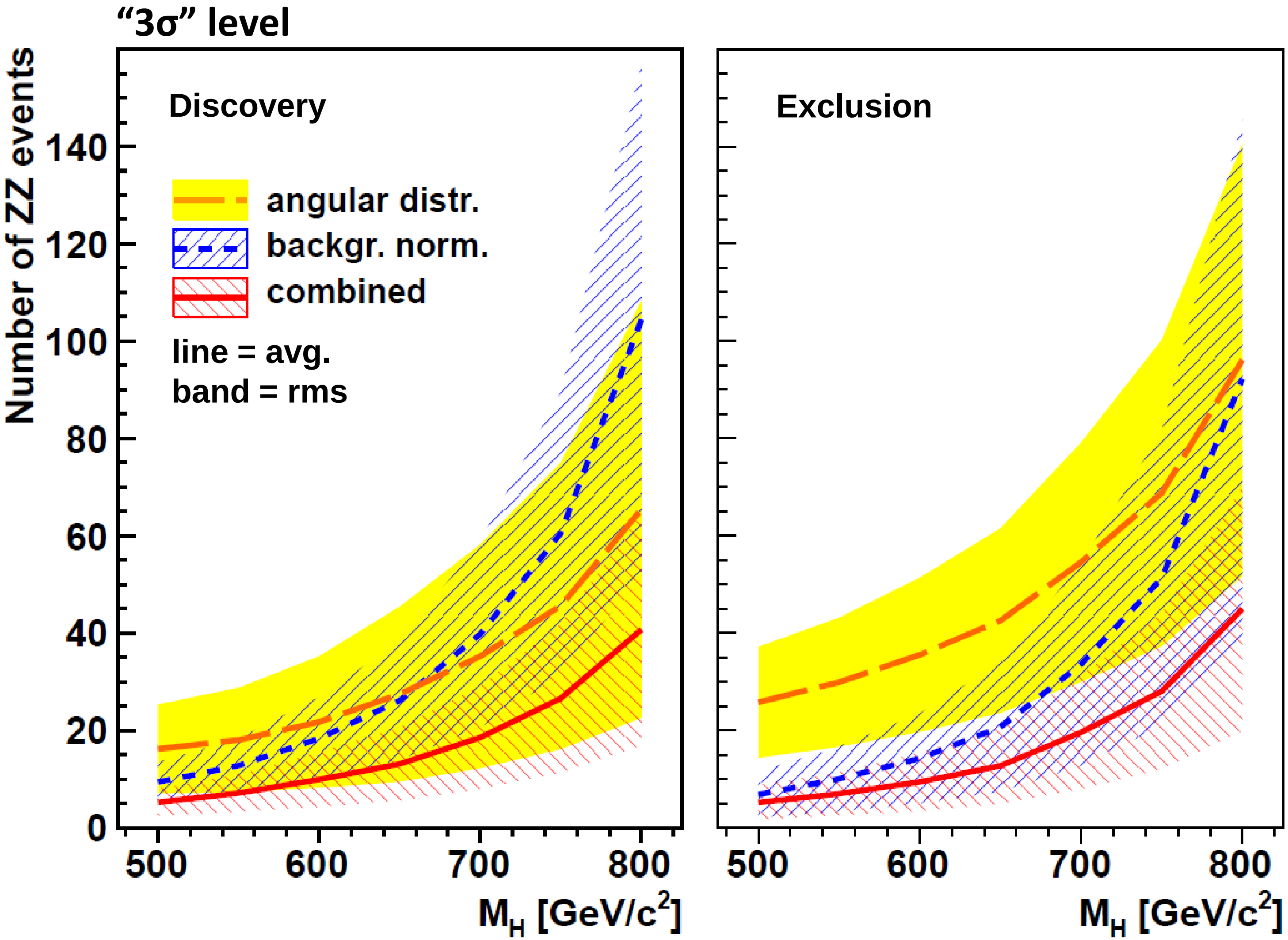




Procedure

- many thousands of toy experiments with varying “luminosity”
- pseudo-data generated in two hypotheses: 1) signal = expected $\rightarrow$ discovery limits
  2) no signal $\rightarrow$ exclusion limits
- SIG and BG defined in the ZZ invariant mass range ± 1 width around m_H
  e.g.: $500 < M_{ZZ} < 900$ GeV/c^2 for $M_H = 700$ GeV/c^2
- ZZ and Higgs kinematics and cross-sections for $\sqrt{s} = 14$ TeV in $|y_{ZZ}| < 2.5$
- experimental filter simulated as: $p_T(\ell) > 15$ GeV/c
  $|\eta(\ell)| < 2.5$

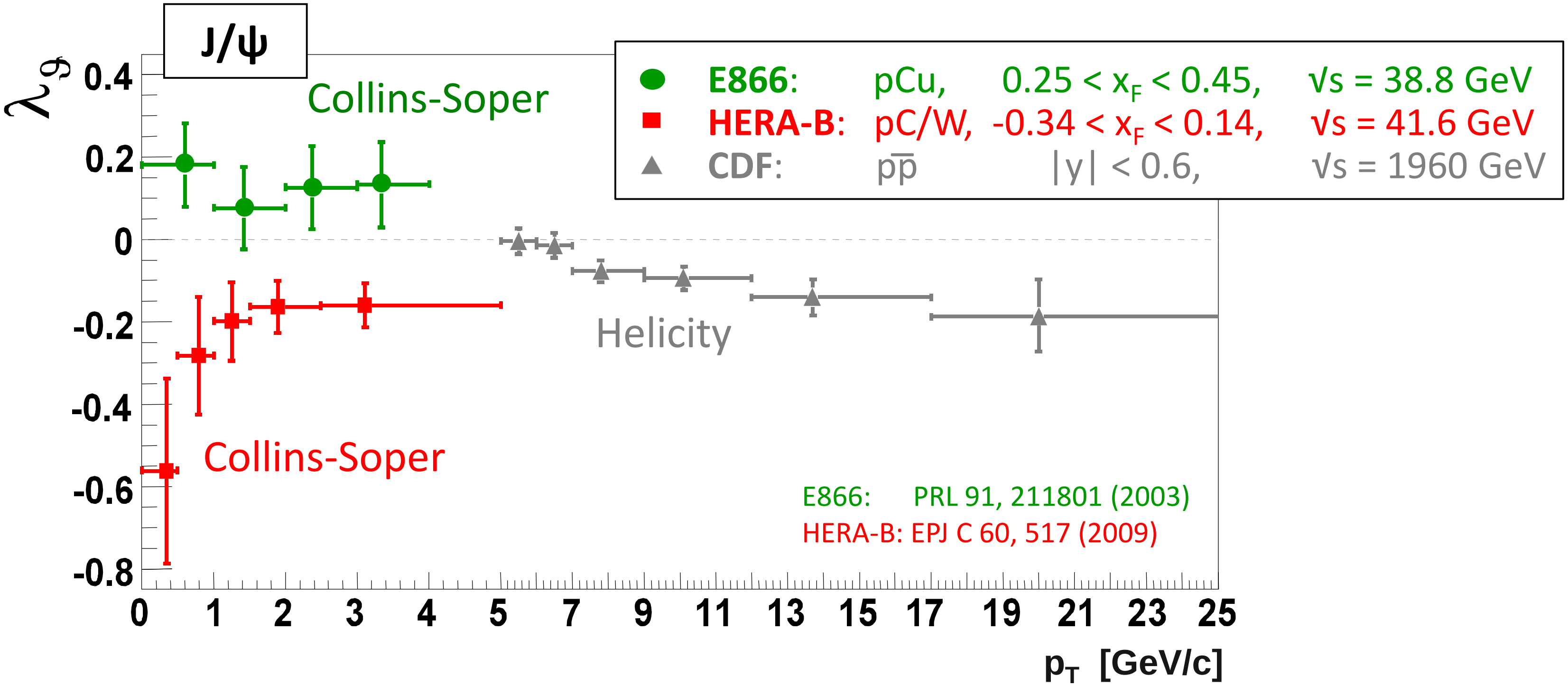
Limits vs m_H



Variation with mass essentially due to varying BG level:
30% for m_H = 500 GeV/c^2 $\rightarrow$ 70% for m_H = 800 GeV/c^2
Angular method more advantageous with higher BG levels

Spare slides

Experimental puzzles: J/ψ in proton-nucleus



- **E866** vs **HERA-B**

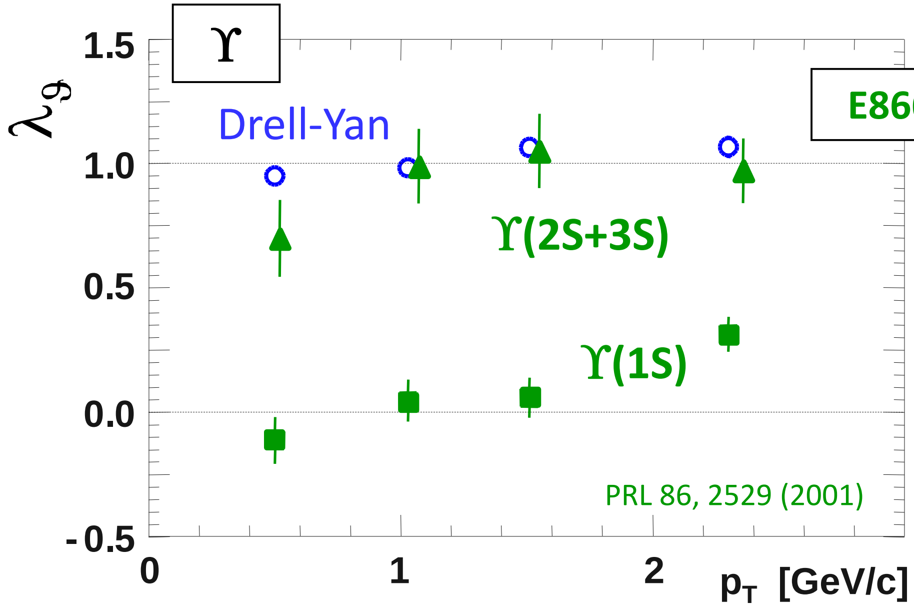
  → *strong p_L dependence?*

- **CDF** vs low-p_T

  → *frame conventions*?

  → nuclear effects?

Experimental puzzles: ϒ in proton-nucleus



E866: pCu, $0 < x_F < 0.6$, $\sqrt{s} = 38.8$ GeV

- **E866** → (≈ directly produced) ϒ(2S+3S) have same polarization as Drell-Yan (***Collins-Soper*** *frame*!)
- E866 **ϒ(1S)** vs **ϒ(2S+3S)** → dominant *feed-down* effects for ϒ(1S)?

Clearest experimental signature !
What indications on ϒ production?

How to test the "unpolarized" quarkonium scenario?

1) is the distribution really isotropic?

→ measure the **full** decay distribution
(not only its polar projection)

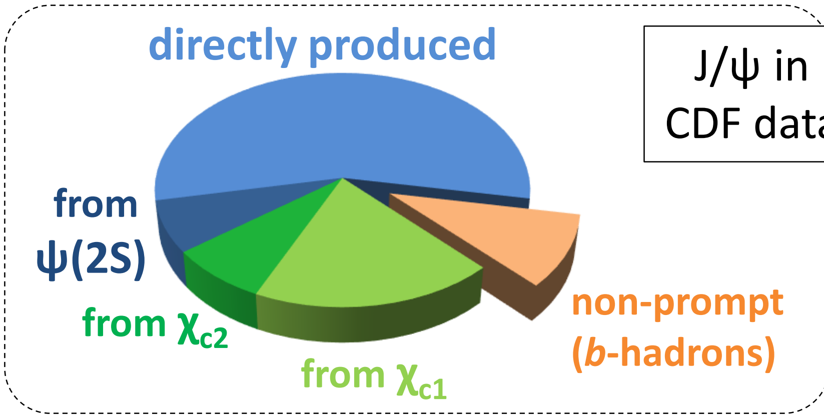
2) is there a mutual cancellation between different processes?

→ isolate different production mechanisms as
much as possible

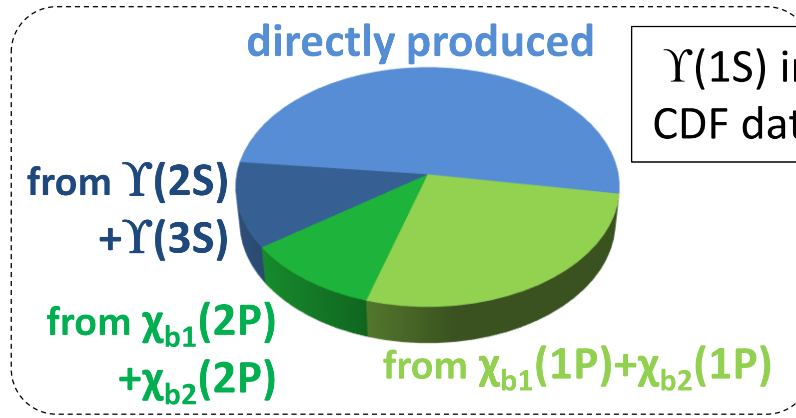
example

Production from decays of heavier quarkonium states

The ***observed prompt J/ψ*** embodies production properties of all charmonium states in a global "average":



Composition of the ***observed*** **ϒ(1S)**:



Polarization transfer in **S-wave → S-wave transitions** is straightforward. E.g.:

polarization of **J/ψ from ψ'** ≅ polarization of **ψ'** ≅ polarization of **direct J/ψ**

di-pion emitted in S-wave state (BES, CLEO)

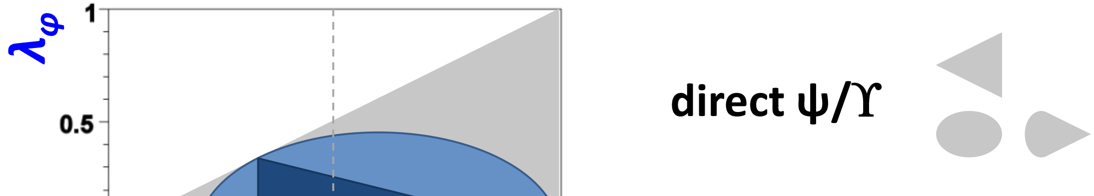
similar production mechanism

P-wave → S-wave transitions are more complex

Direct ψ/ϒ's vs ψ/ϒ's from χ

In general, we expect completely different polarizations for direct ψ/ϒ's and ψ/ϒ's from χ:

- different production mechanisms (both partonic processes and long-distance effects)
- different parameter space of the decay distribution:



Example:

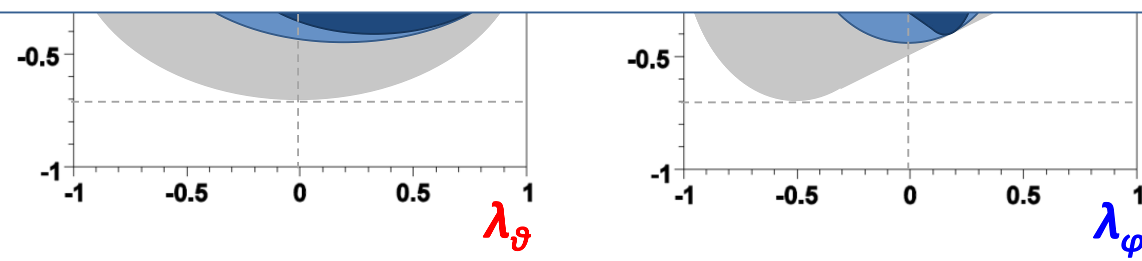
$|\chi_{c1}\rangle = |0\rangle \;\rightarrow\; |J/\psi\rangle = \begin{cases} |+1\rangle \\ |-1\rangle \end{cases} \;\rightarrow\; \boldsymbol{\lambda_\vartheta = +1}$

"longitudinal" χ_{c1} → "transverse" J/ψ

$|\chi_{c1}\rangle = |\pm1\rangle \;\rightarrow\; |J/\psi\rangle = \begin{cases} |+1\rangle + |0\rangle \\ |-1\rangle + |0\rangle \end{cases} \;\rightarrow\; \boldsymbol{\lambda_\vartheta = -1/3}$

"transverse" χ_{c1} → 50% "longitudinal" 50% "transverse" J/ψ

$$\boldsymbol{-1/3 \;<\; \lambda_\vartheta(J/\psi \text{ from } \chi_{c1}) \;<\; +1}$$



[PRD 83, 096001]

Example: direct vs prompt J/ψ

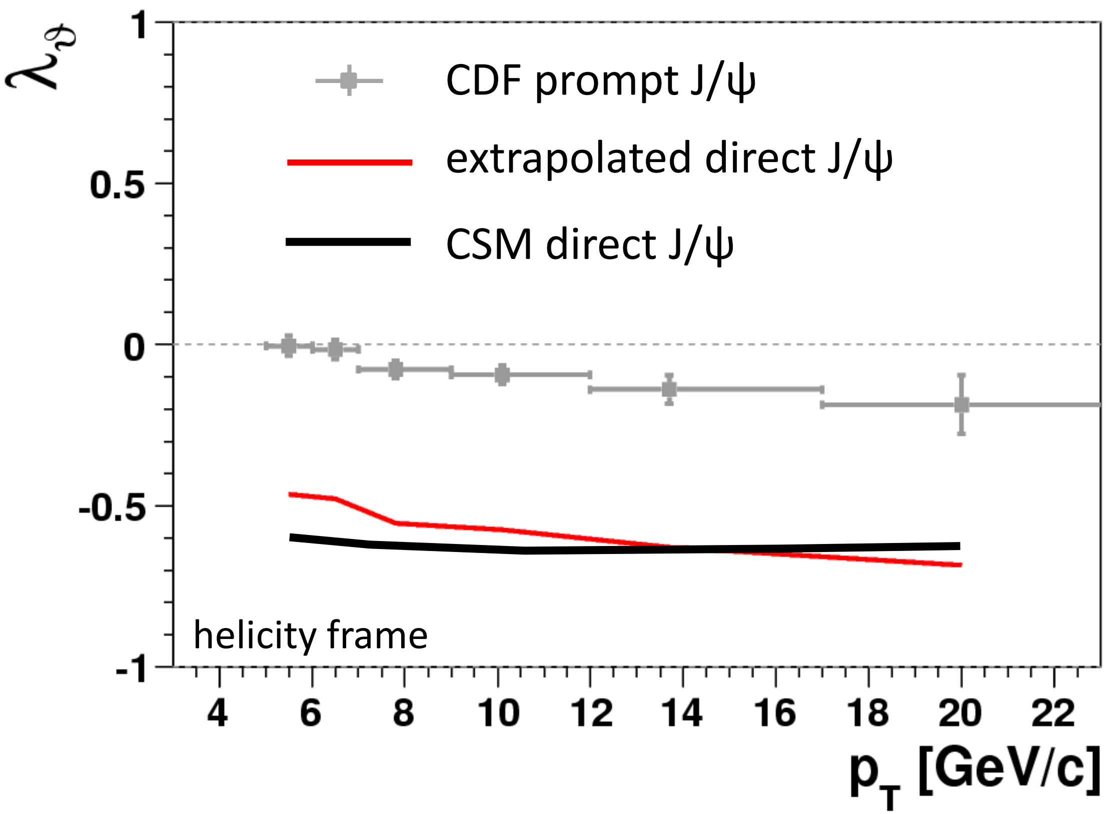
The <u>direct</u>-J/ψ polarization can be derived from the <u>prompt</u>-J/ψ polarization measurement of CDF knowing

- the **χ_c-to-J/ψ feed-down fractions**
- the **χ_c polarizations**

CDF data

$R(\chi_{c1})+R(\chi_{c2})$ = 30 ± 6 %
$R(\chi_{c2})/R(\chi_{c1})$ = 40 ± 2 %

taking



using the values
$R(\chi_{c1})+R(\chi_{c2})$ = 42 % (+2σ)
$R(\chi_{c2})/R(\chi_{c1})$ = 40 %

the CSM prediction of direct-J/ψ polarization agrees very well with the CDF data *in the scenario* *h*(χ_{c1}) = 0 and *h*(χ_{c2}) = ±2

0 ±1
0 ±2

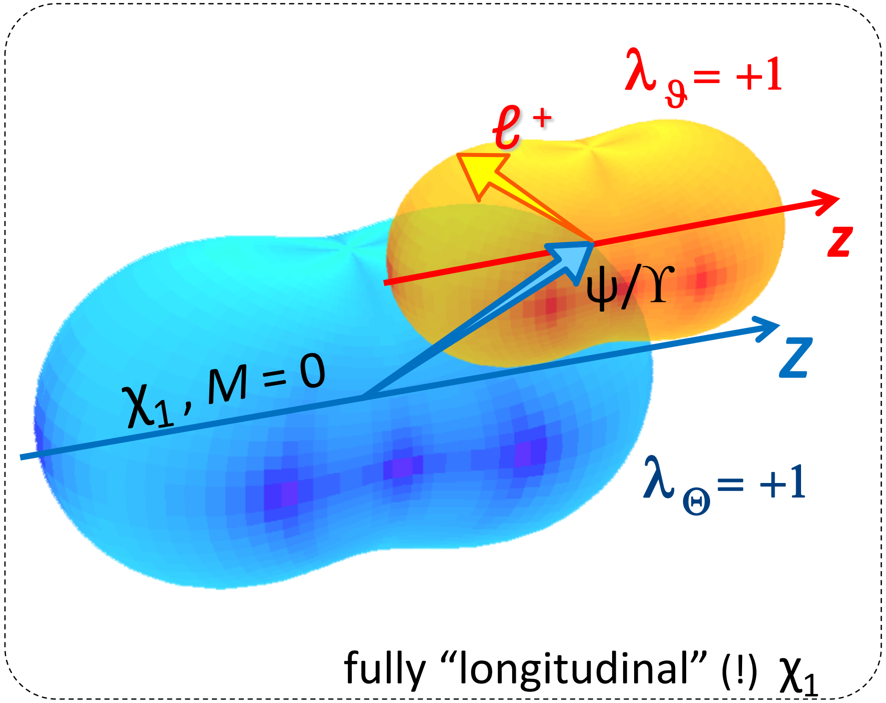
To exclude that the J/ψ is strongly polarized is crucial to isolate the J/ψ from χ_c !

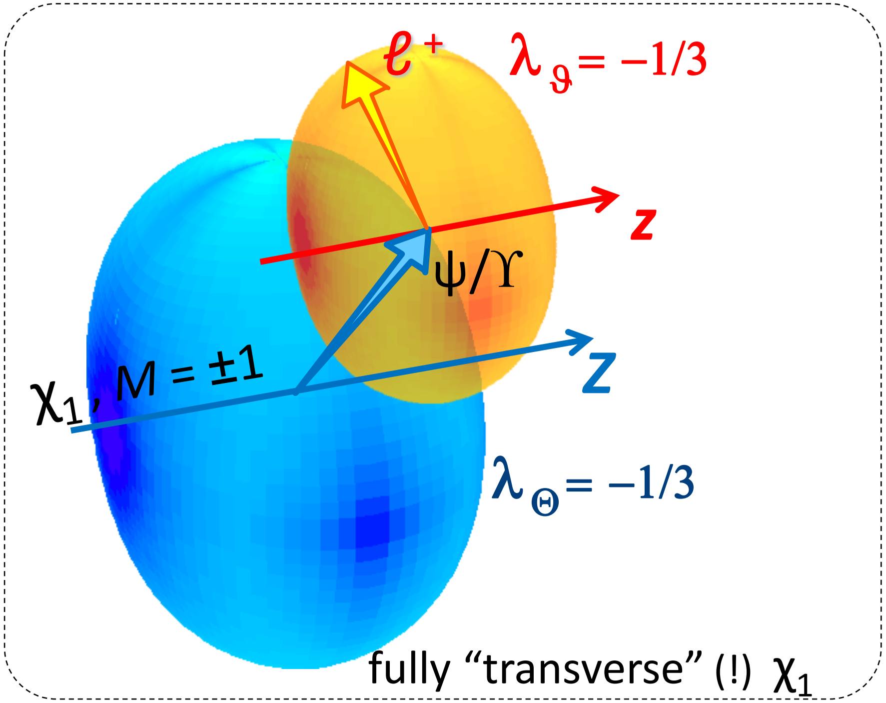
Measuring polarization of ψ/ϒ from χ is the same as measuring χ polarization

$\chi \to \psi/\Upsilon\ \gamma \to \ell^+\ell^-\gamma$

[PRD 83, 096001 (2011)]

The dilepton distribution contains as much information on the χ polarization as the photon distribution. The two distributions are even ***identical*** (with respect to *one* common frame) when higher-order multipoles are neglected.





χ polarizations can be measured from *dilepton* distributions alone.
And they *should*: the photon distribution is modified by not fully known higher-order multipoles, the dilepton distribution is not

Rotation-invariant parity asymmetry

parity-violating terms

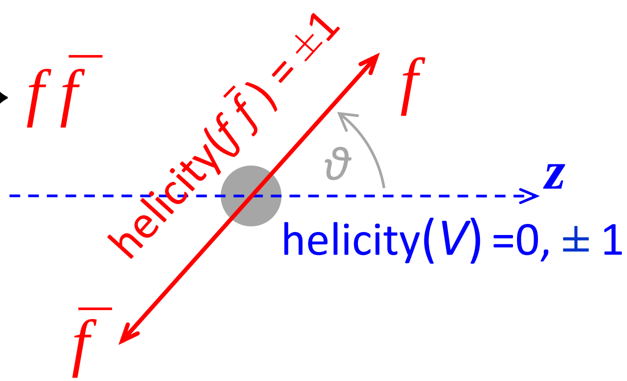
$$\frac{dN}{d\Omega} \propto 1 + \ldots + 2\boldsymbol{A_\theta} \cos\theta + 2\boldsymbol{A_\varphi} \sin\theta\cos\varphi + 2\boldsymbol{A_\varphi^\perp} \sin\theta\sin\varphi$$

$$\tilde{\mathcal{A}} = \frac{4}{3+\lambda_\vartheta}\sqrt{A_\theta^2 + A_\varphi^2 + A_\varphi^{\perp 2}}$$

is invariant under *any* rotation

It represents the magnitude of the *maximum observable parity asymmetry*, i.e. of the *net* asymmetry as it can be measured along the polarization axis that maximizes it (which is the one minimizing the helicity-0 component)

$V \rightarrow f\bar{f}$



$$\tilde{\mathcal{A}} = \max_{z} \frac{P(\pm1,\pm1) - P(\pm1,\mp1)}{P(\pm1,\pm1) + P(\pm1,\mp1)}$$

[PRD 82, 096002]

Frame-independent “forward-backward” asymmetry

The rotation invariant parity asymmetry can also be written as

$$\tilde{\mathcal{A}} = \frac{4}{3}\sqrt{\mathcal{A}^2_{\cos\theta} + \mathcal{A}^2_{\cos\varphi} + \mathcal{A}^{\perp 2}_{\sin\varphi}}$$

$$\mathcal{A}_{\cos\theta} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N_{\mathrm{tot}}} = \mathcal{A}_{\mathrm{FB}}$$

- Z “forward-backward asymmetry”
- (related to) W “charge asymmetry”

experiments usually measure these in the Collins-Soper frame

$$\mathcal{A}_{\cos\varphi} = \frac{N(\cos\varphi > 0) - N(\cos\varphi < 0)}{N_{\mathrm{tot}}}$$

$$\mathcal{A}_{\sin\varphi} = \frac{N(\sin\varphi > 0) - N(\sin\varphi < 0)}{N_{\mathrm{tot}}}$$

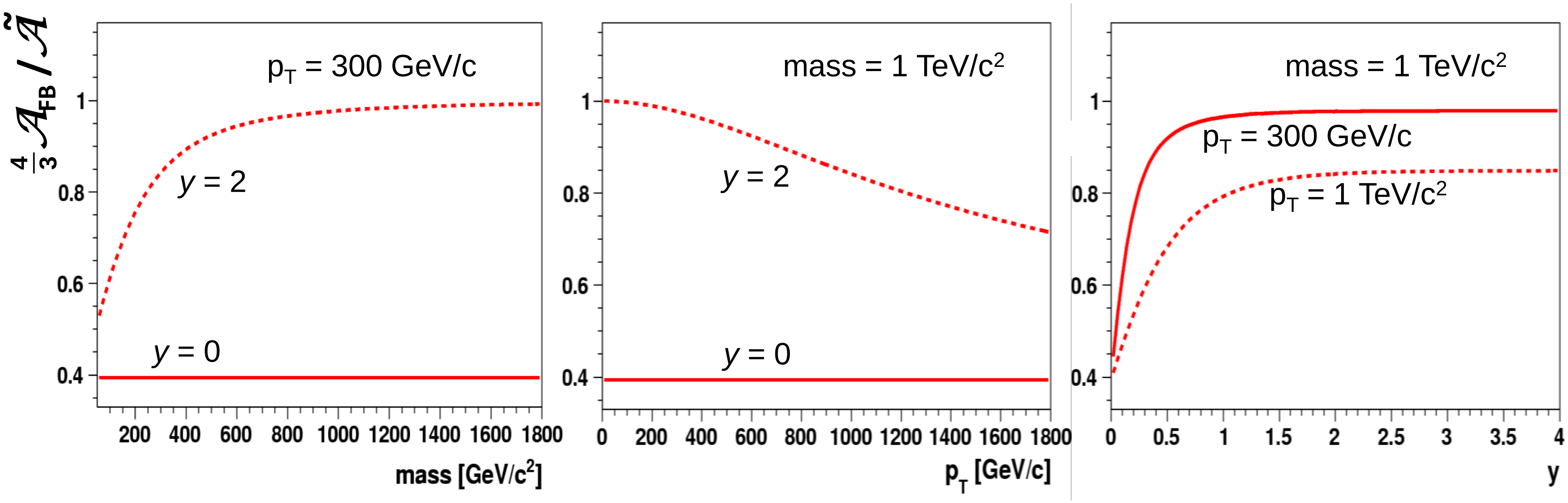
$\tilde{\mathcal{A}}$ can provide a better measurement of parity violation:

- it is not reduced by a non-optimal frame choice
- It is free from extrinsic kinematic dependencies
- it can be checked in two “orthogonal” frames

$\mathcal{A}_{FB}$(CS) vs $\tilde{\mathcal{A}}$

By measuring only the azimuthal “projection” of the asymmetry ($\mathcal{A}_{FB}$) wrt some chosen axis, in general we lose significance.
This is especially relevant if we do not know a priori the optimal quantization axis

Example: imagine an unknown massive boson
70% polarized in the HX frame and 30% in the CS frame
How much is $\mathcal{A}_{FB}$(CS) smaller than $\tilde{\mathcal{A}}$ if we measure in the CS frame?



Larger loss of significance for smaller mass, higher p_T , mid-rapidity