Physics at the LHC, LIP

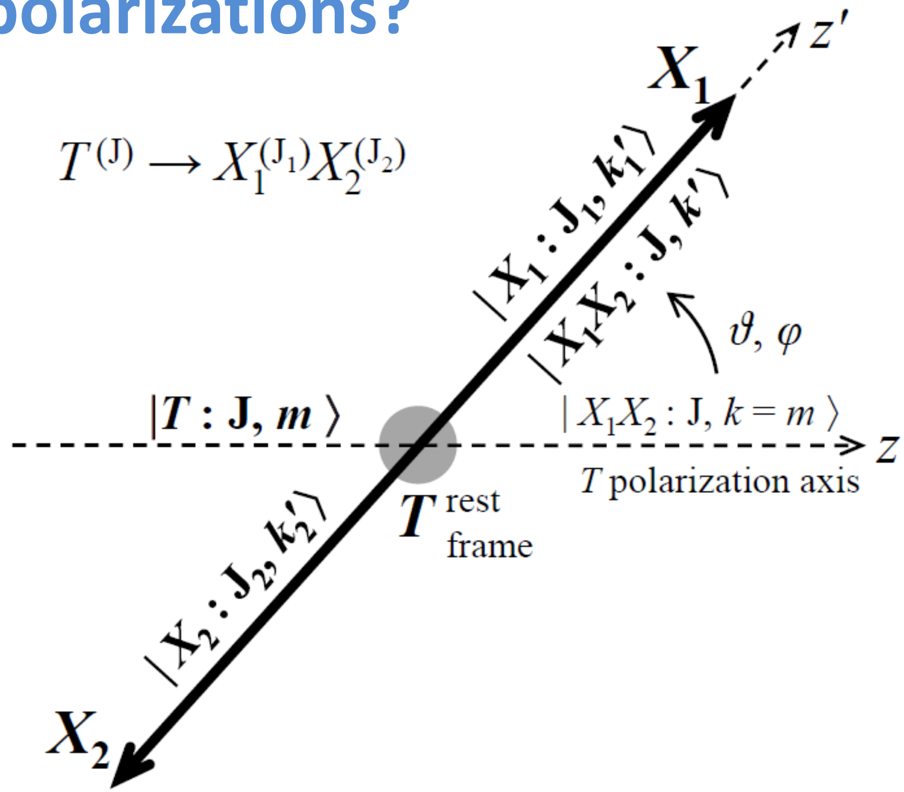
Particle polarizations in LHC physics

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:
  new resonances vs continuum background in the $Z\,Z$ channel

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*-*Q*bar bound states** (produced at the LHC in gluon-gluon fusion) acquire their quantum numbers.
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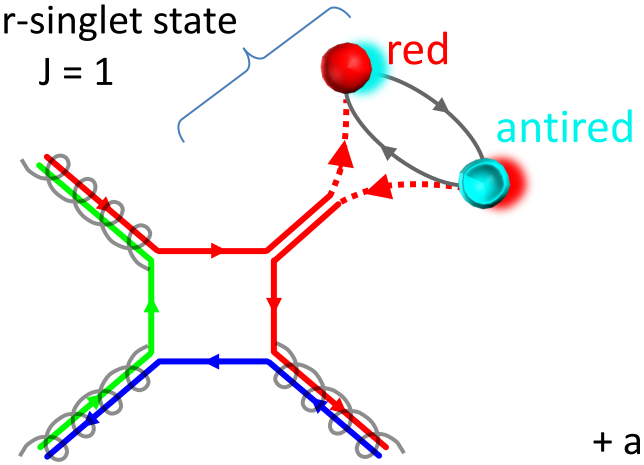
- **Colour-singlet processes**: quarkonia produced directly as observable ***colour-neutral*** *Q-Q*bar pairs

purely perturbative



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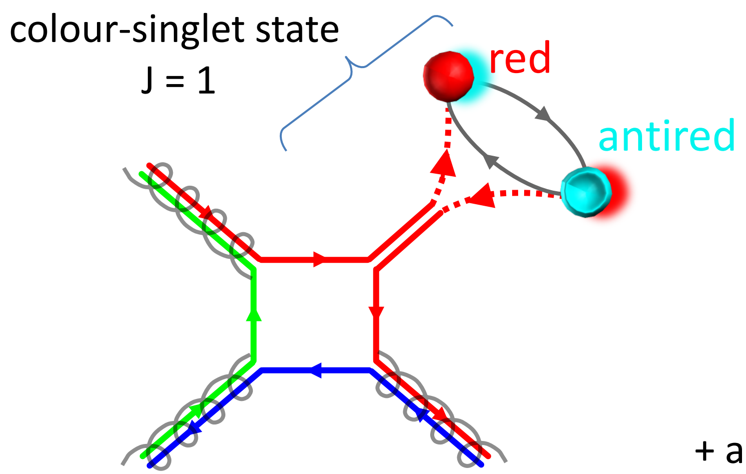

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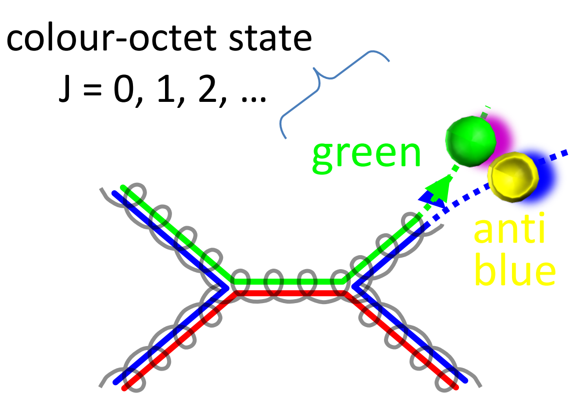
- **Colour-octet processes**: quarkonia are produced through ***coloured*** *Q*-*Q*bar pairs *of any possible quantum numbers*



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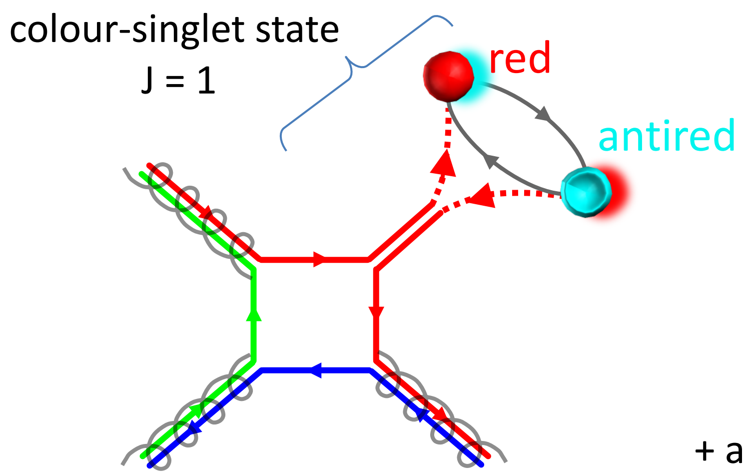

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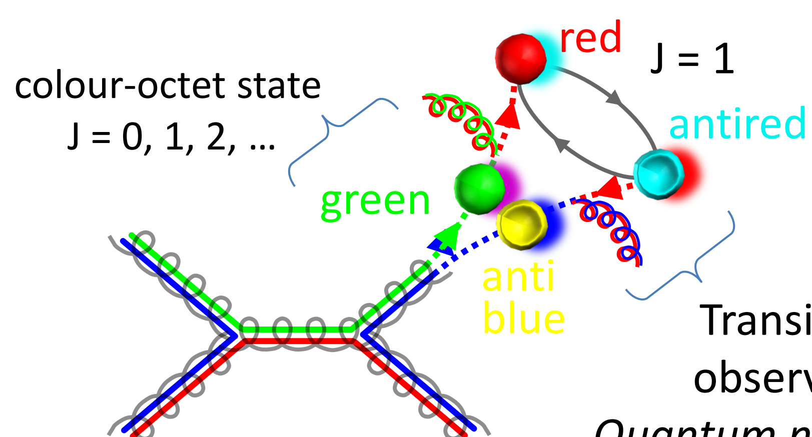
  perturbative
  ⊗
  non-perturbative



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

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

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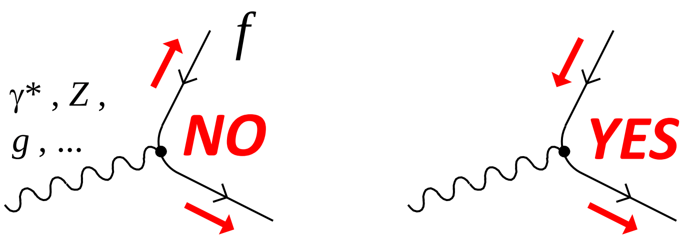

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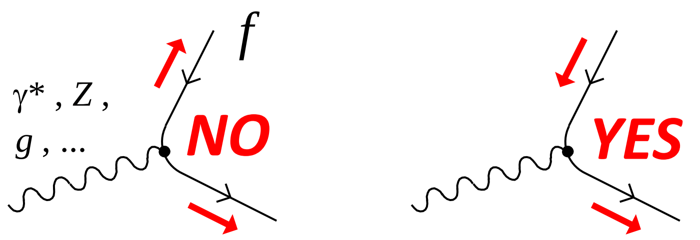
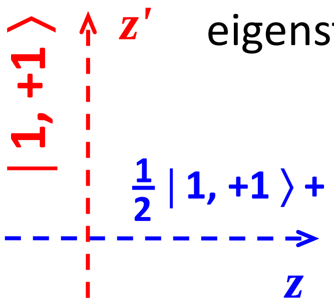


2) rotational covariance of angular momentum eigenstates



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

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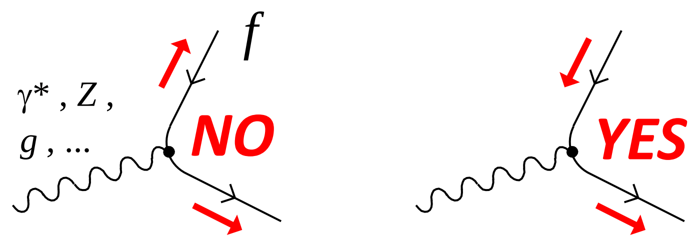

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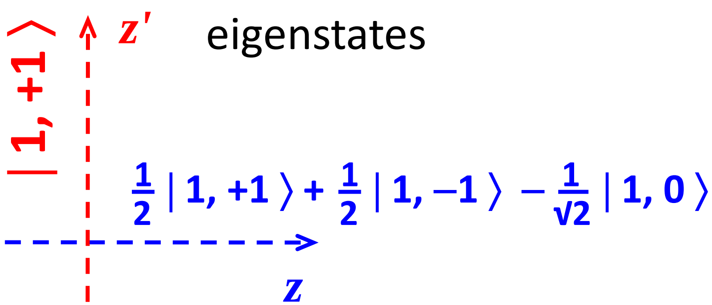
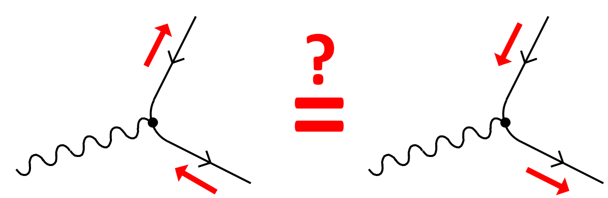
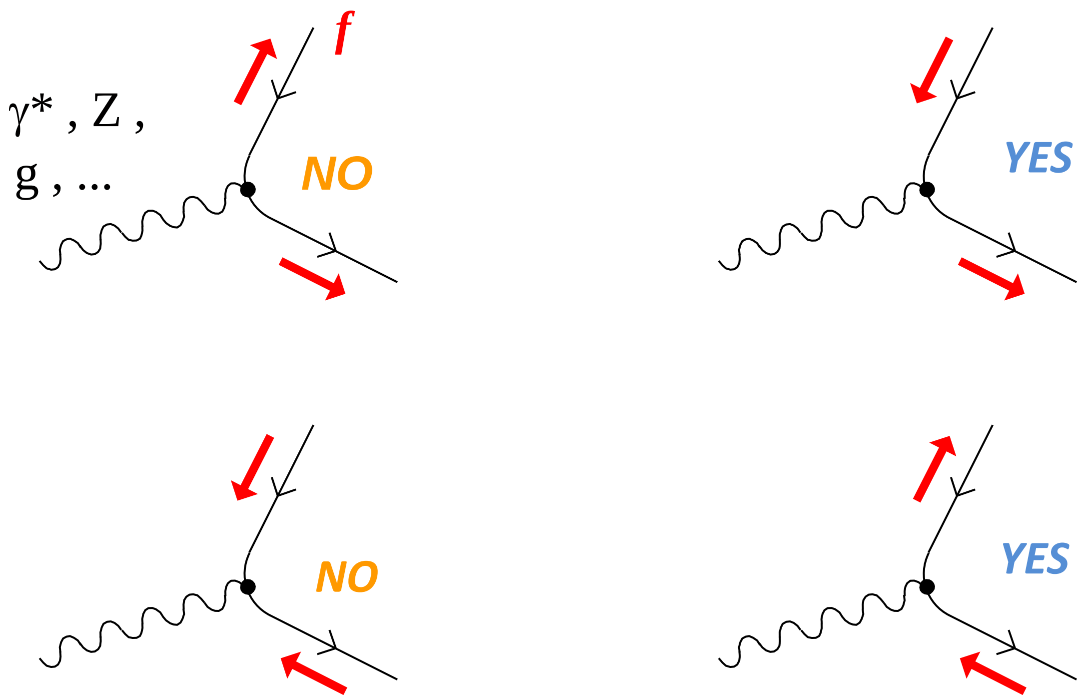


3) parity properties

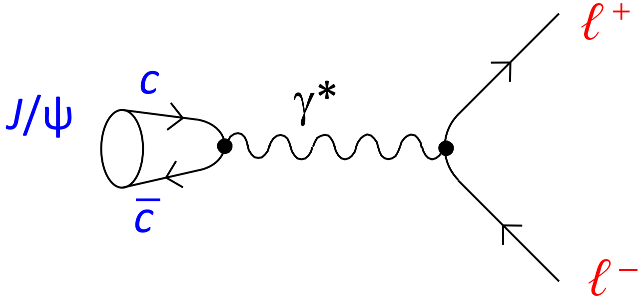


1: helicity conservation

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



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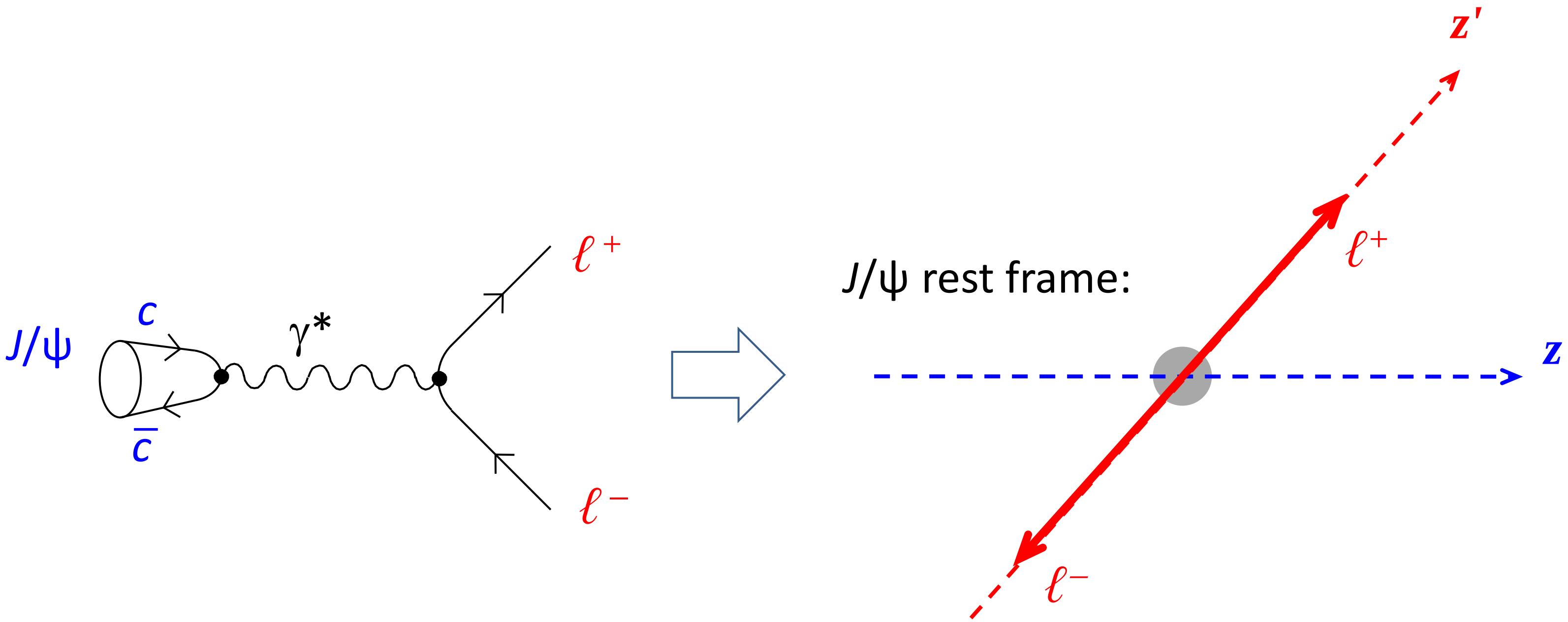

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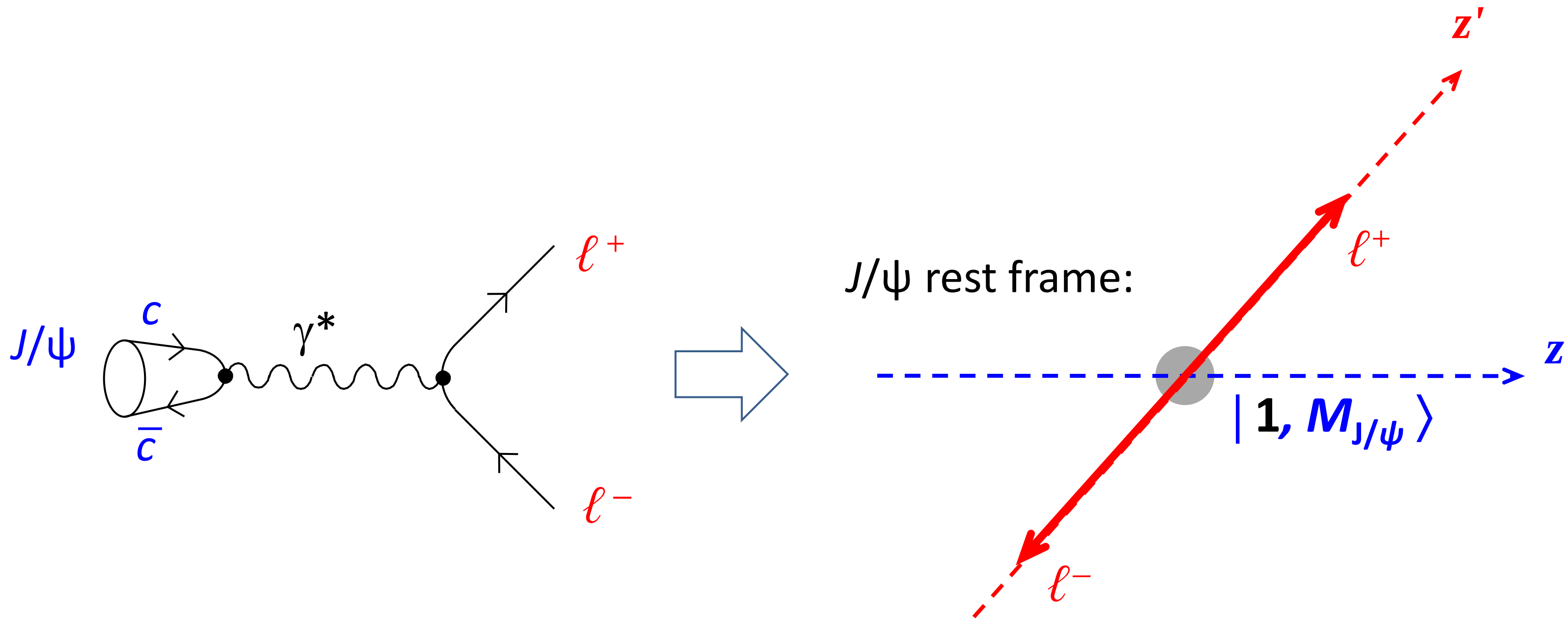

J/ψ angular momentum component along the polarization axis ***z:***

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

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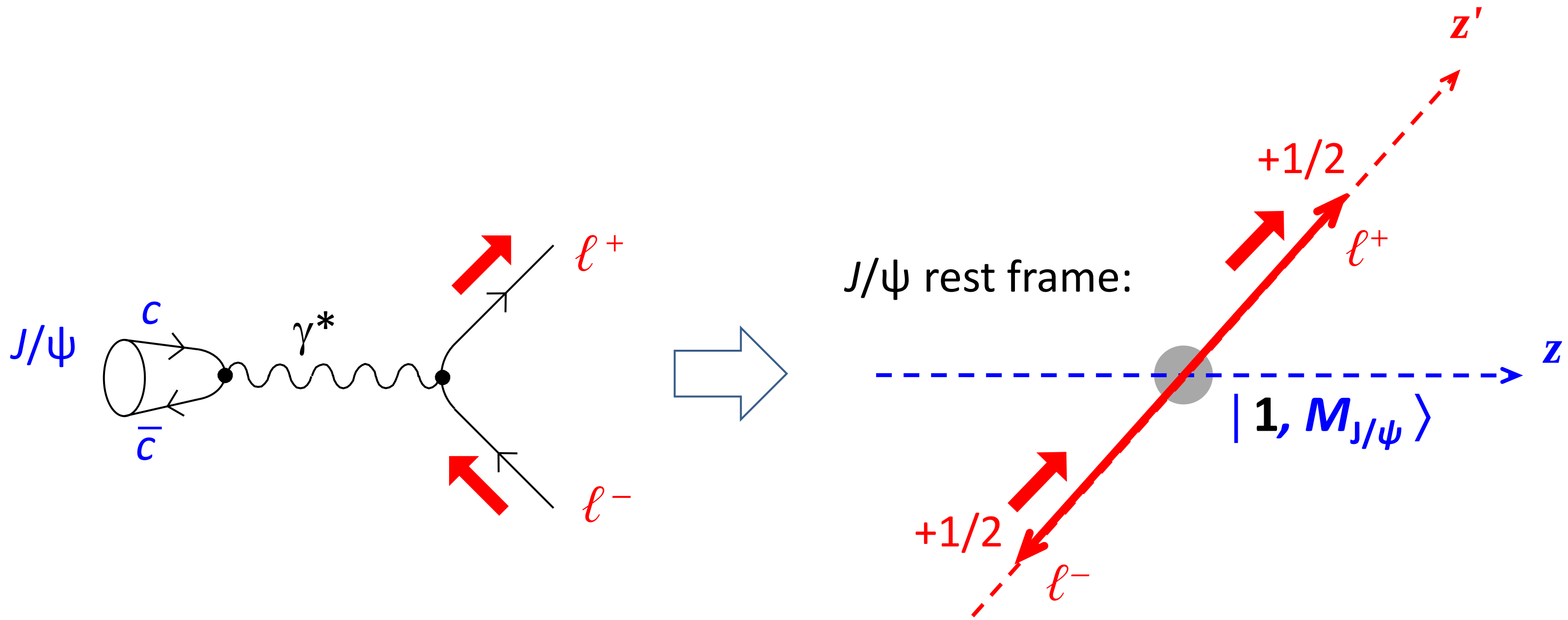

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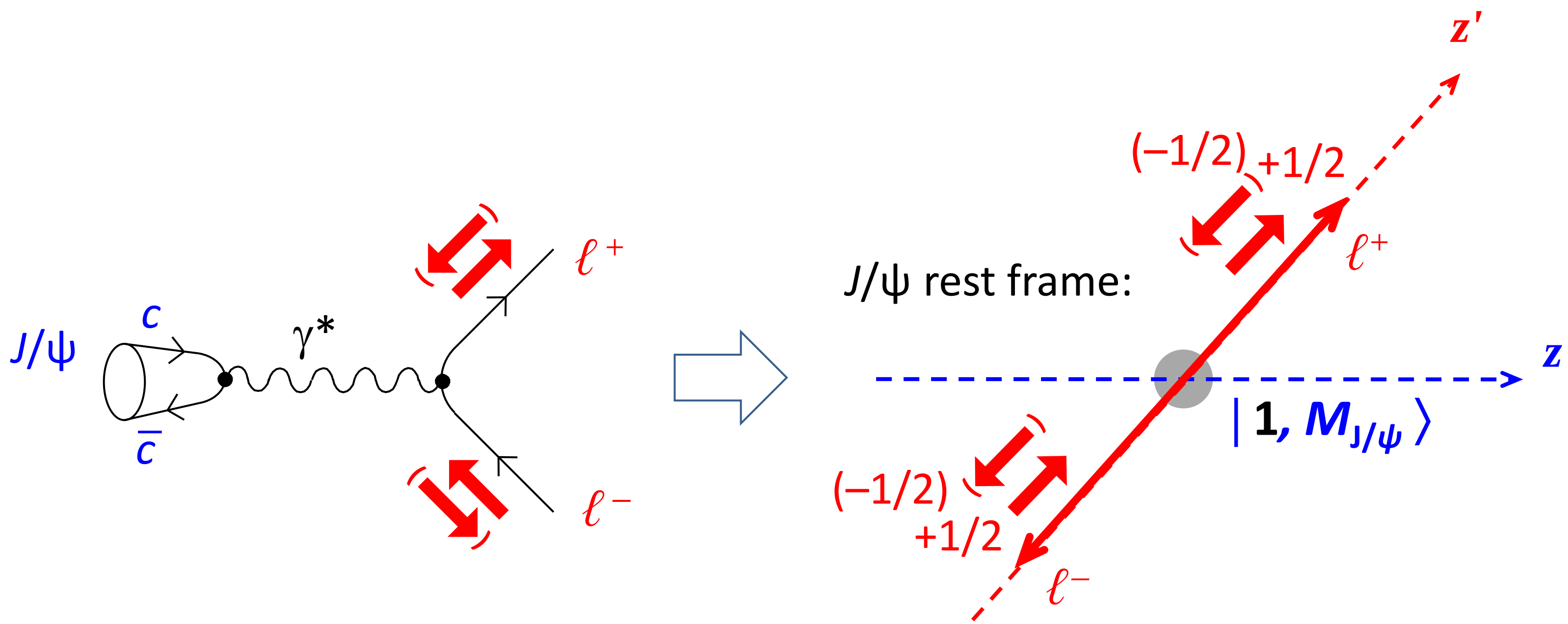

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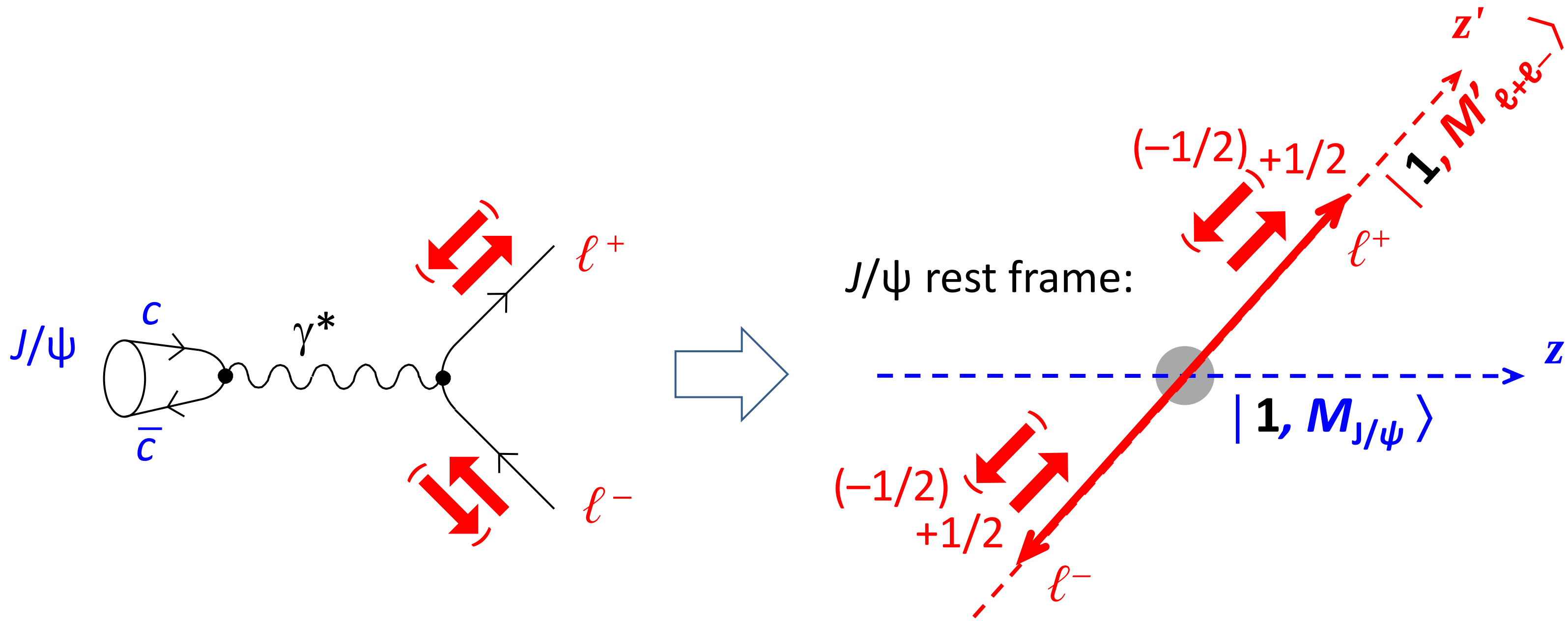

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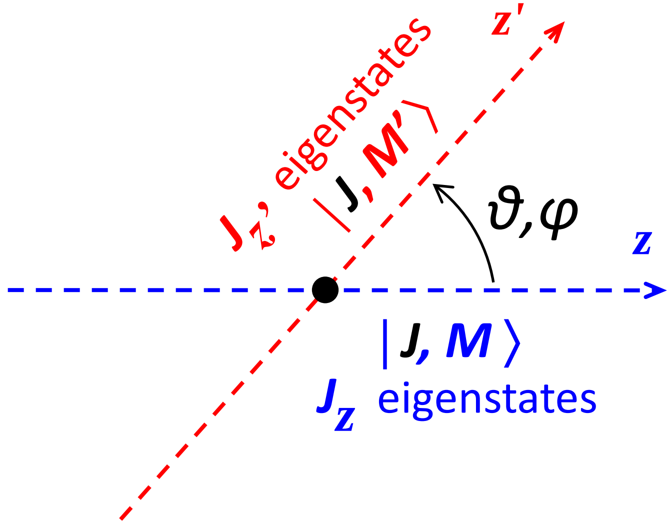
The **two leptons** can only have total angular momentum component

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

0 is forbidden

2: rotation of angular momentum eigenstates



change of quantization frame:

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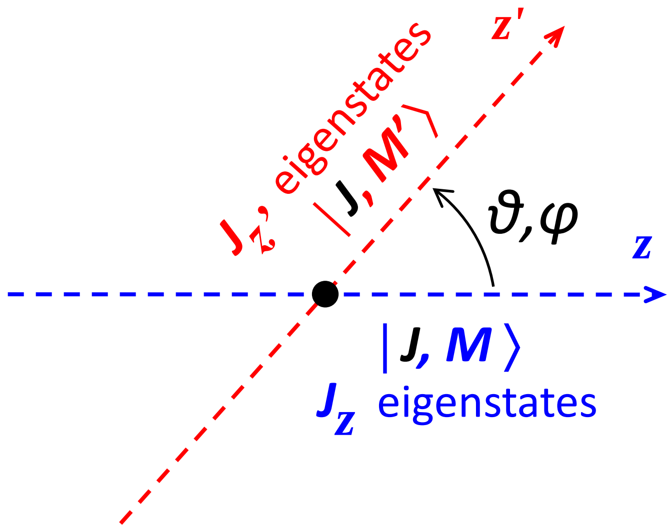

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↑ Wigner D-matrices

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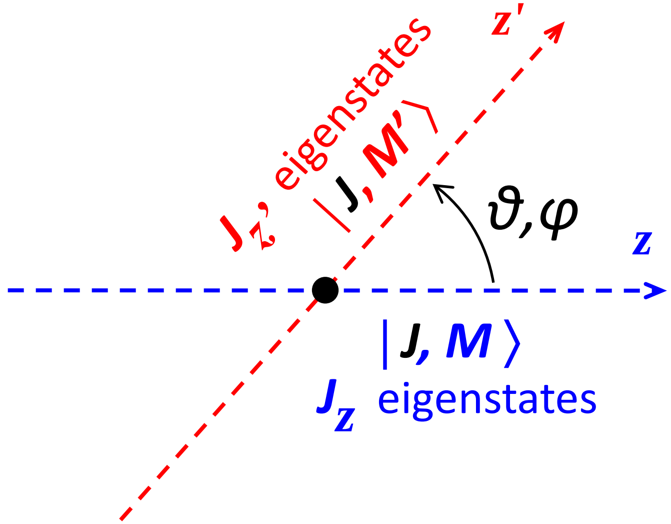

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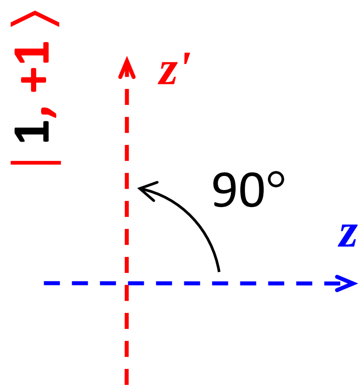

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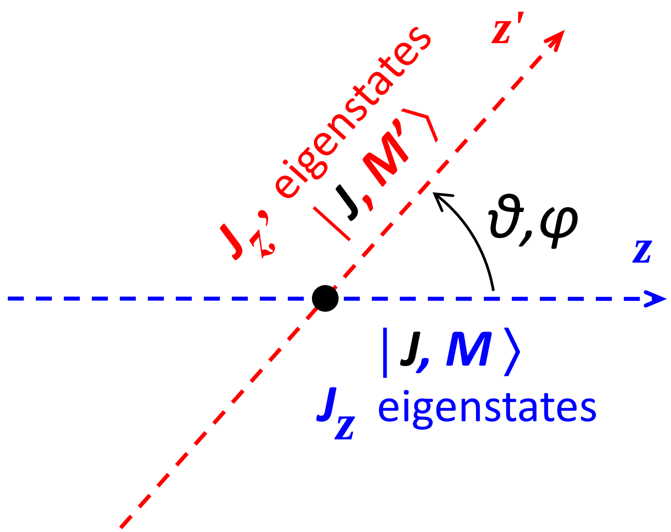

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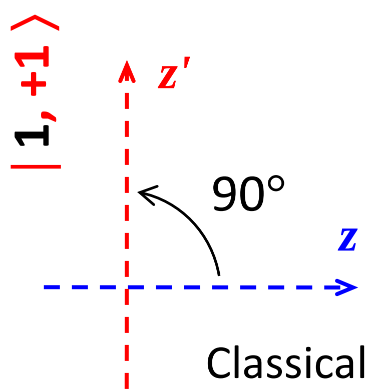

Classically, we would expect $|1, 0\rangle$

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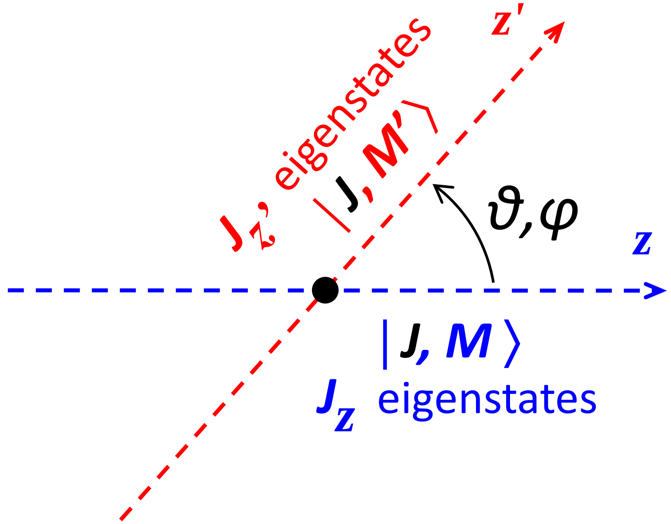

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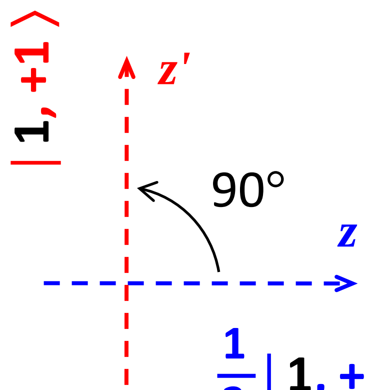
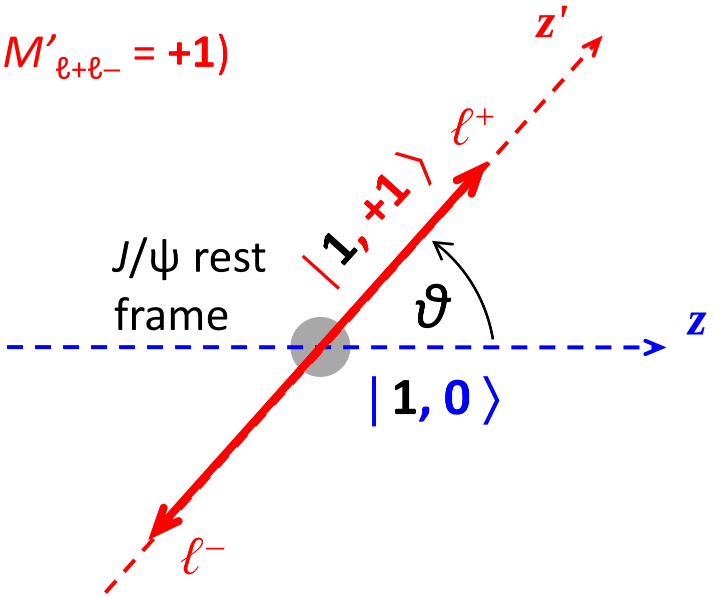


$$\frac{1}{2}\,|1, +1\rangle + \frac{1}{2}\,|1, -1\rangle - \frac{1}{\sqrt{2}}\,|1, 0\rangle$$

example: M = 0

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



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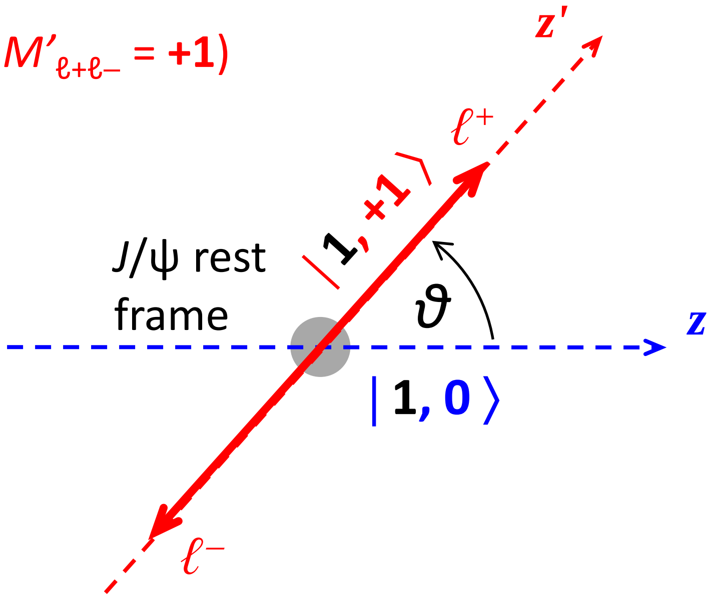

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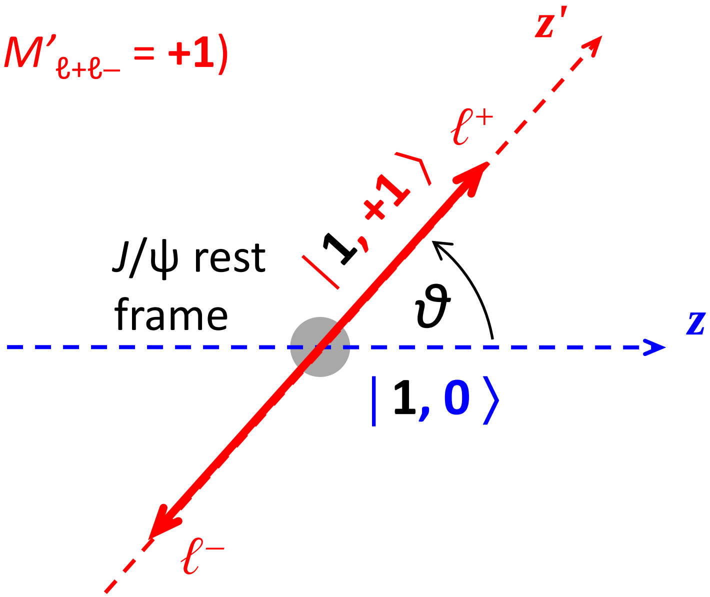

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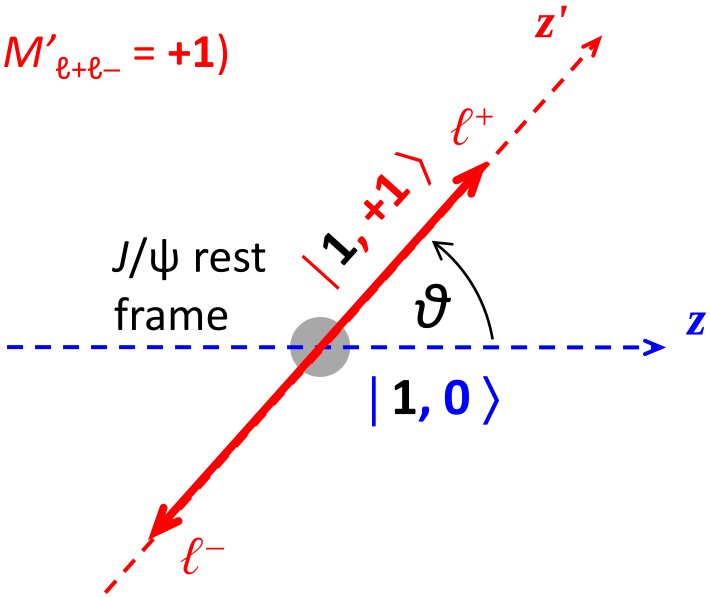

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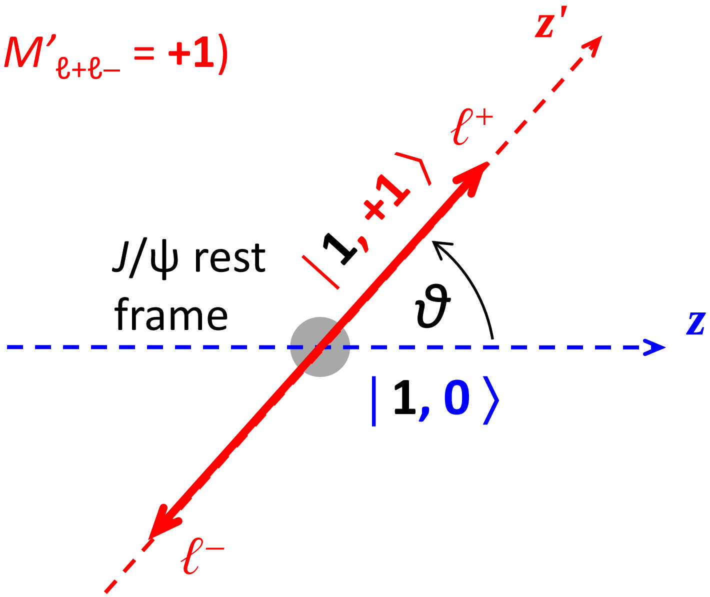

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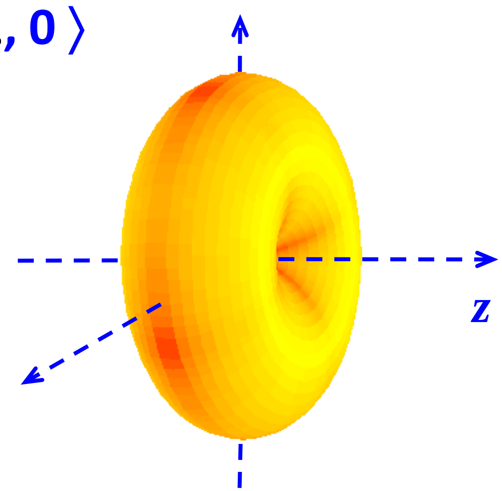

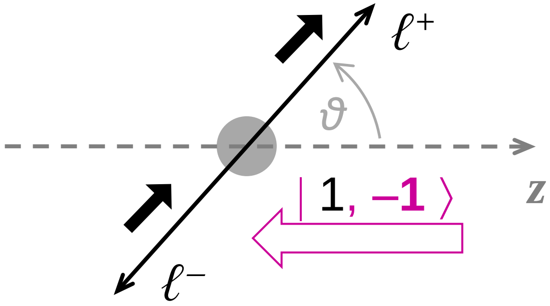

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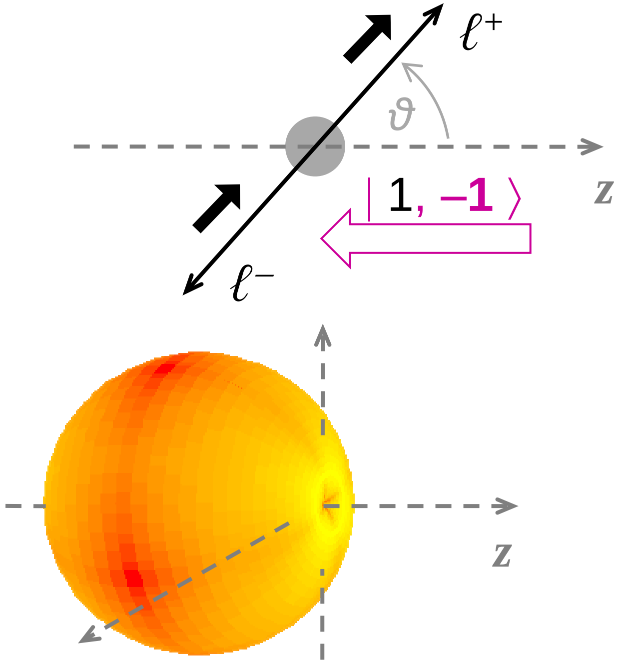

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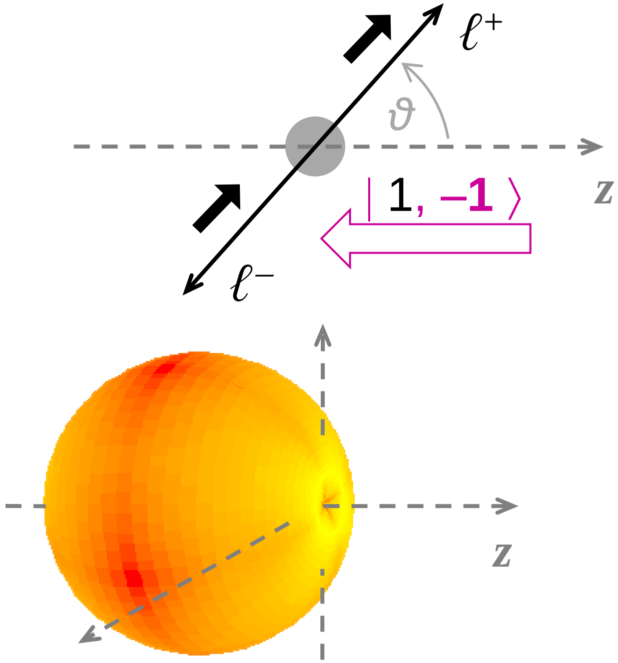

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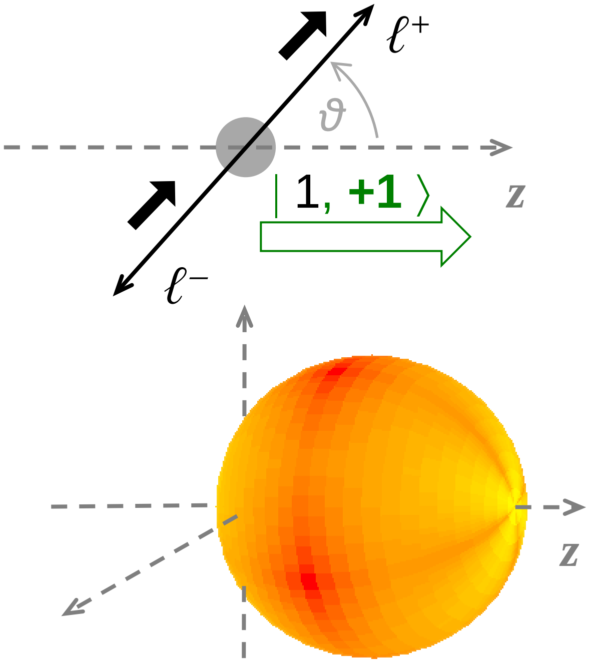

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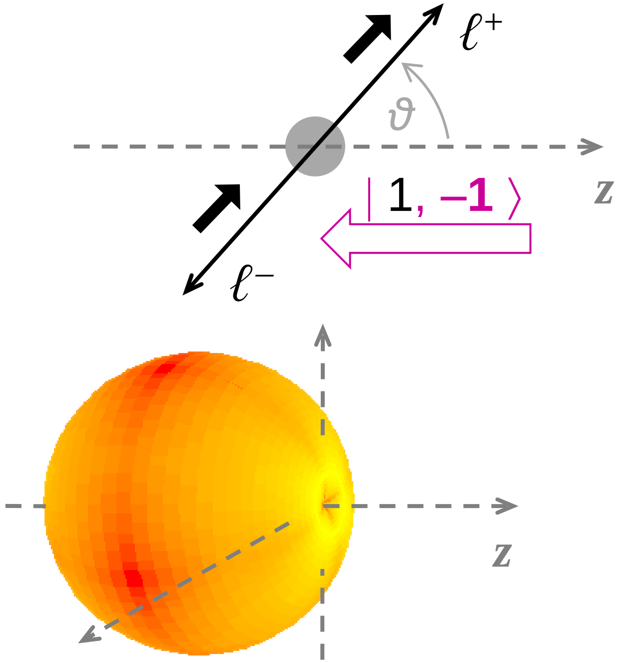

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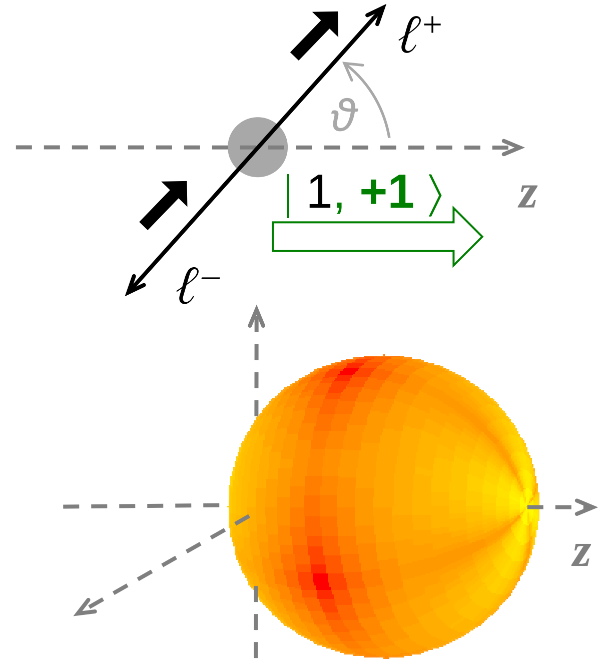

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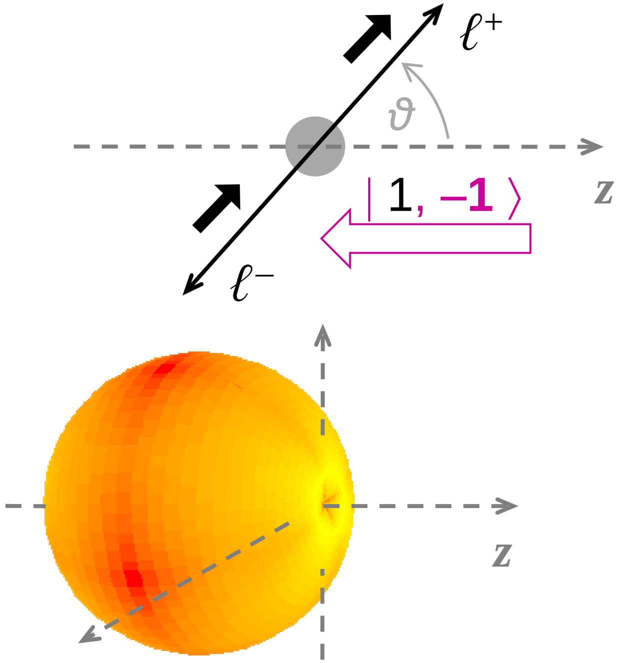

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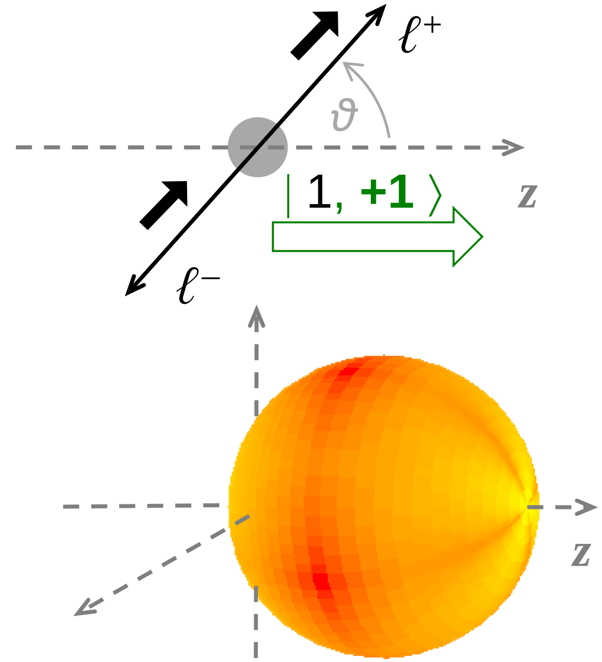

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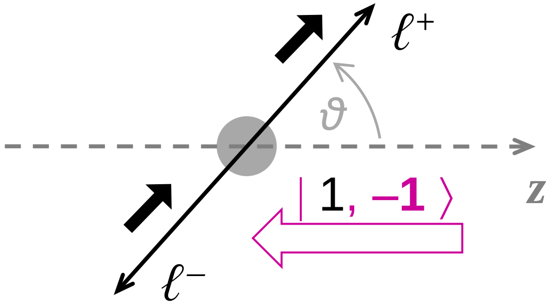
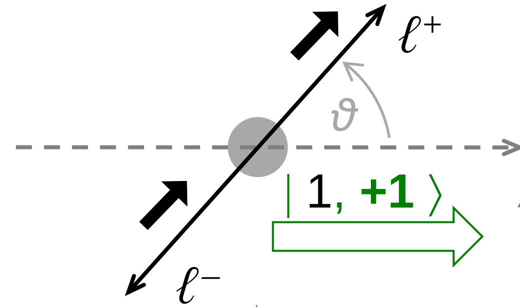
$$\frac{dN}{d\Omega} \propto |D^{1*}_{+1,+1}(\vartheta,\varphi)|^2 \propto 1 + \cos^2\vartheta + \mathbf{2\cos\vartheta}$$

Are they equally probable?

3: parity





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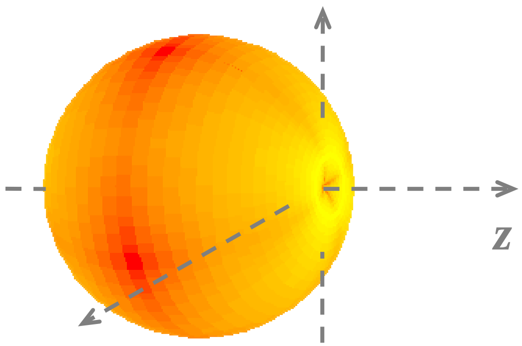

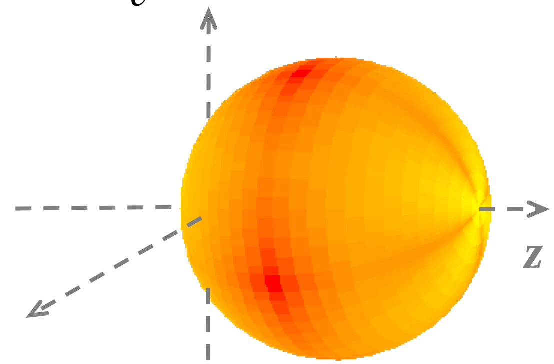

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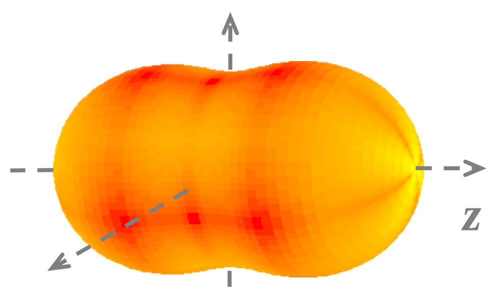
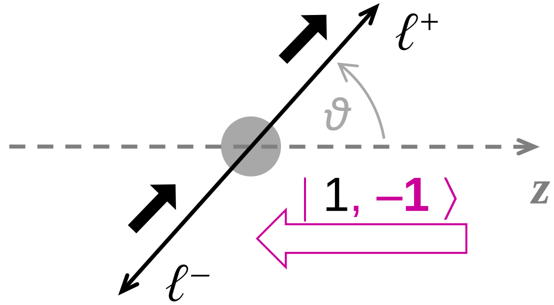
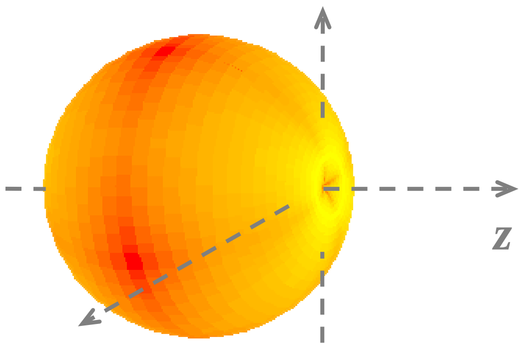
Are they equally probable?



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

3: parity





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| 1, –1 ⟩ and | 1, +1 ⟩
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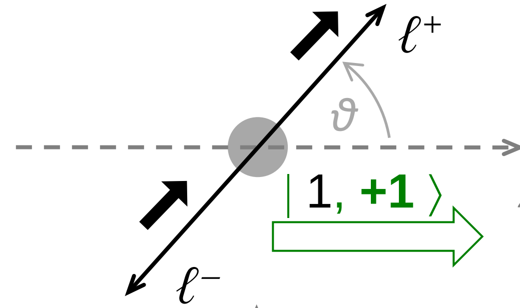

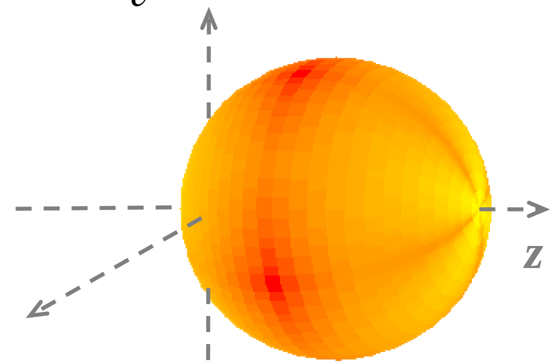

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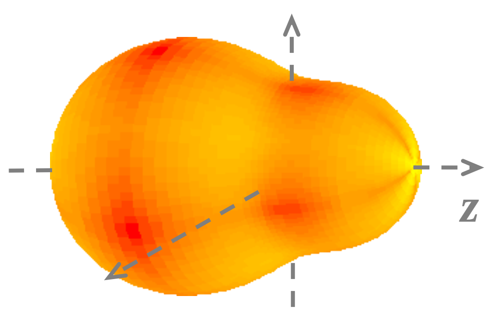

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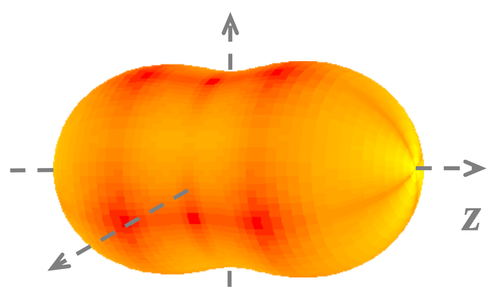

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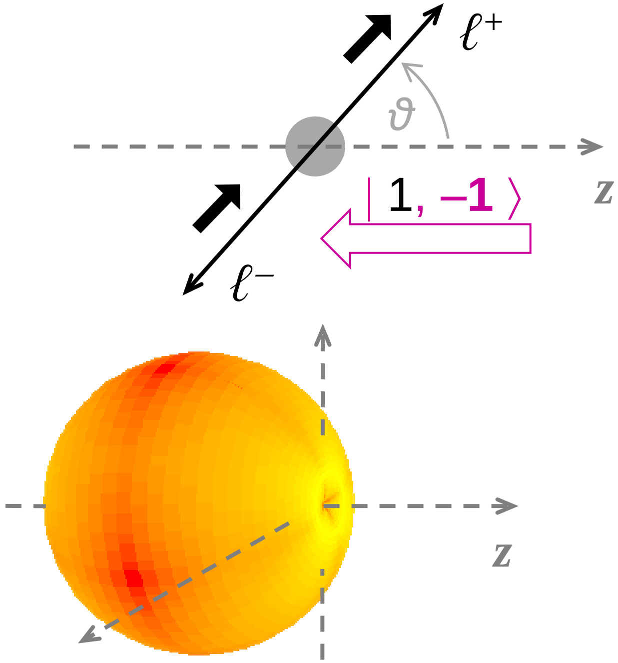

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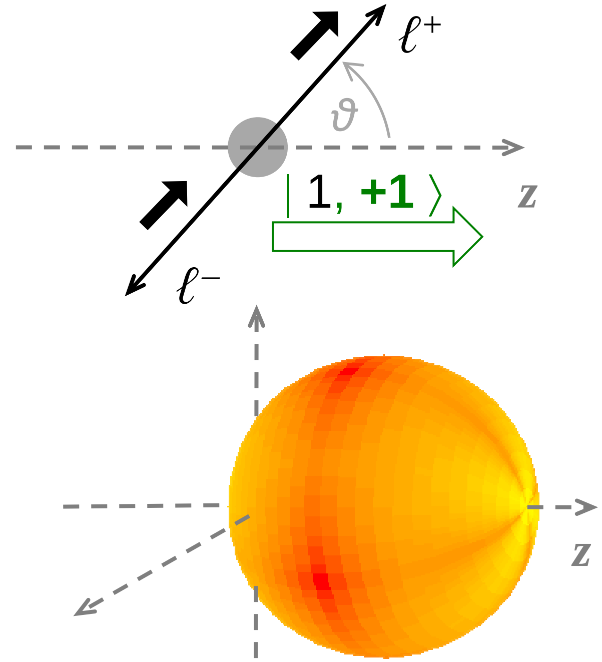

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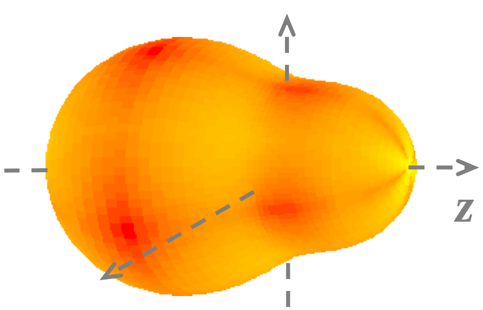

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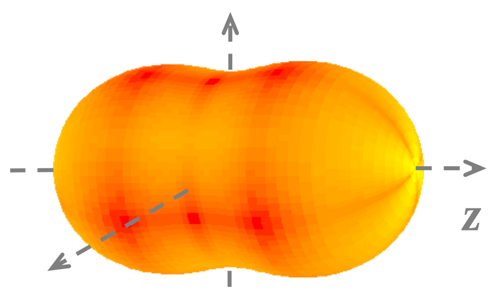

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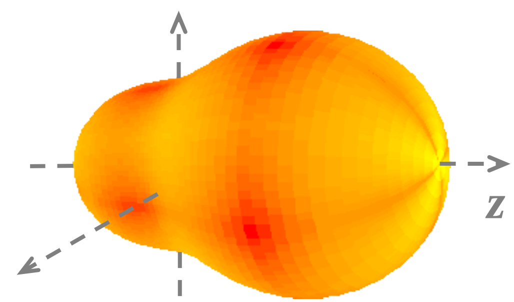

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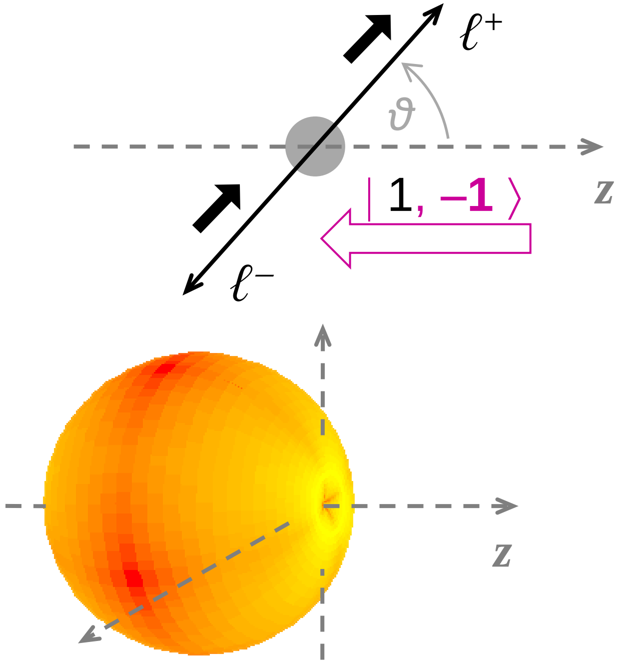

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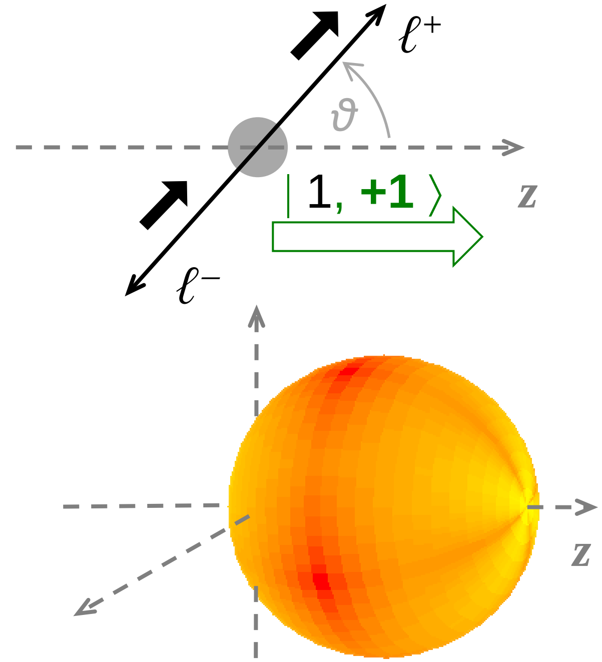

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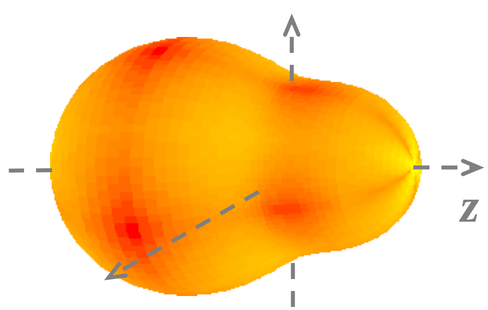

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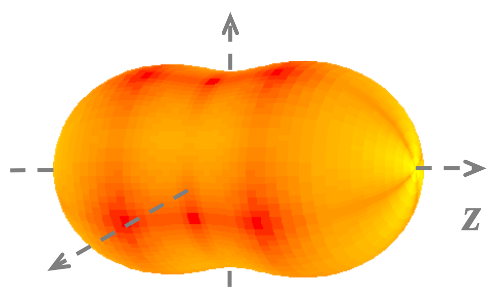

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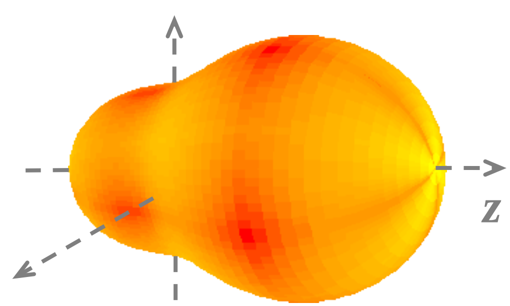

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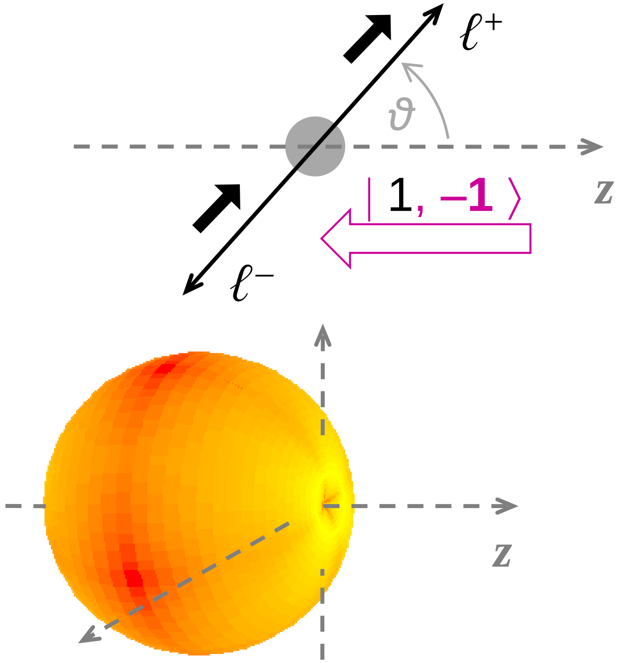

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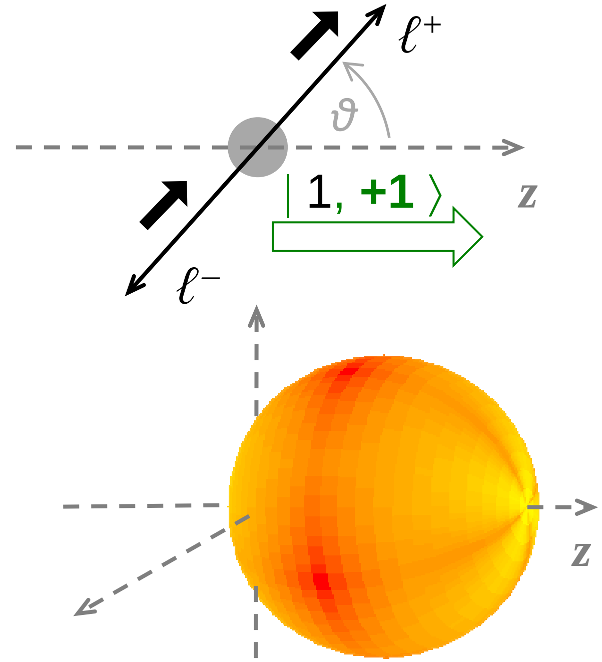

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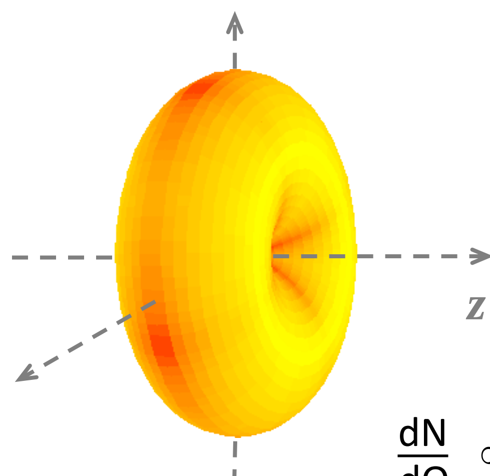
Decay distribution of | 1, 0 ⟩ state is always parity-symmetric:



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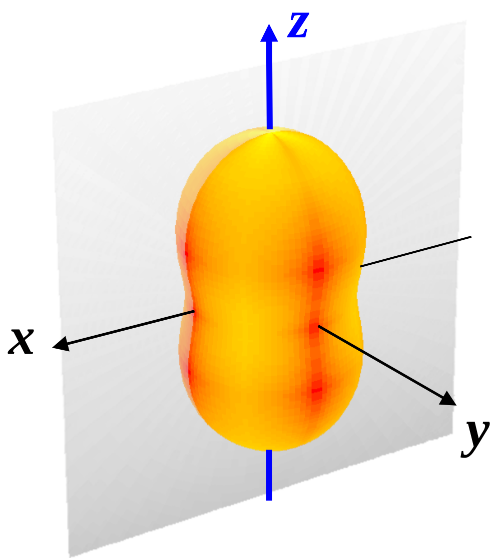
“Transverse” and “longitudinal”



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

or $| 1, \mathbf{-1} \rangle$

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

(parity-conserving case)

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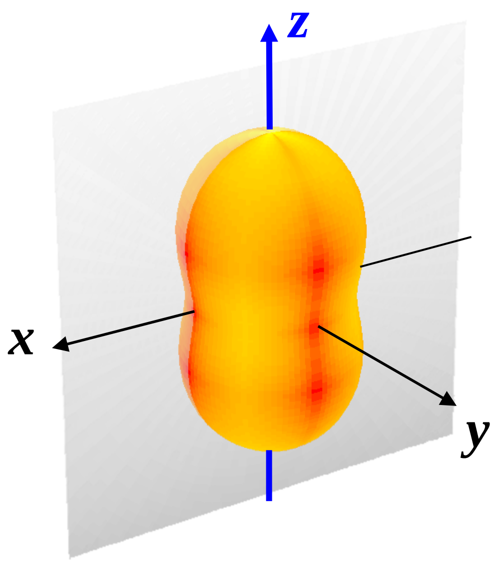

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"Transverse" polarization, like for *real photons*. The word refers to the alignment of the *field* vector, not to the *spin* alignment!

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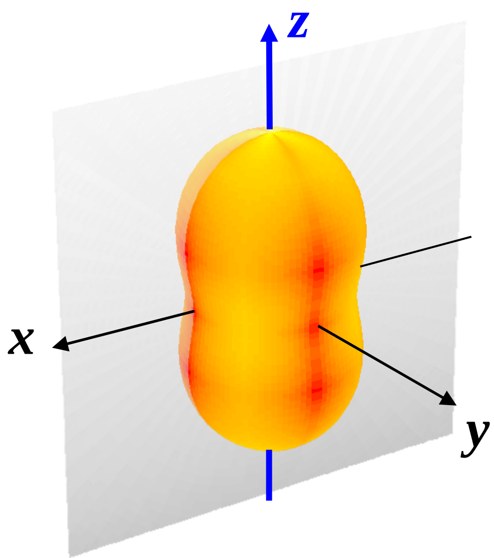

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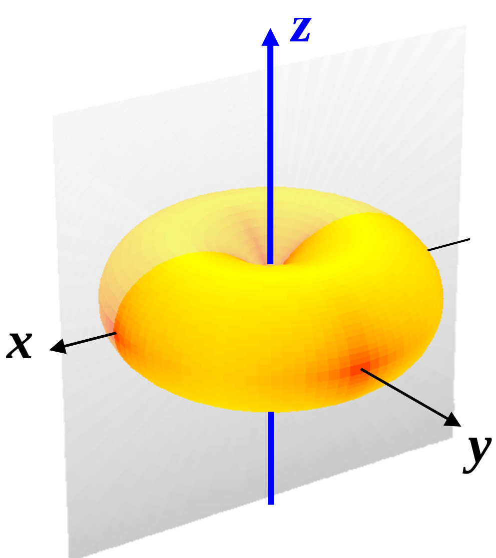

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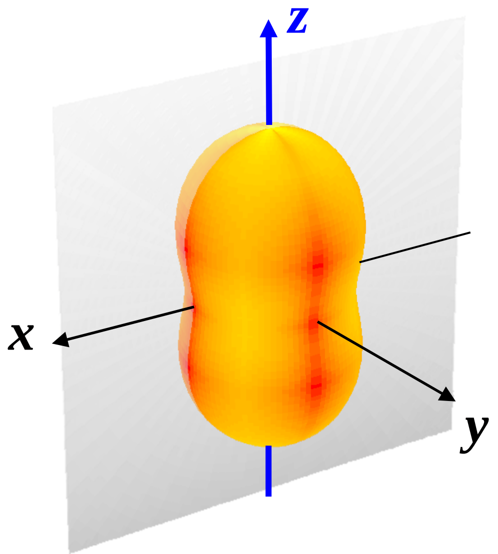

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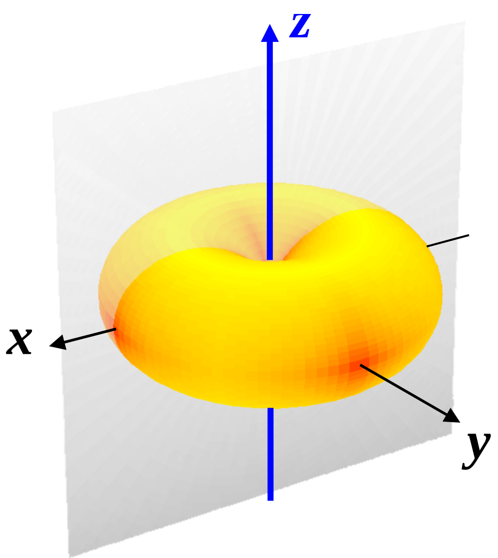

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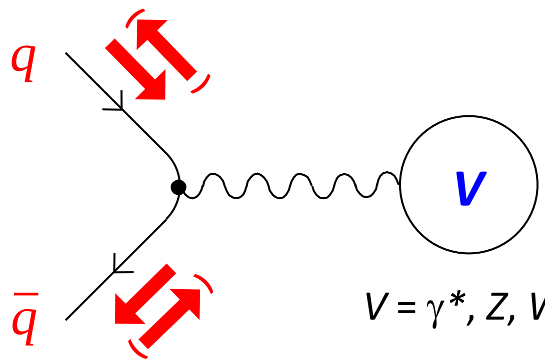
"Longitudinal" polarization

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



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

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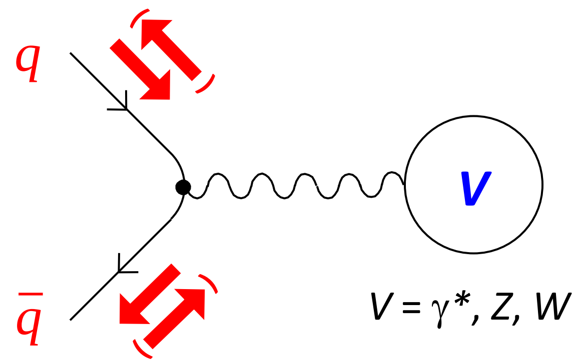
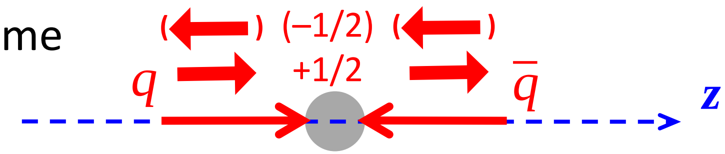


q-$\bar{q}$ rest frame
= V rest frame



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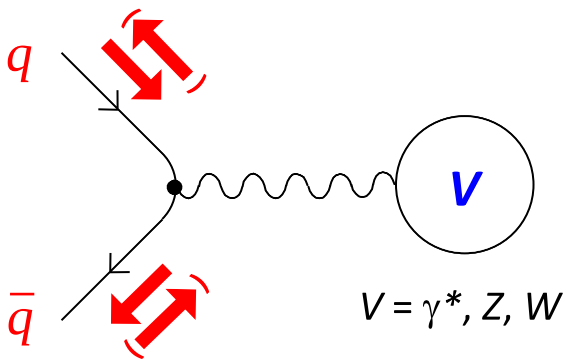

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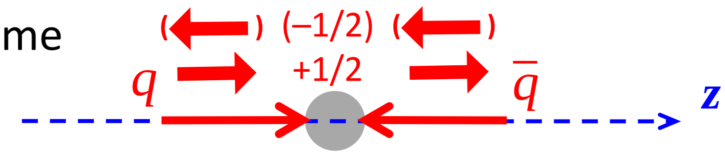

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The "natural" polarization axis in this case is the *relative direction of the colliding fermions* ***(Collins-Soper axis)***

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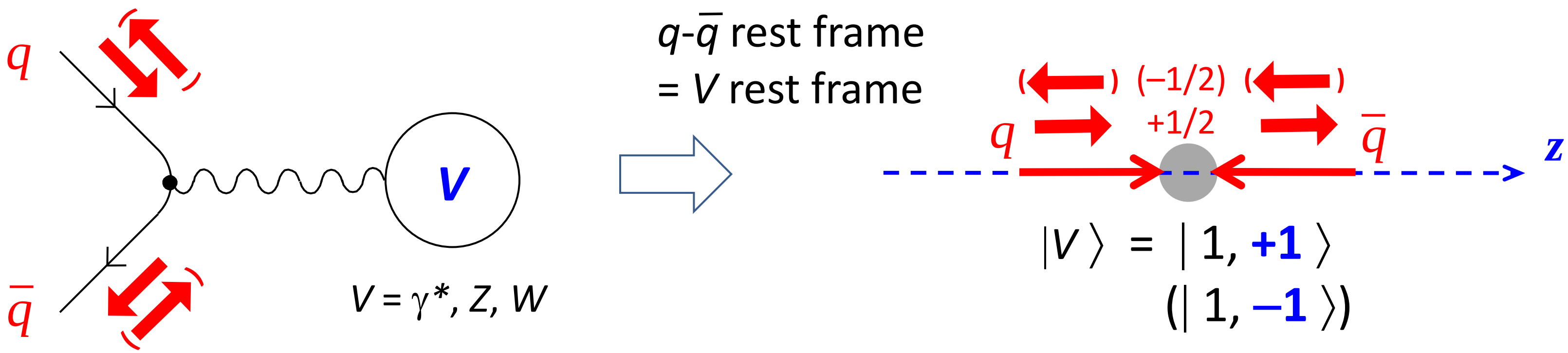

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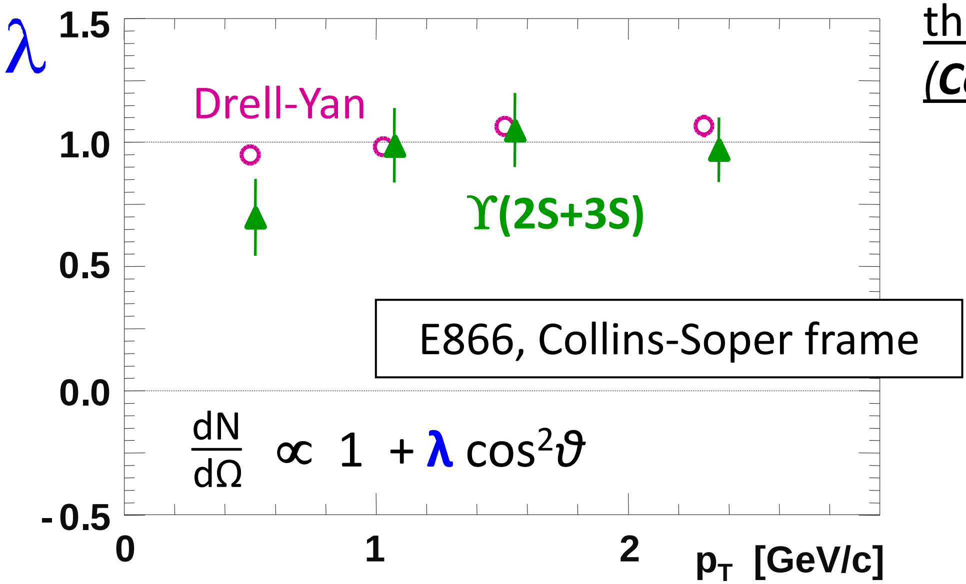
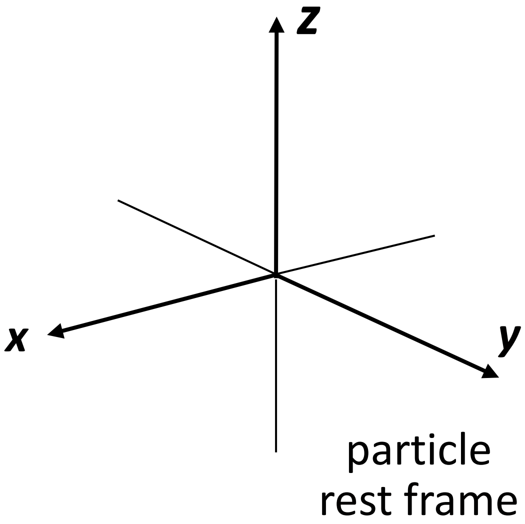


Drell-Yan is a paradigmatic case

But not the only one

The most general distribution



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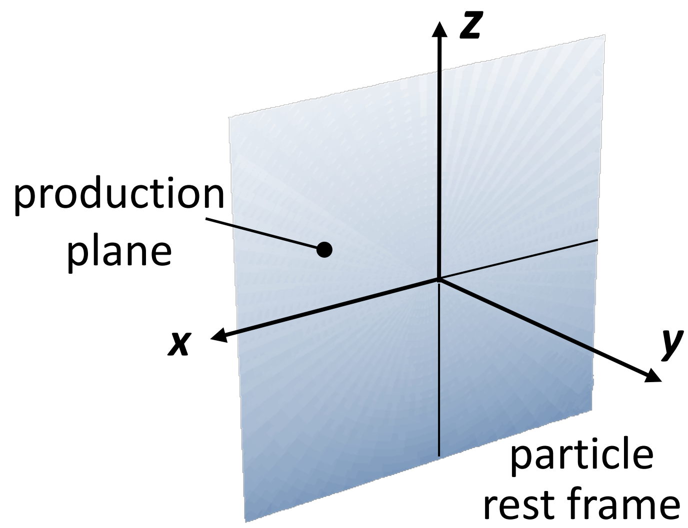

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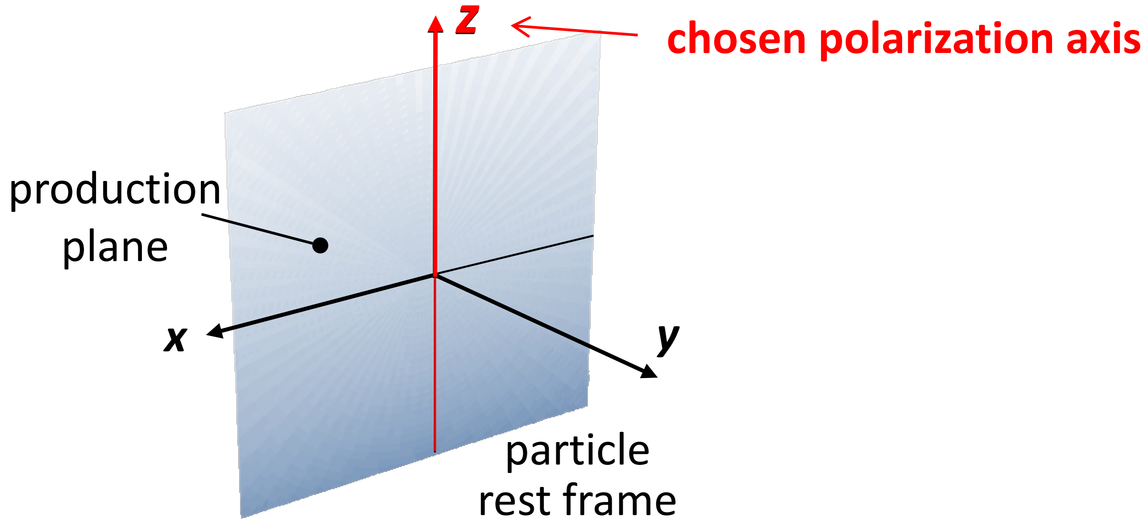

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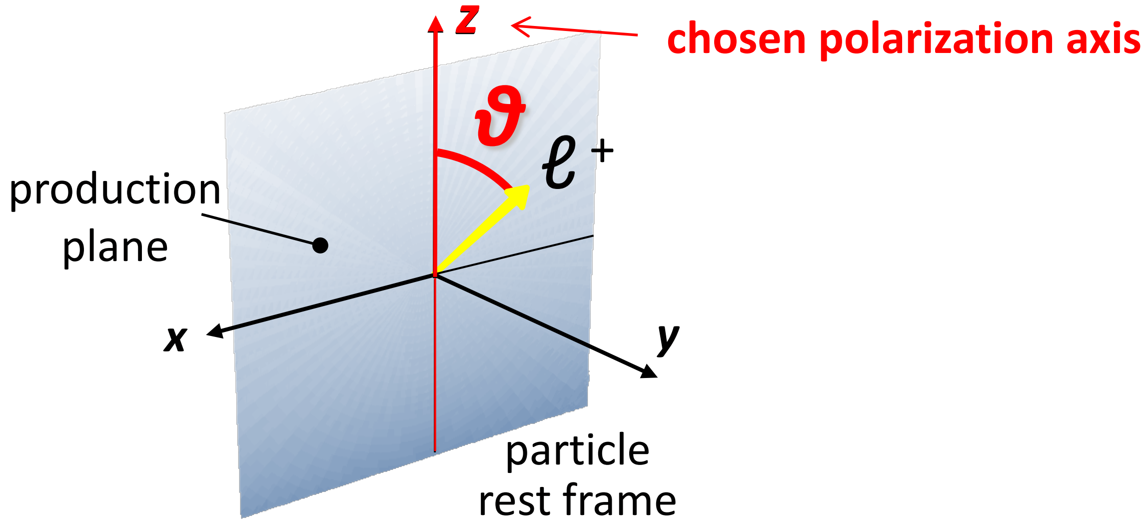

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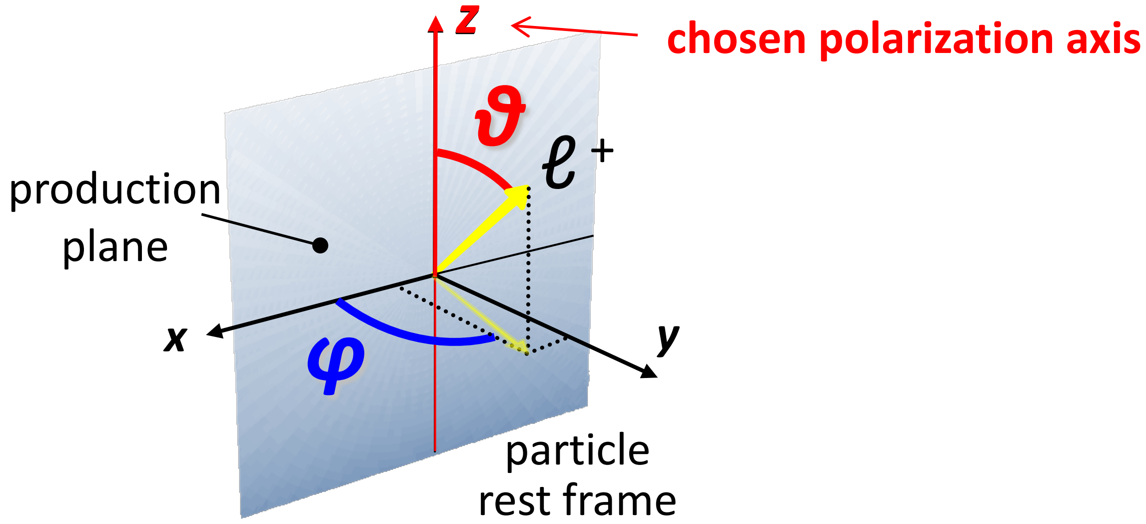

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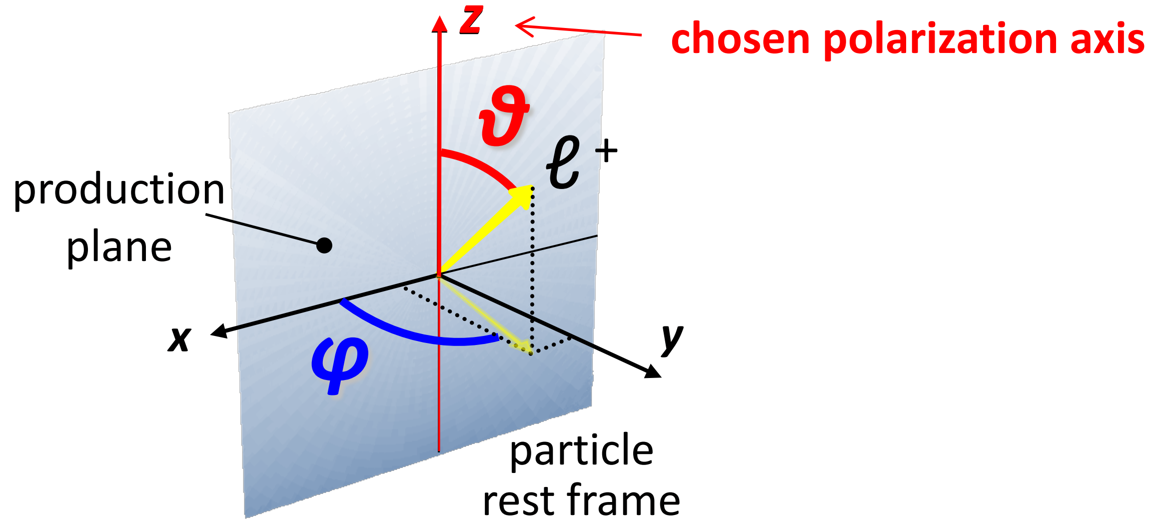

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

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

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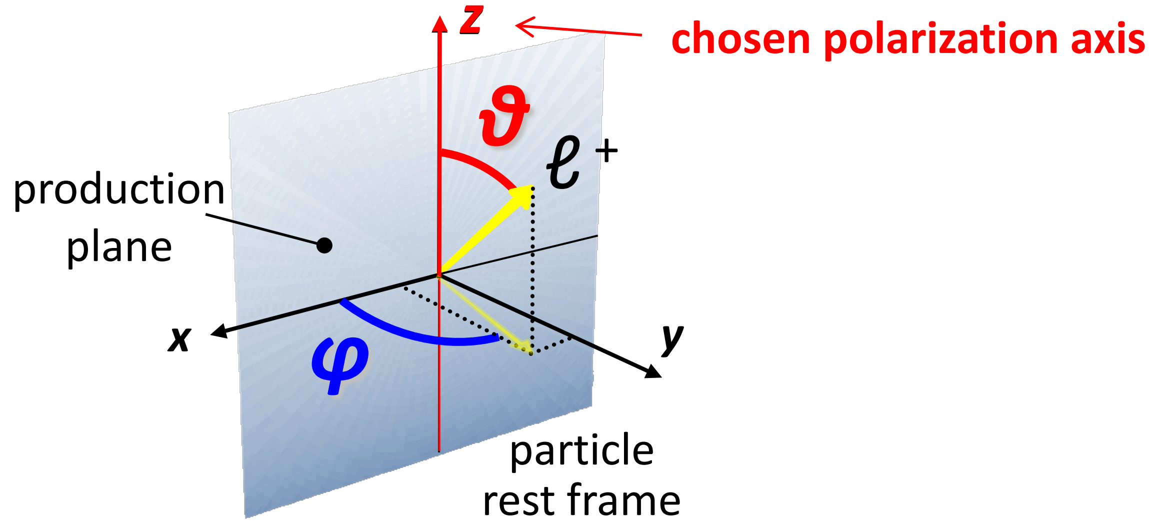

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parity violating

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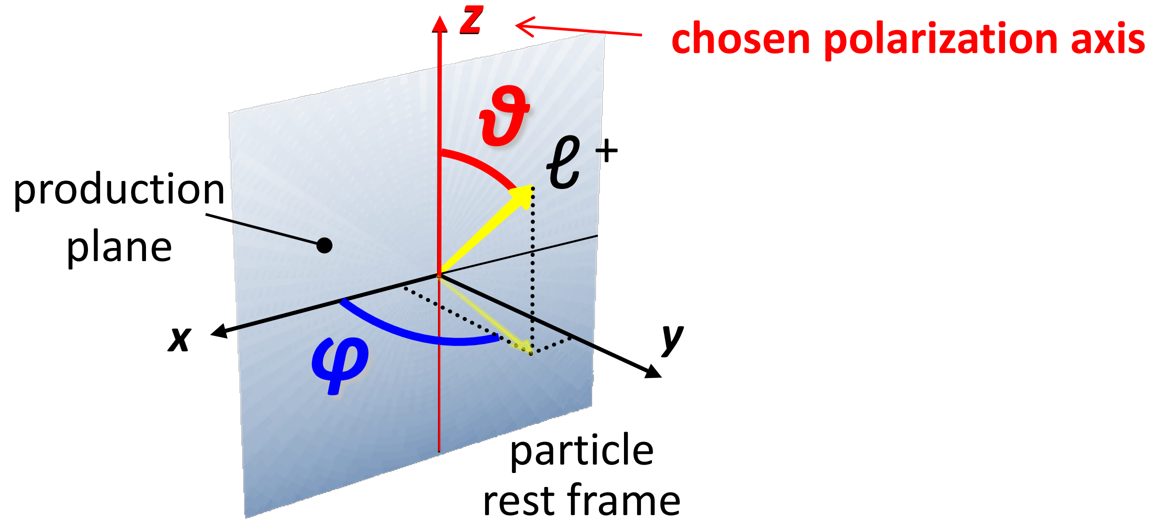

average
polar anisotropy

average
azimuthal anisotropy

correlation
polar - azimuthal

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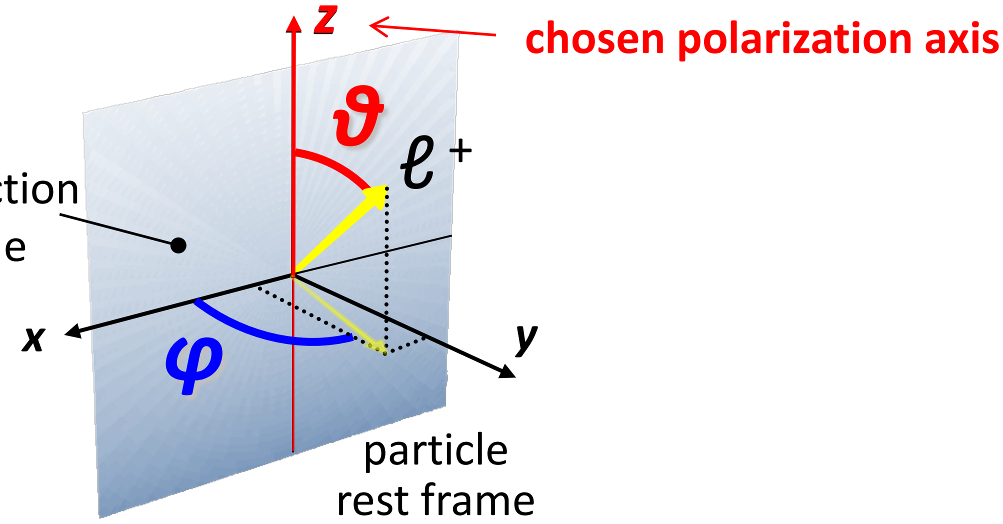

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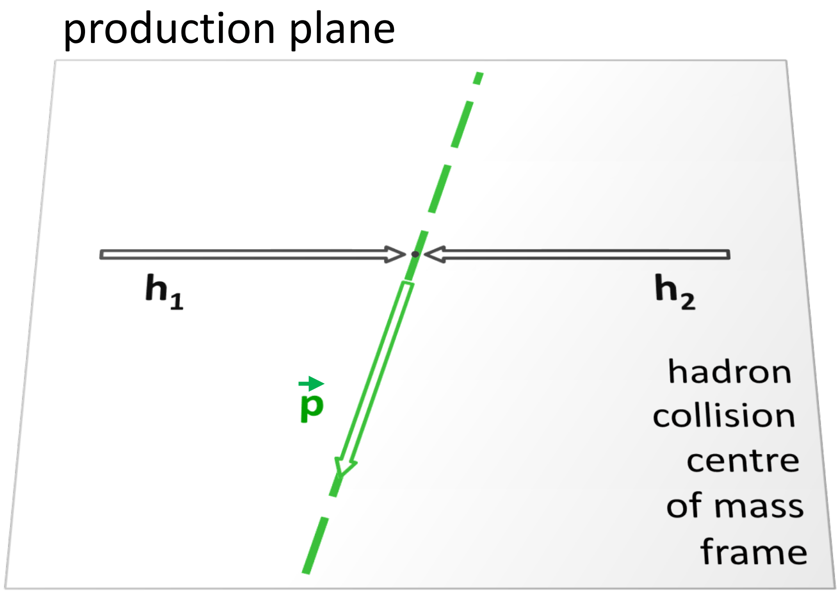
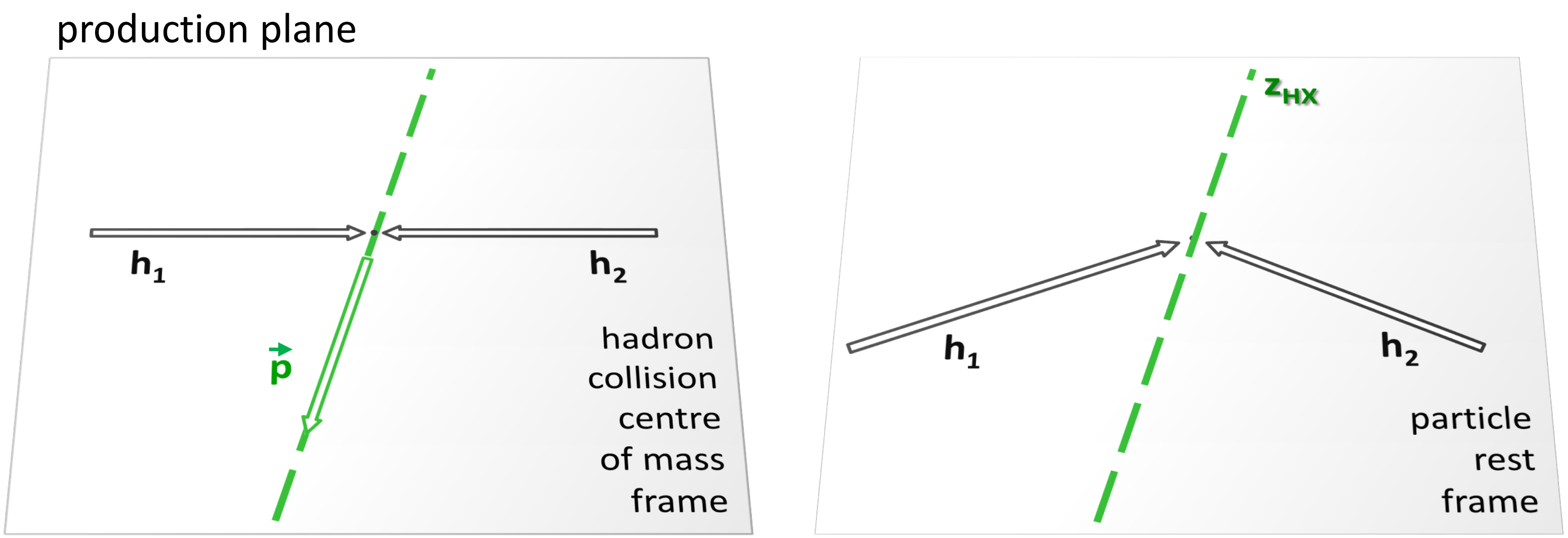
Polarization frames



Polarization frames

Helicity axis (HX): quarkonium momentum direction

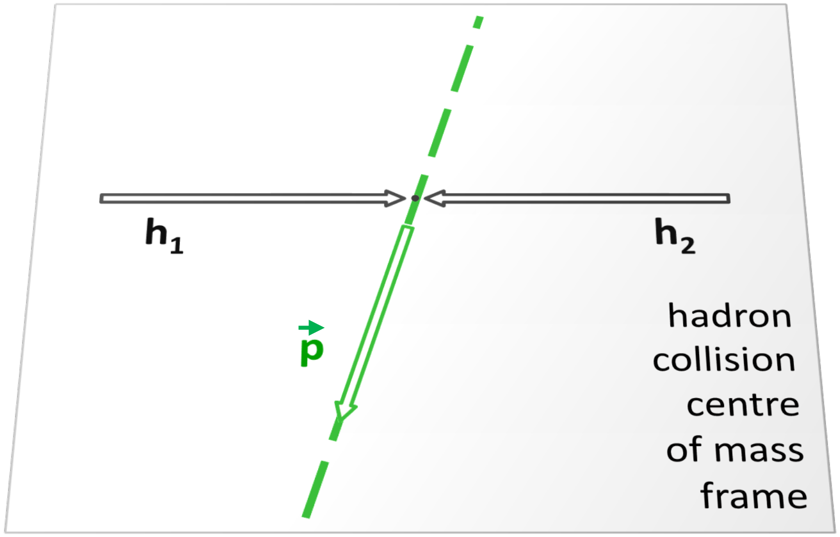


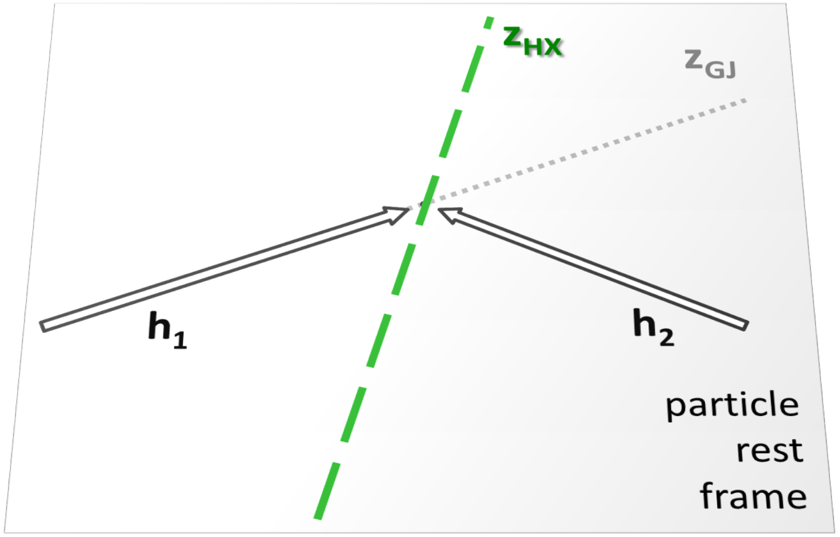
Polarization frames

Helicity axis (HX): quarkonium momentum direction

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

production plane





Polarization frames

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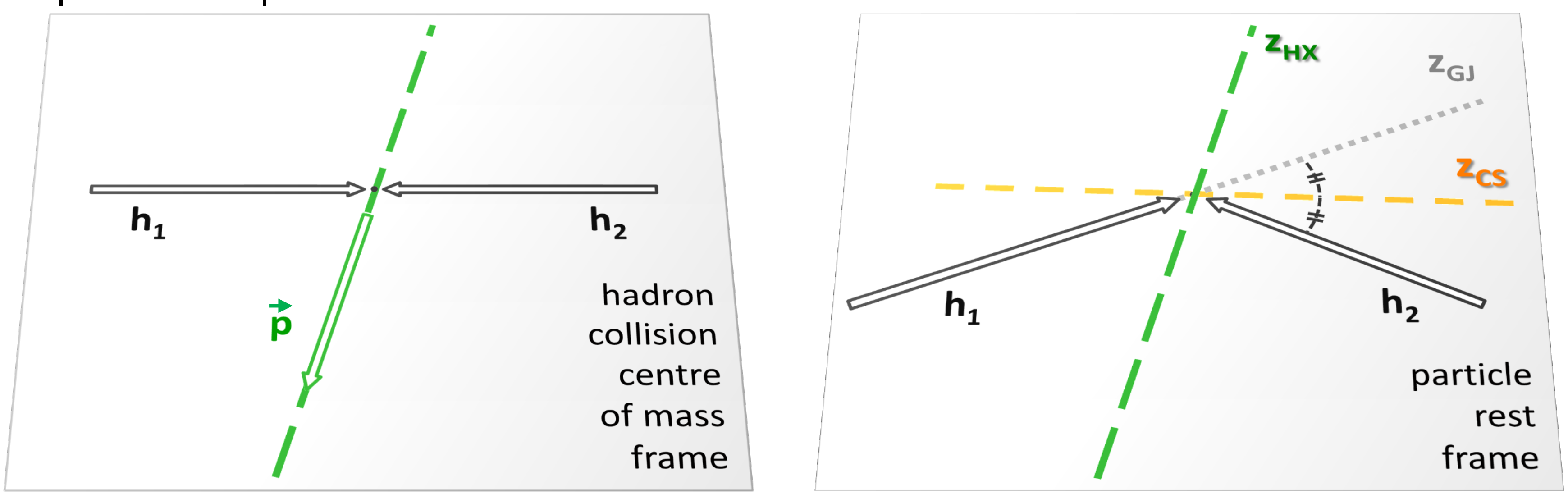
Gottfried-Jackson axis (GJ): direction of one or the other beam

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

production plane



Polarization frames

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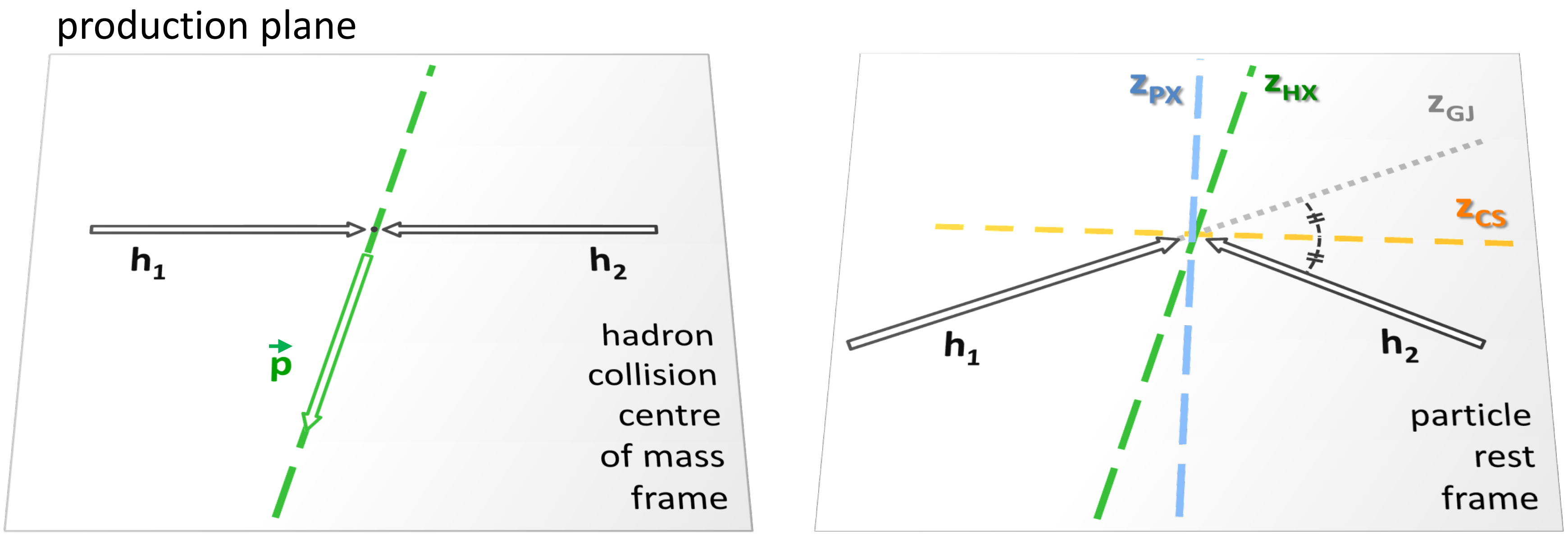
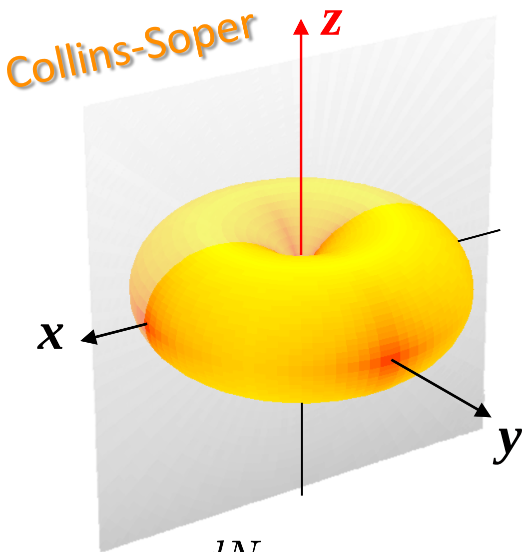
Collins-Soper axis (CS): average of the two beam directions

Perpendicular helicity axis (PX): perpendicular to CS



The observed polarization depends on the frame

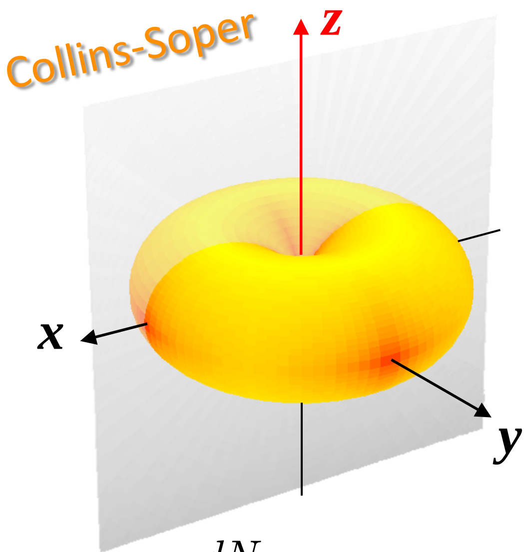


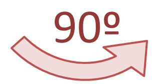
$$\frac{dN}{d\Omega} \propto 1 - \cos^2\theta$$

longitudinal

The observed polarization depends on the frame

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





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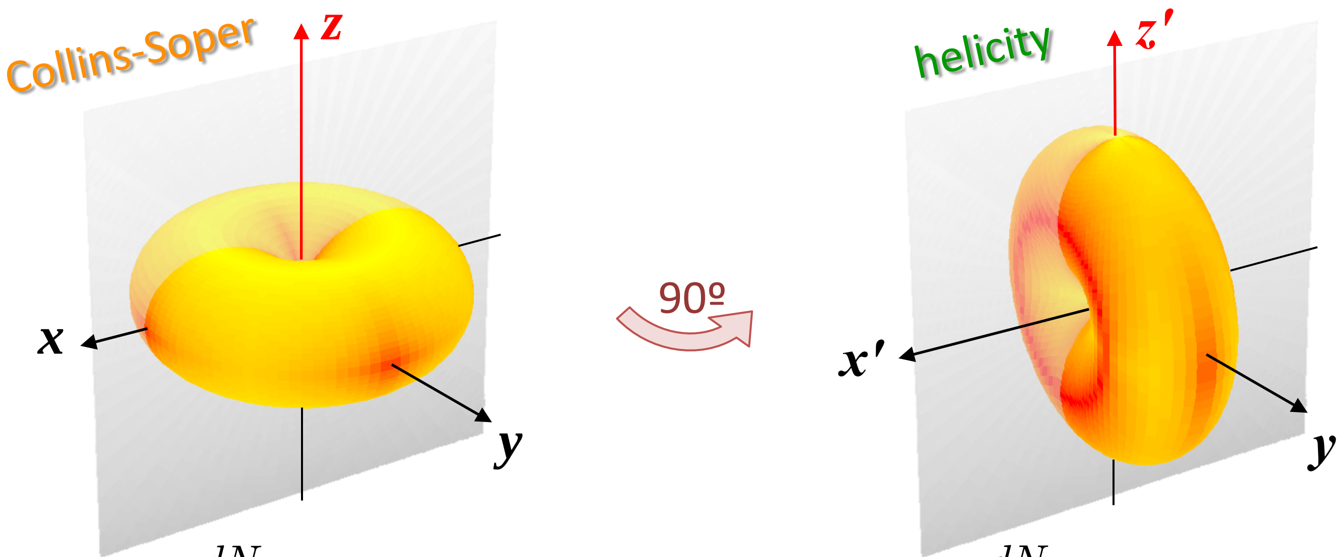

$$\frac{dN}{d\Omega} \propto 1 - \cos^2\theta$$

longitudinal

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

“transverse”

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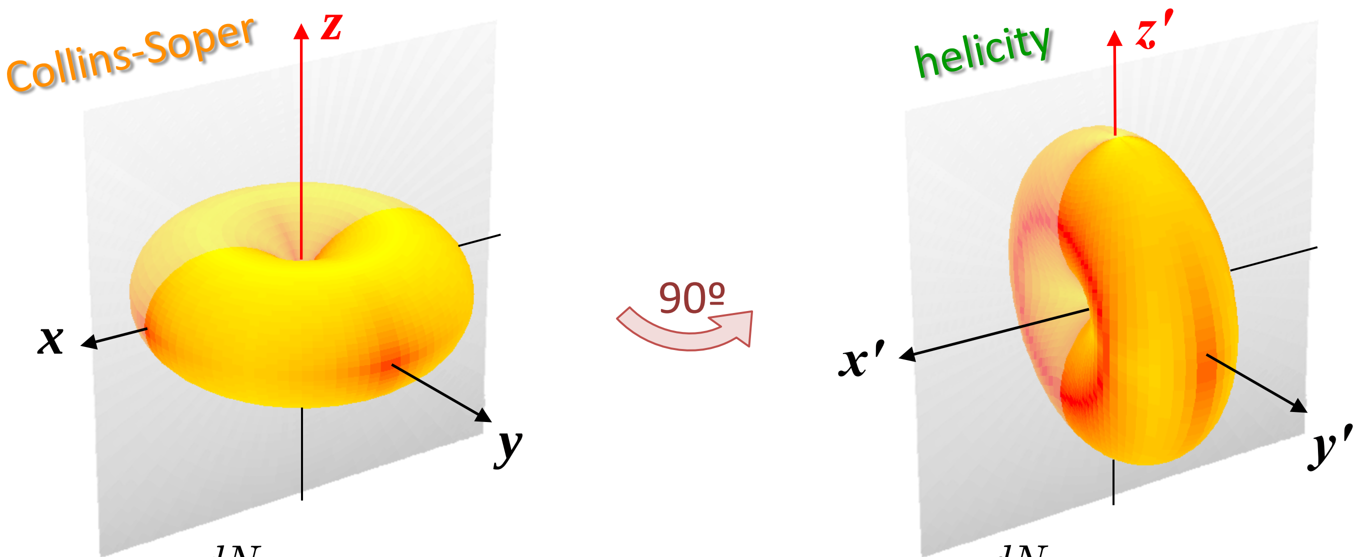

$$\frac{dN}{d\Omega} \propto 1 - \cos^2\theta$$

longitudinal

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

(pure state)

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

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

(mixed state)

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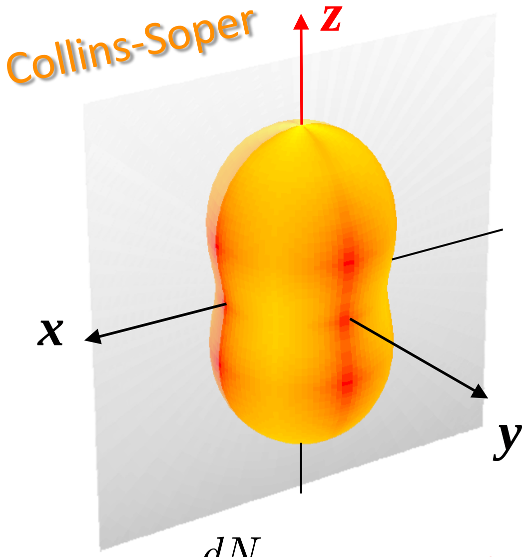

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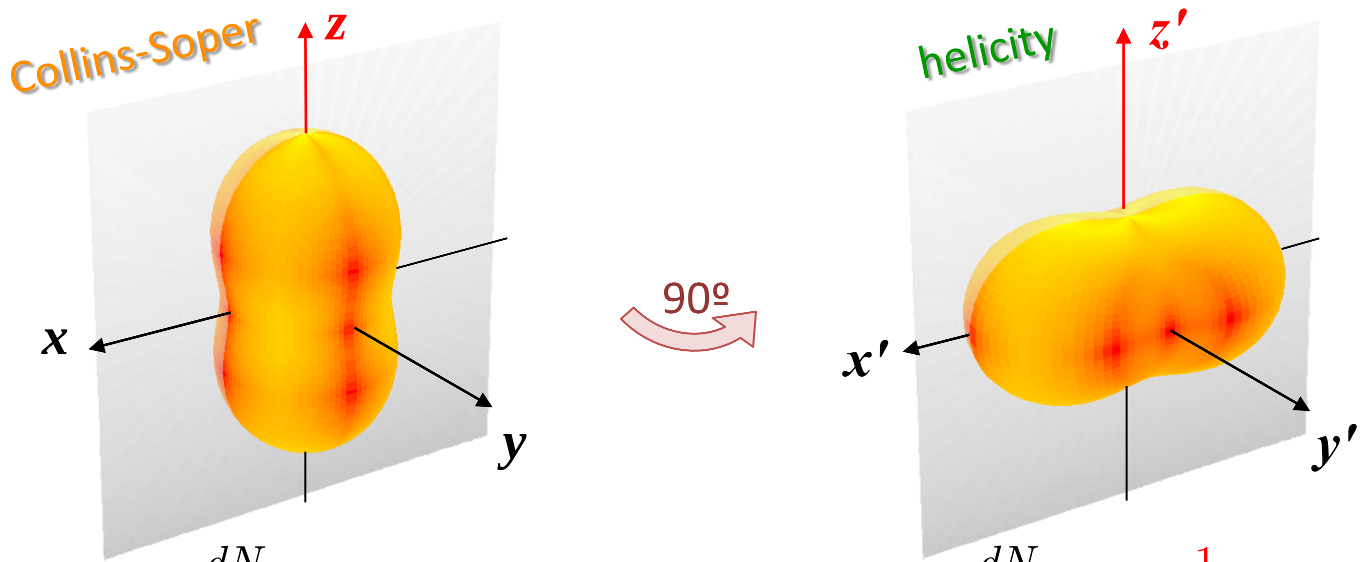

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$$\frac{dN}{d\Omega} \propto 1 - \frac{1}{3}\cos^2\theta + \frac{1}{3}\sin^2\theta\cos 2\varphi$$

moderately “longitudinal”

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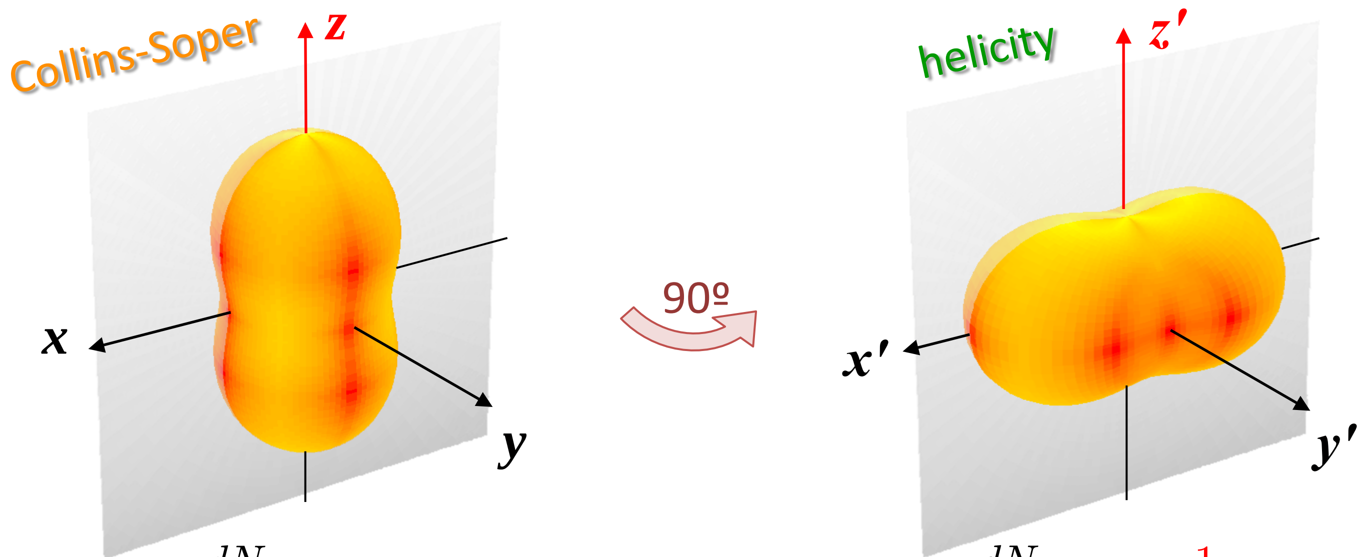

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moderately "longitudinal"

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

(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^-	$\|y\| < 0.9$
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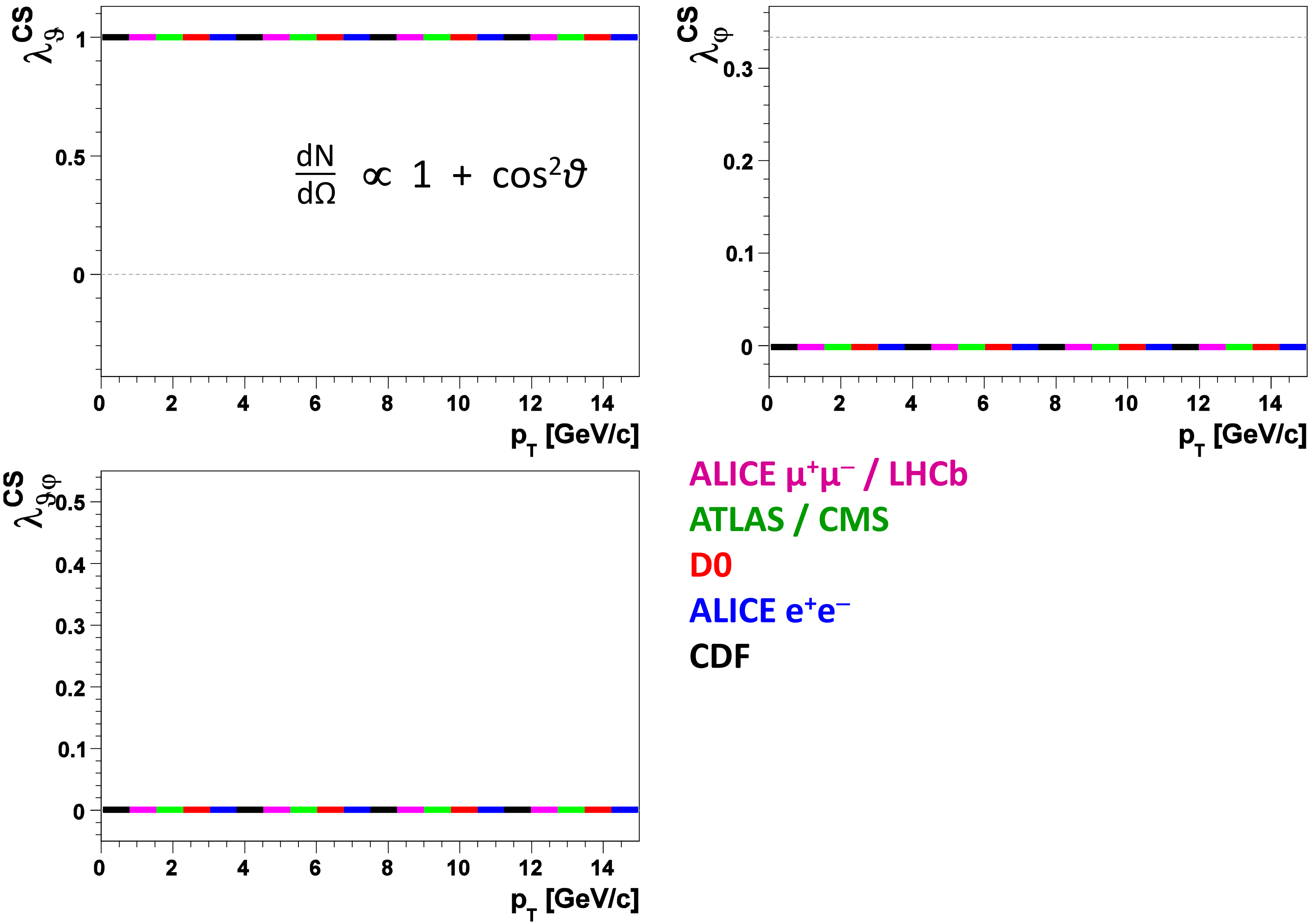
The lucky frame choice

(CS in this case)



Less lucky choice

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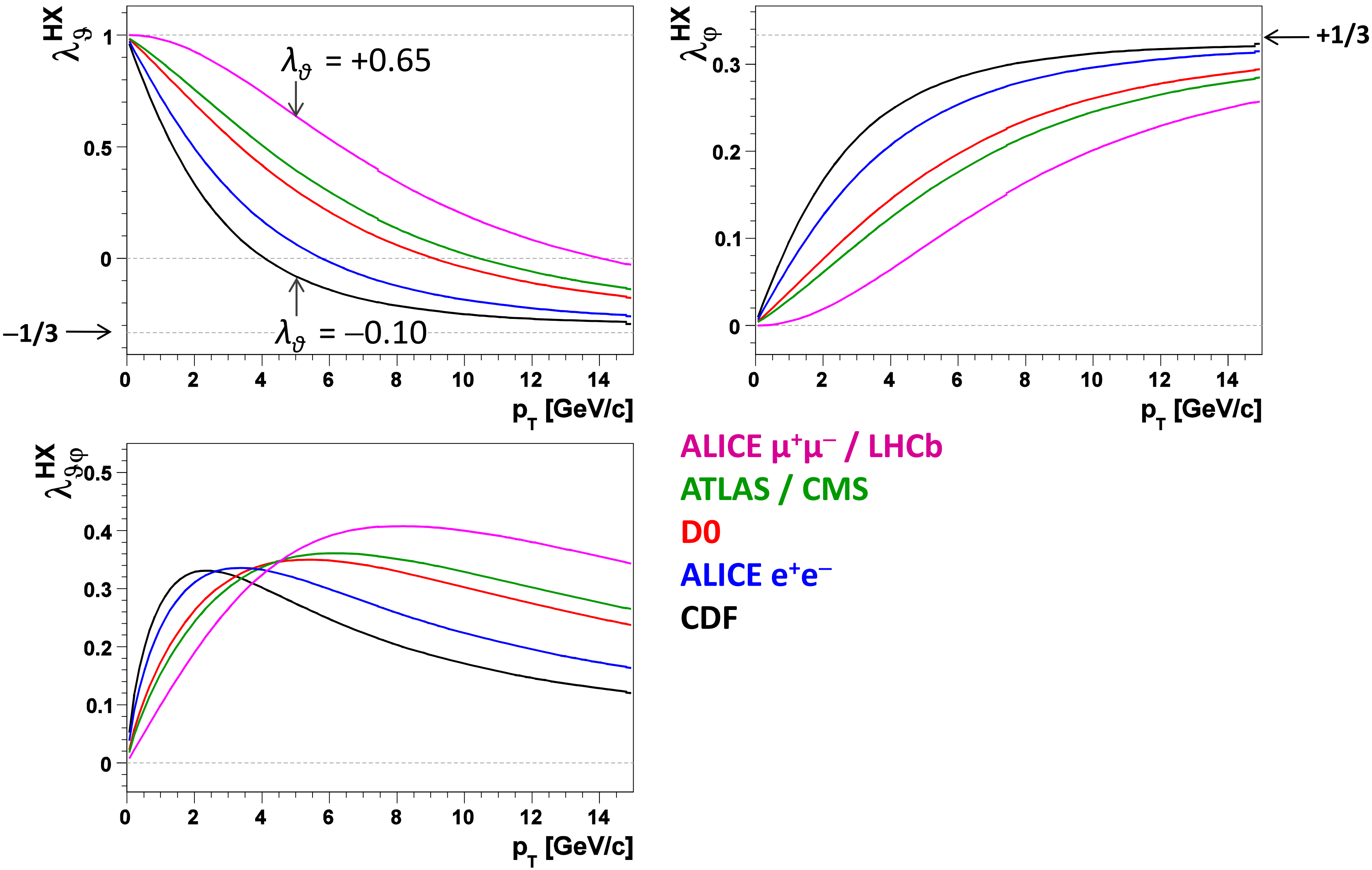

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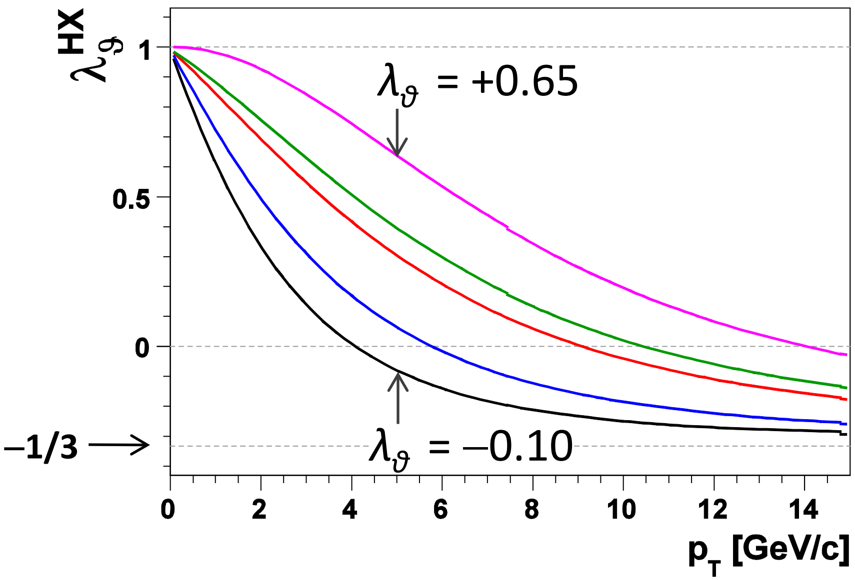
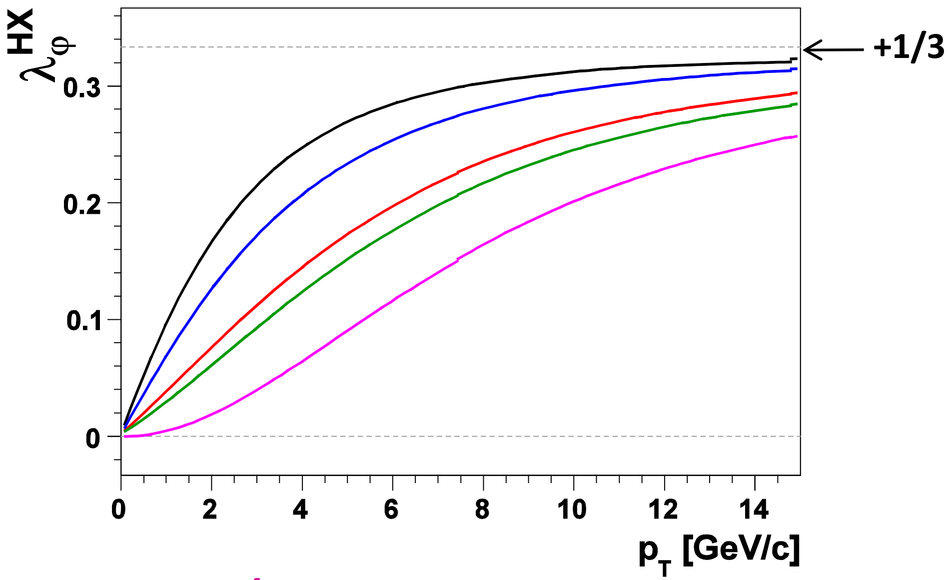
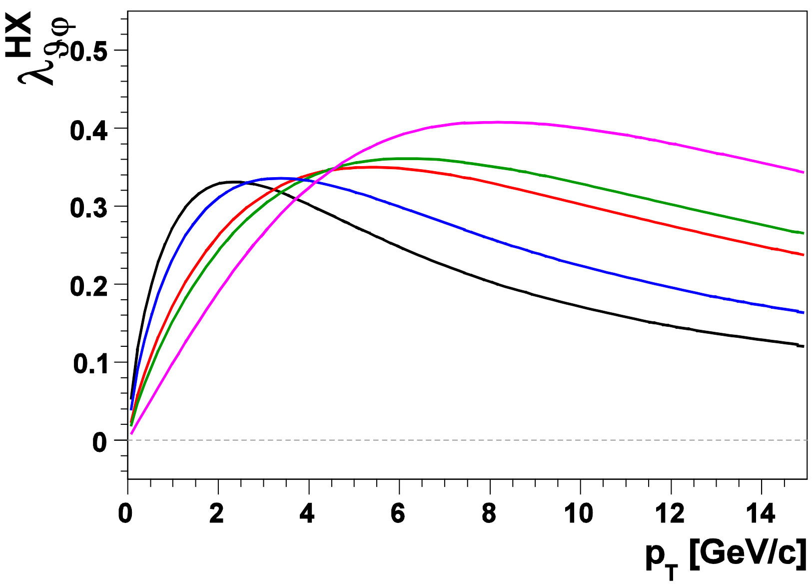






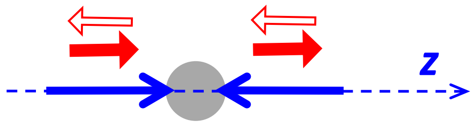
ALICE $\mu^+\mu^-$ / LHCb
ATLAS / CMS
D0
ALICE e^+e^-
CDF

artificial (experiment-dependent!) kinematic behaviour
→ measure in more than one frame!

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***

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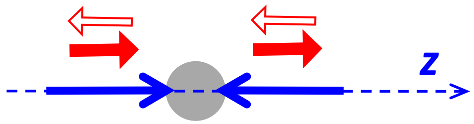

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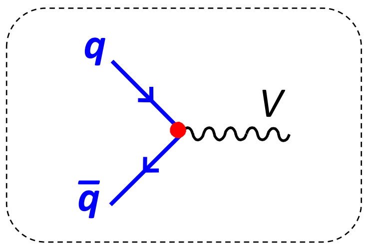
- ...but with respect to a ***subprocess-dependent quantization axis***

$O(\alpha_S^0)$ →



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

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

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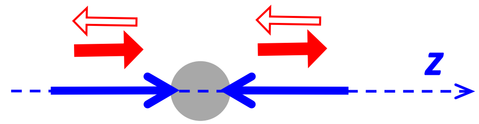

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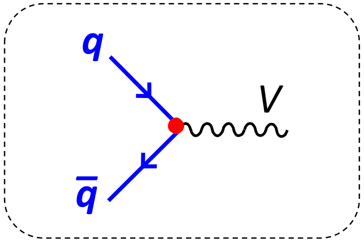

z = relative dir. of incoming *q* and *q*bar
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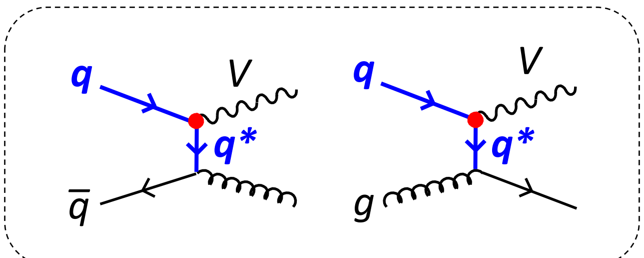
$O(\alpha_S^1)$
QCD
corrections



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

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

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

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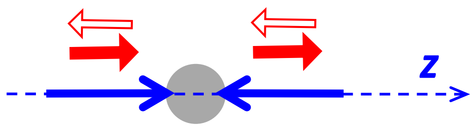

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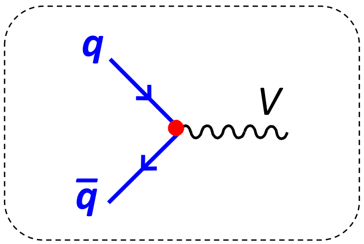

z = relative dir. of incoming *q* and *q*bar
(~ **Collins-Soper frame**)

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

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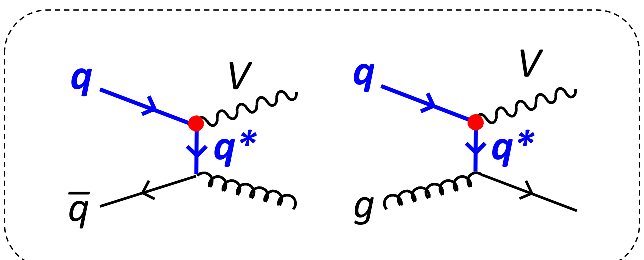
corrections



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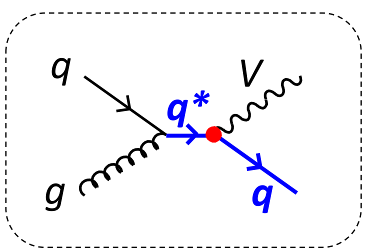
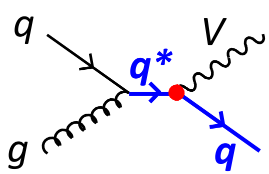


z = dir. of outgoing *q*
(= **parton-cms-helicity** ≈ **lab-cms-helicity**)

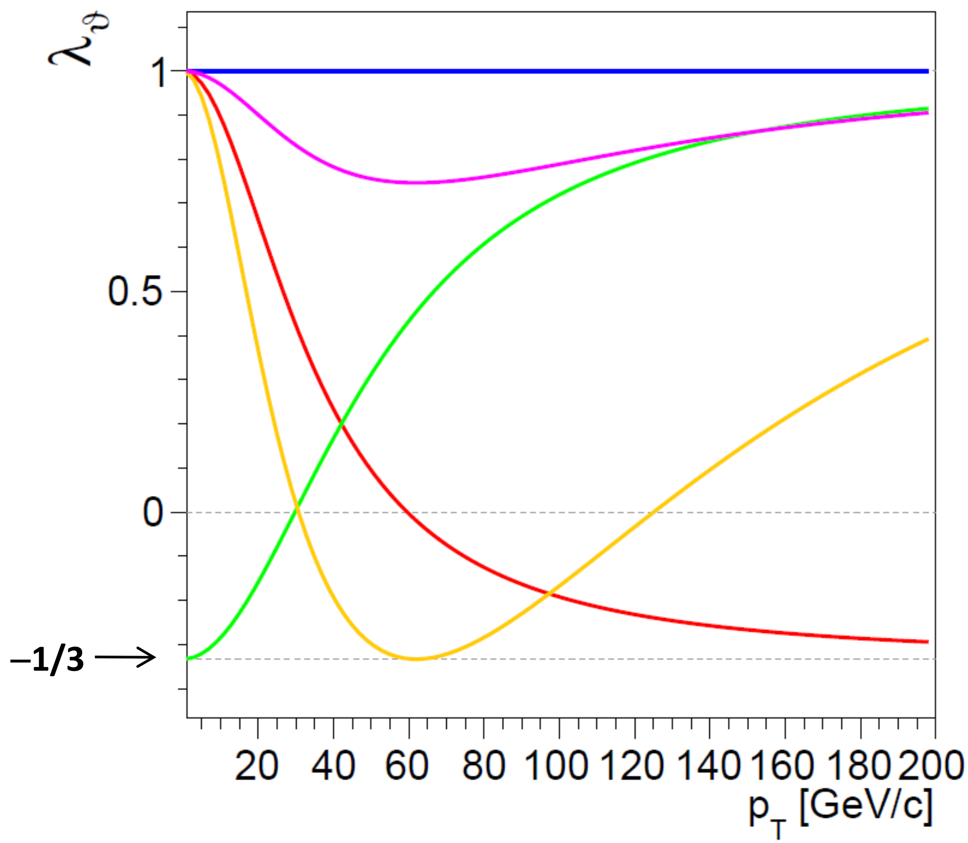
"Optimal" frames for Drell-Yan, *Z* and *W* polarizations

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!)

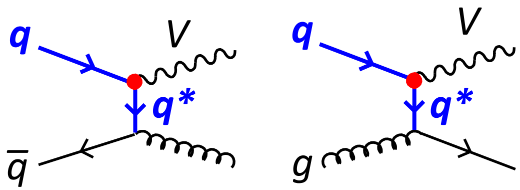


HX
CS
PX
GJ1 (negative beam)
GJ2 (positive beam)

example: Z
$y = +0.5$

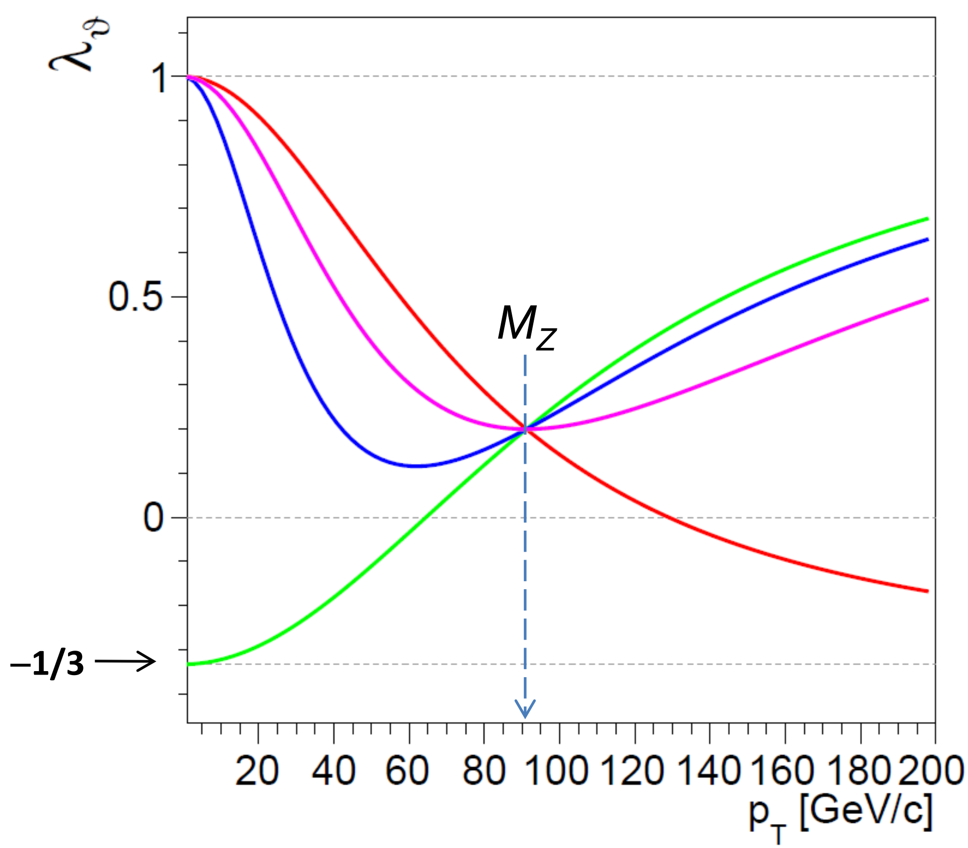
“Optimal” frames for Drell-Yan, *Z* and *W* polarizations

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*)**



HX
CS
PX
GJ1 = GJ2

example: Z
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A complementary approach: frame-independent polarization

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

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→ it can be characterized by frame-independent parameters:

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

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

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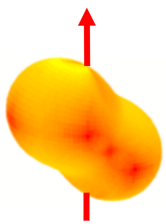
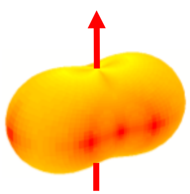
$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$



$\lambda_\vartheta = +1/5$
$\lambda_\varphi = +1/5$



$\lambda_\vartheta = -1/3$
$\lambda_\varphi = +1/3$

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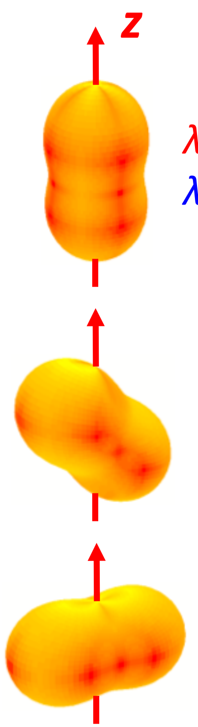

λ_ϑ = +1
λ_φ = 0

λ_ϑ = +1/5
λ_φ = +1/5

λ_ϑ = −1/3
λ_φ = +1/3

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

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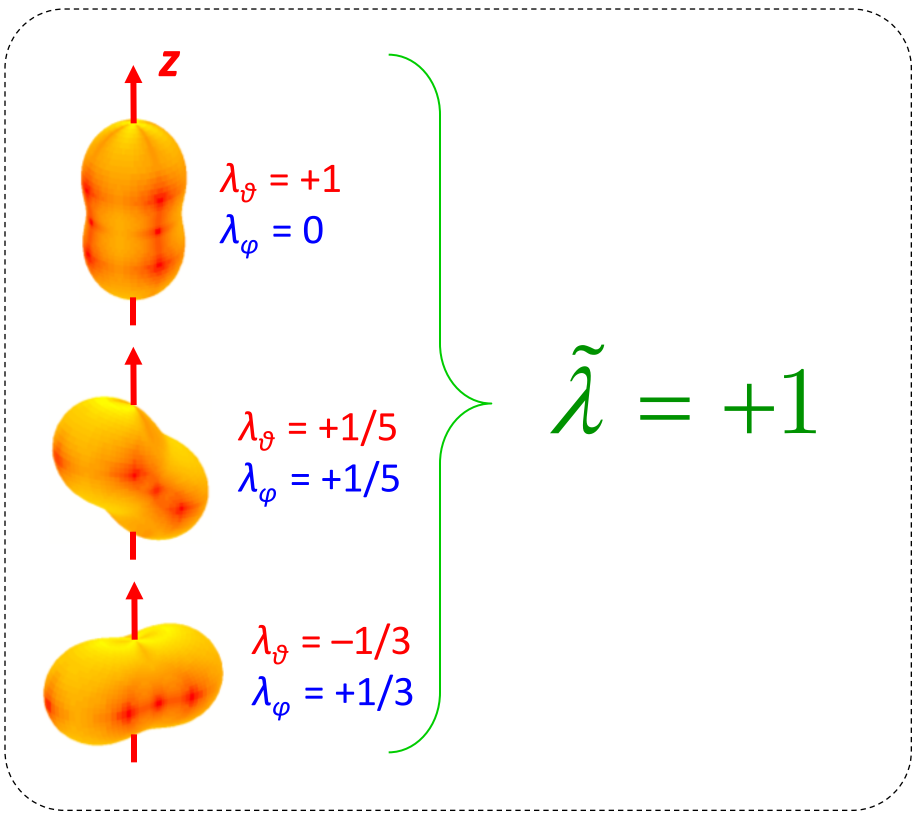

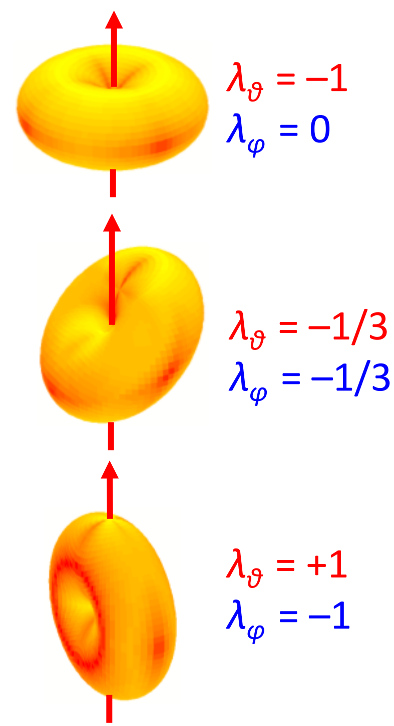

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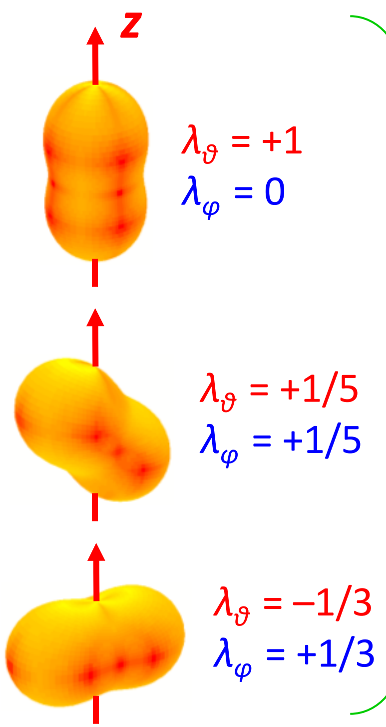
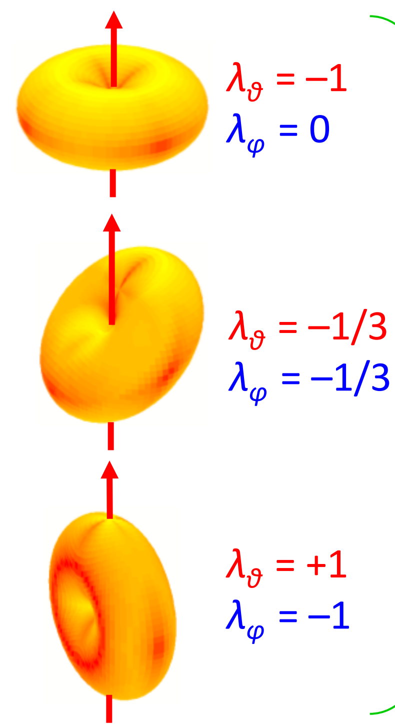


$$\tilde{\lambda} = +1$$



$$\tilde{\lambda} = -1$$

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

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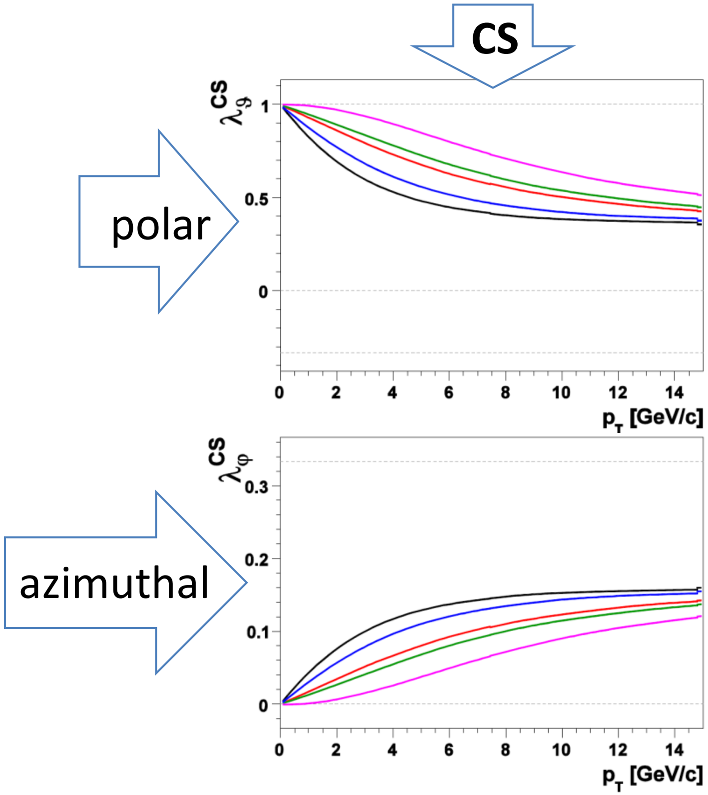

M = 10 GeV/c^2

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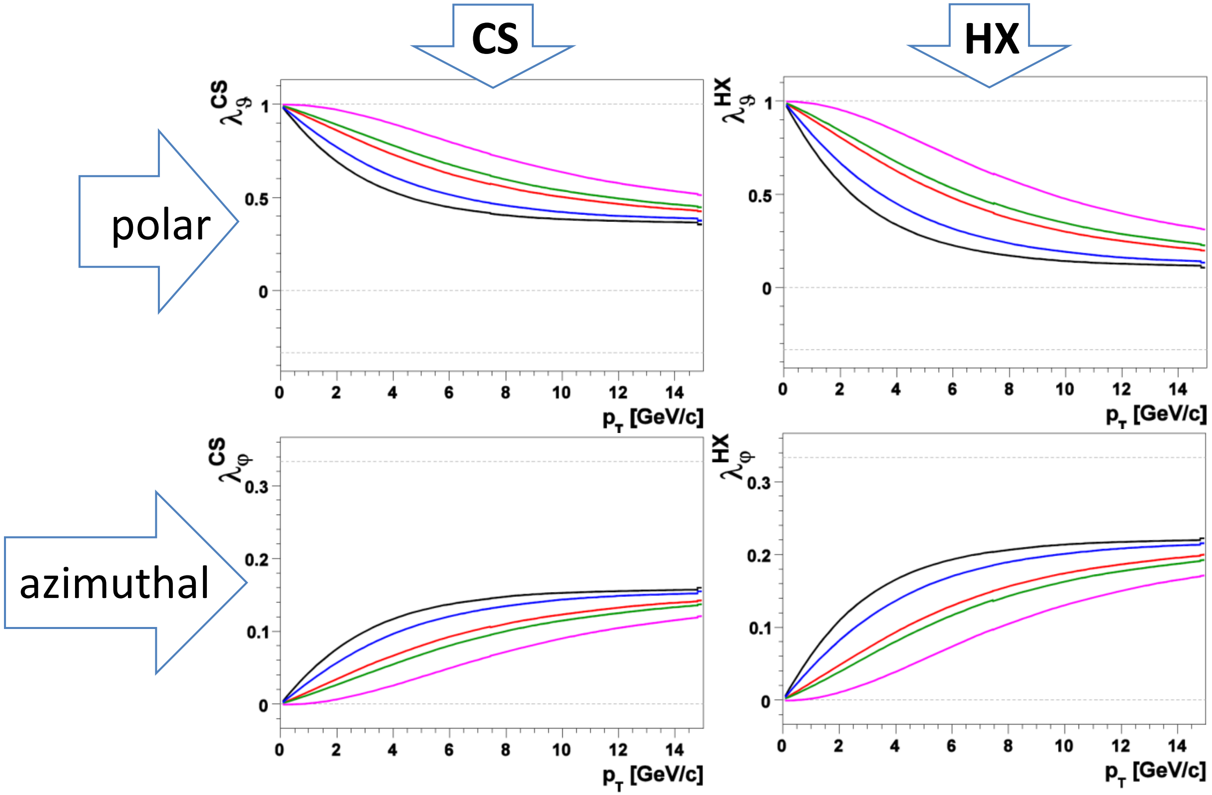

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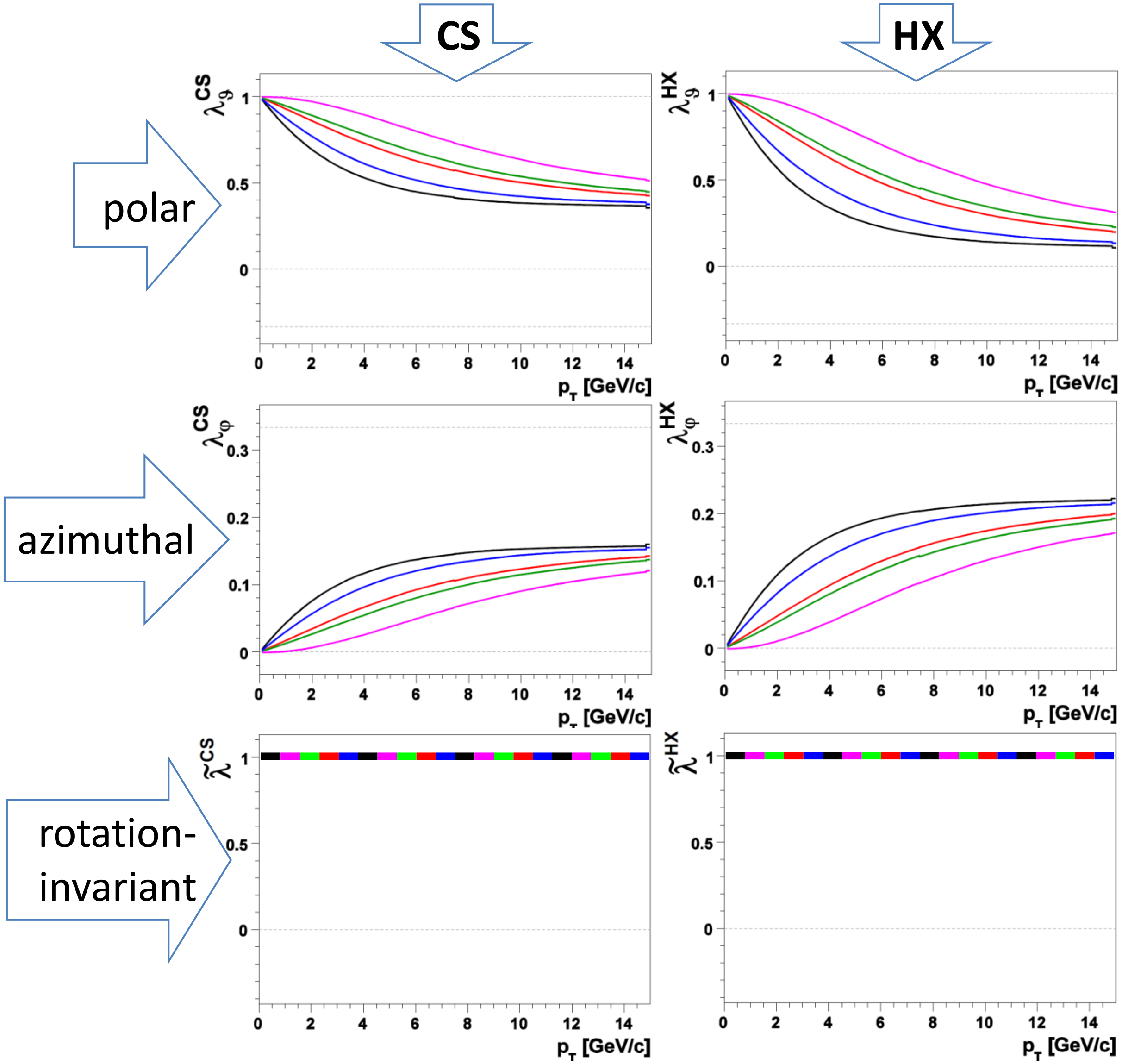

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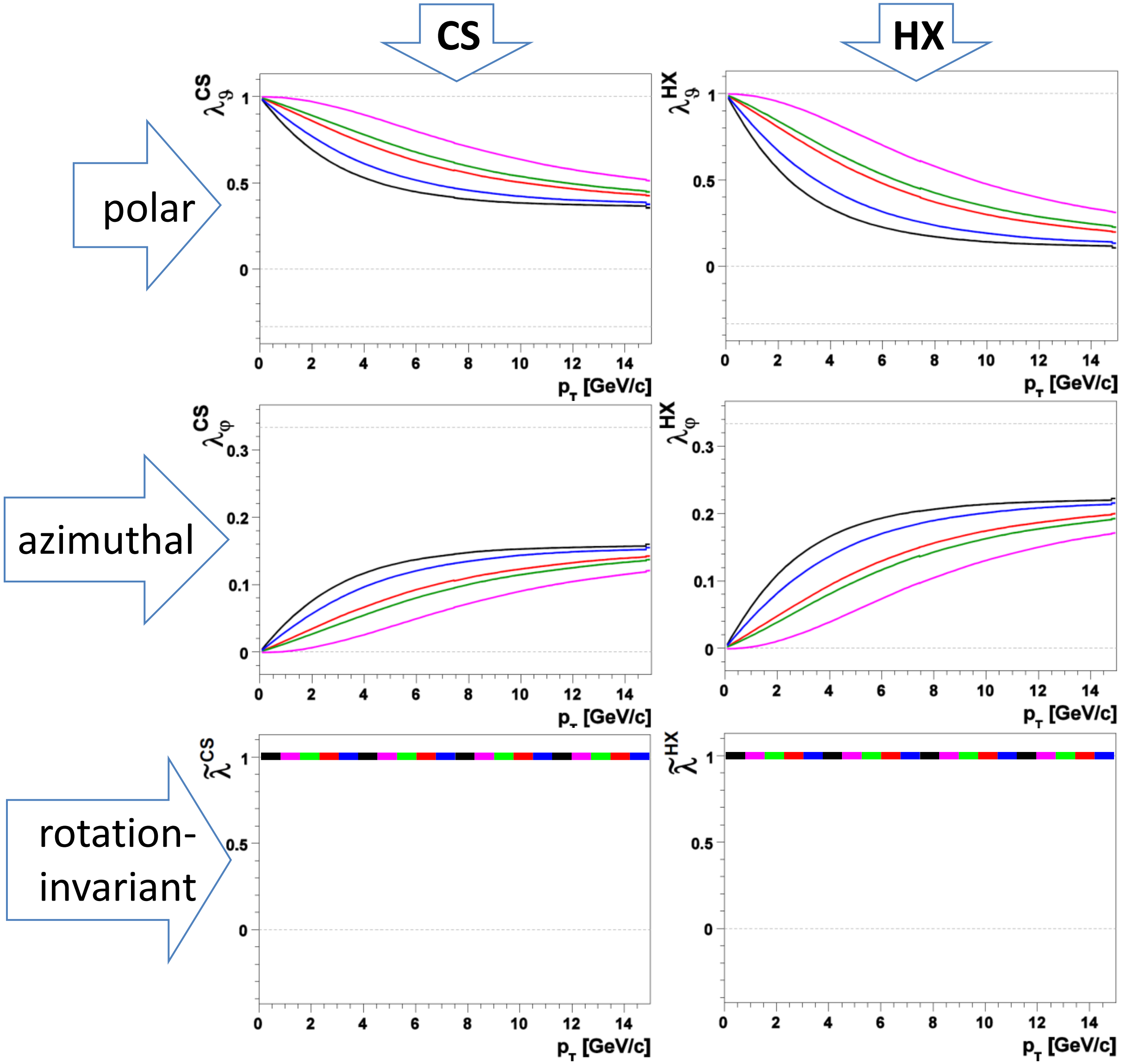

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- Immune to "extrinsic" kinematic dependencies

→ *less acceptance-dependent*

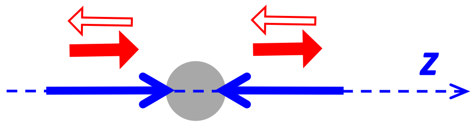
→ *facilitates comparisons*

- *useful as closure test*

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

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

V = γ^*, *Z*, *W*



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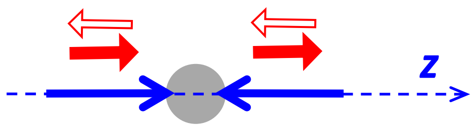

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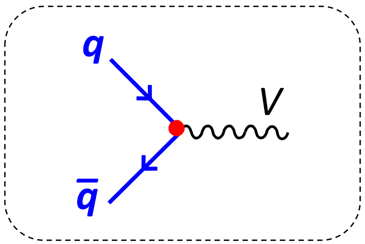
$O(\alpha_S^0) \rightarrow$



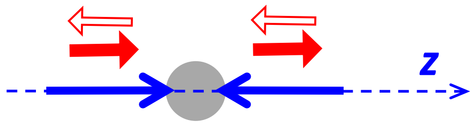
"natural" z = relative dir. of *q* and *q*bar
$\rightarrow$ **λ_ϑ("CS") = +1**

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

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

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

V = γ*, *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***

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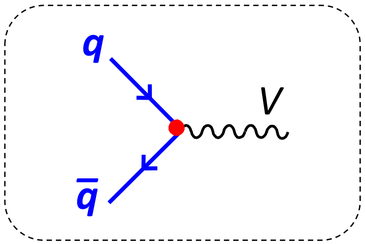

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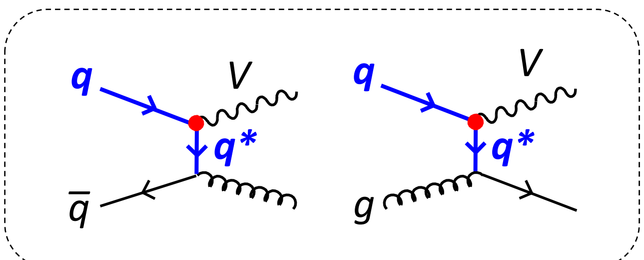
$O(\alpha_S^1)$
(LO) QCD corrections



z = dir. of *one* incoming quark
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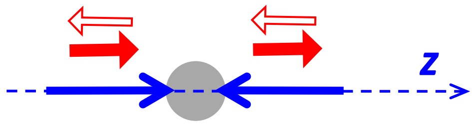
$V = \gamma^*, Z, W$



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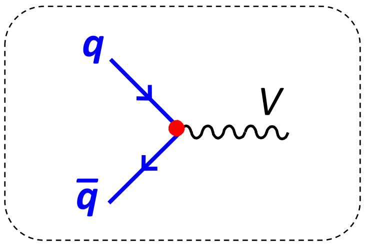

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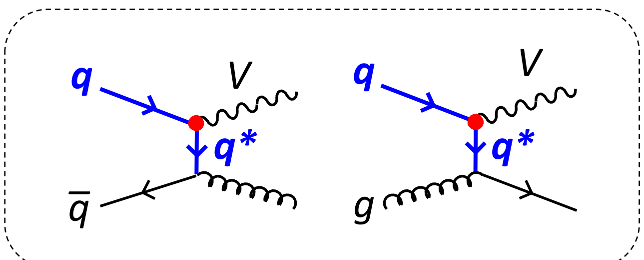

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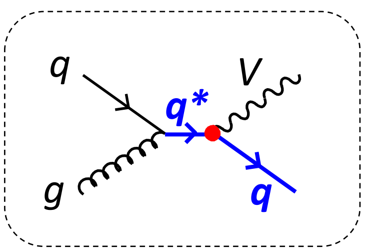

z = dir. of outgoing *q*

→ λ_ϑ("HX") = +1

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

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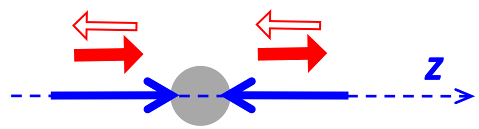

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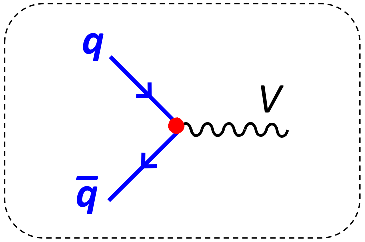

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(LO) QCD
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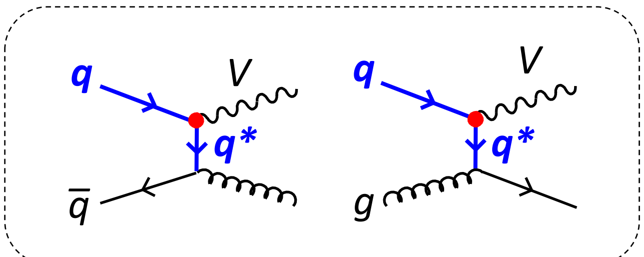

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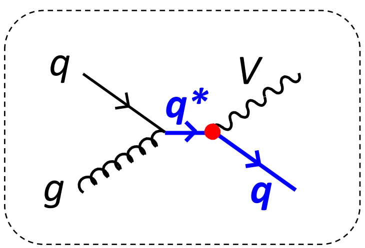

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N.B.: $\tilde{\lambda} = +1$ in both
pp-HX and qg-HX frames!

$\tilde{\lambda} = +1$
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:

λ_ϑ vs $\tilde{\lambda}$

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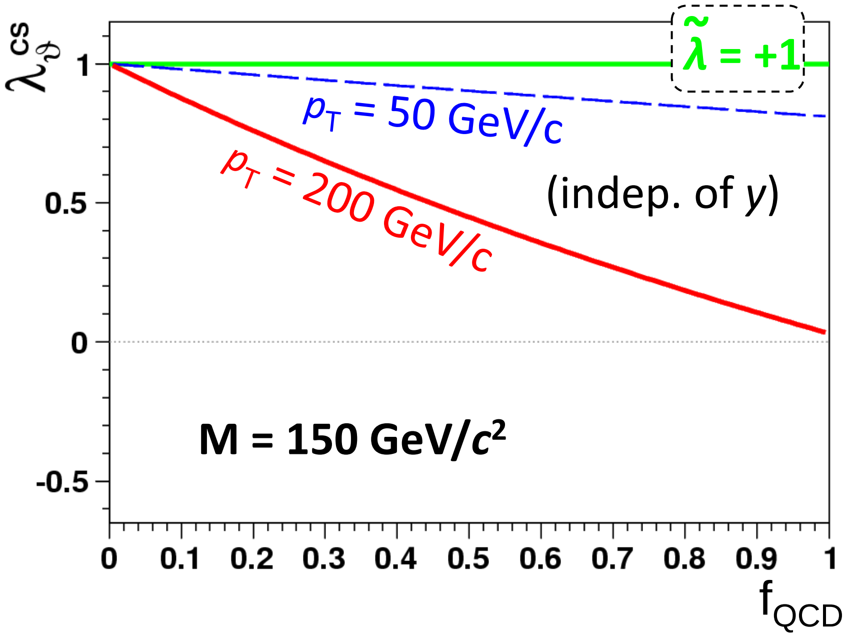

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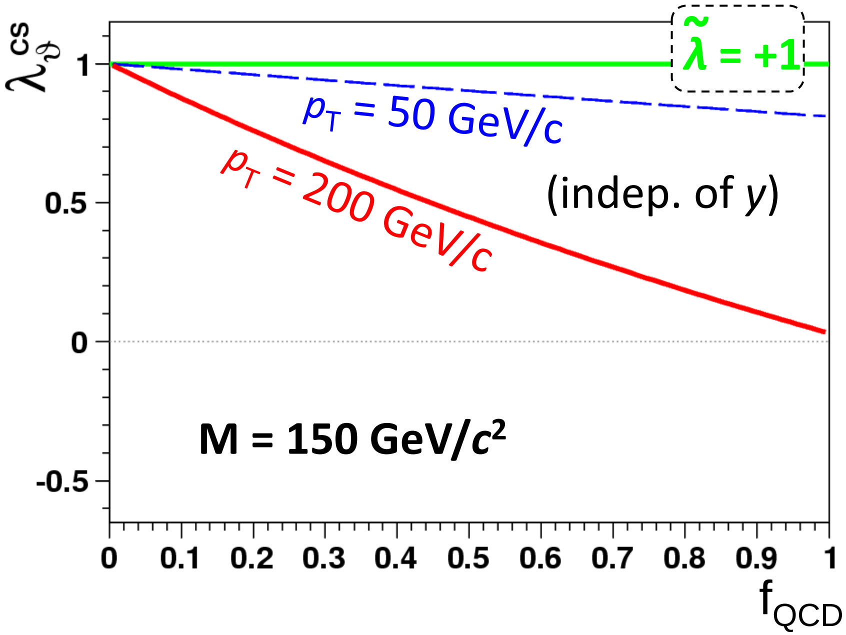
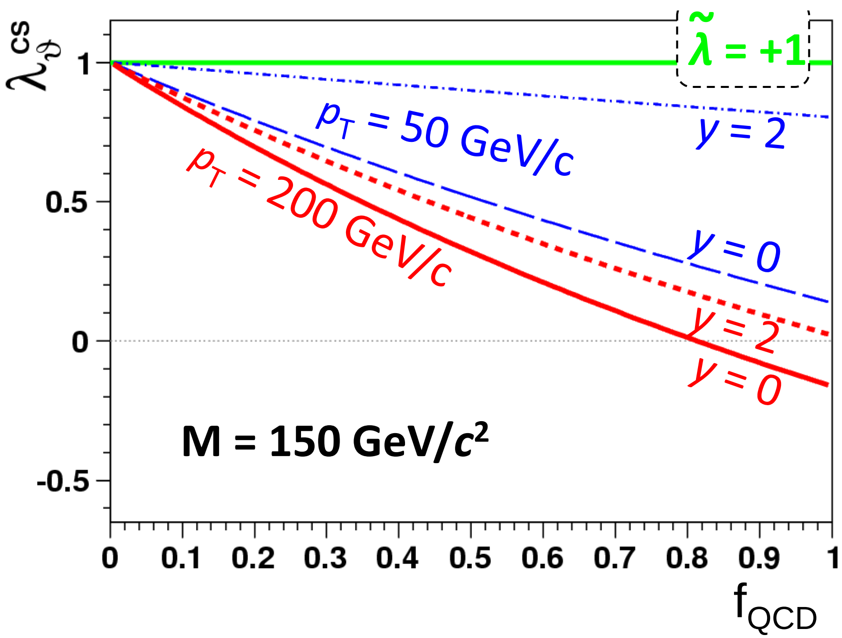


Case 2: dominating ***q-g*** QCD corrections



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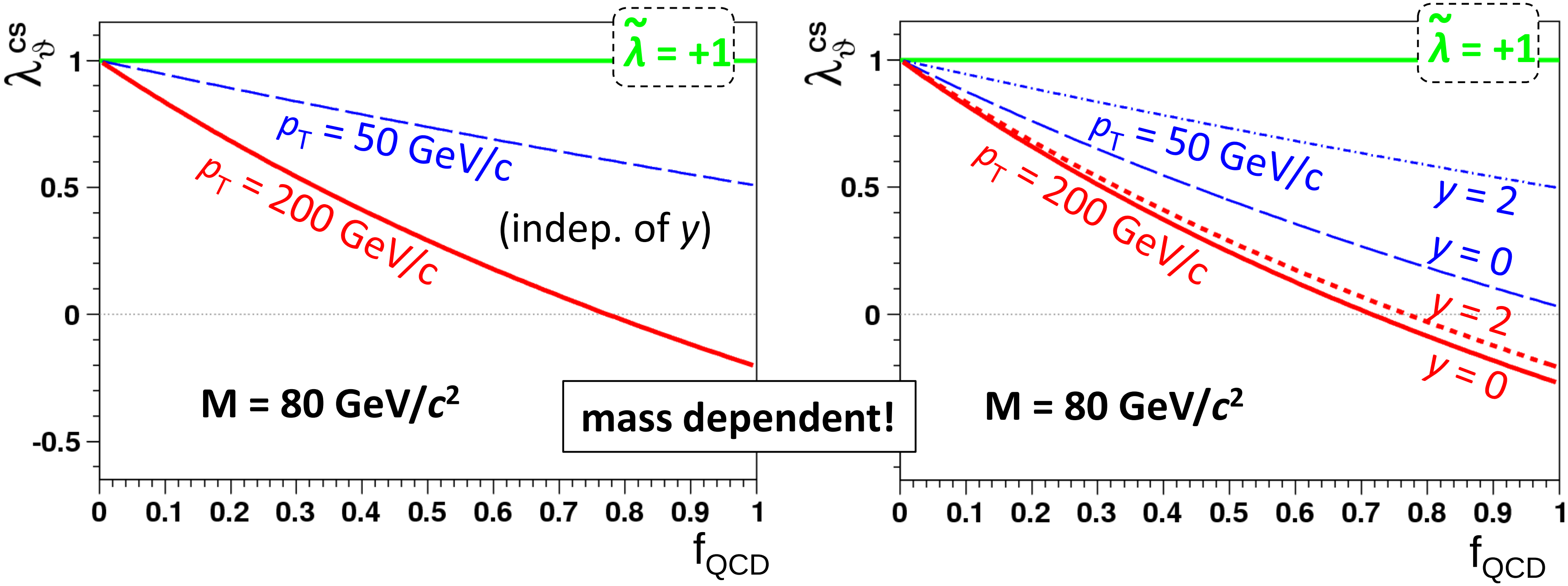

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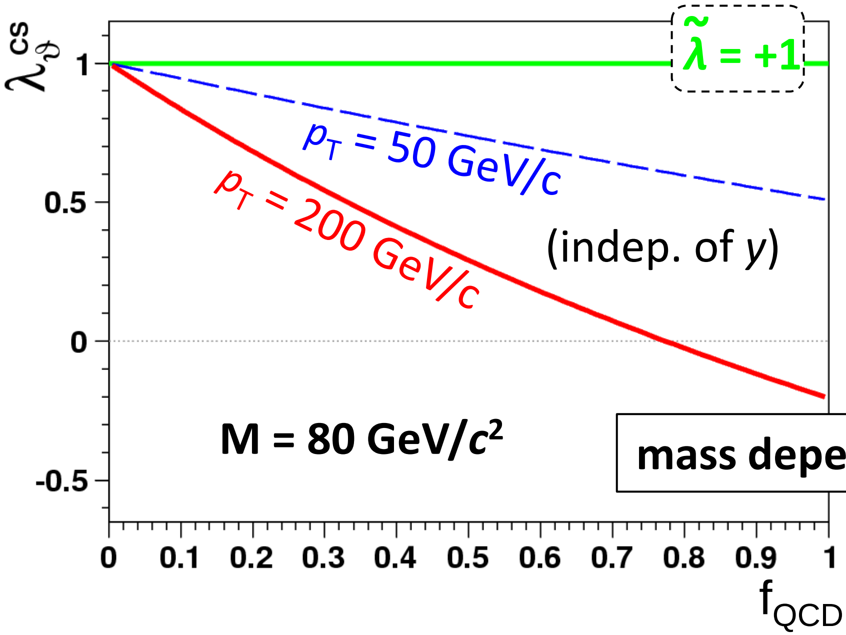
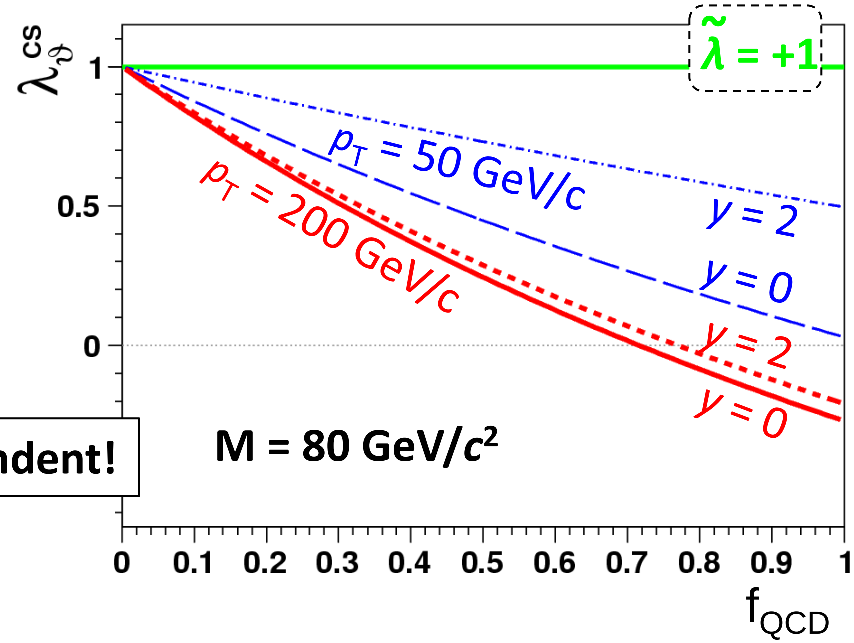
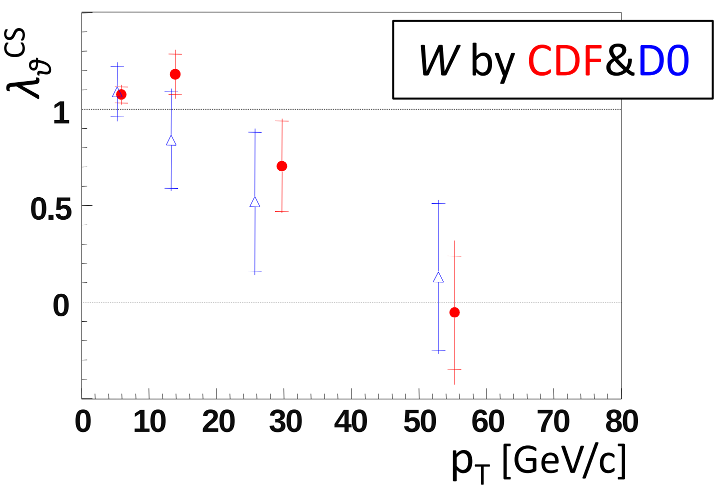


Case 2: dominating ***q-g*** QCD corrections



mass dependent!



λ_ϑ vs $\tilde{\lambda}$

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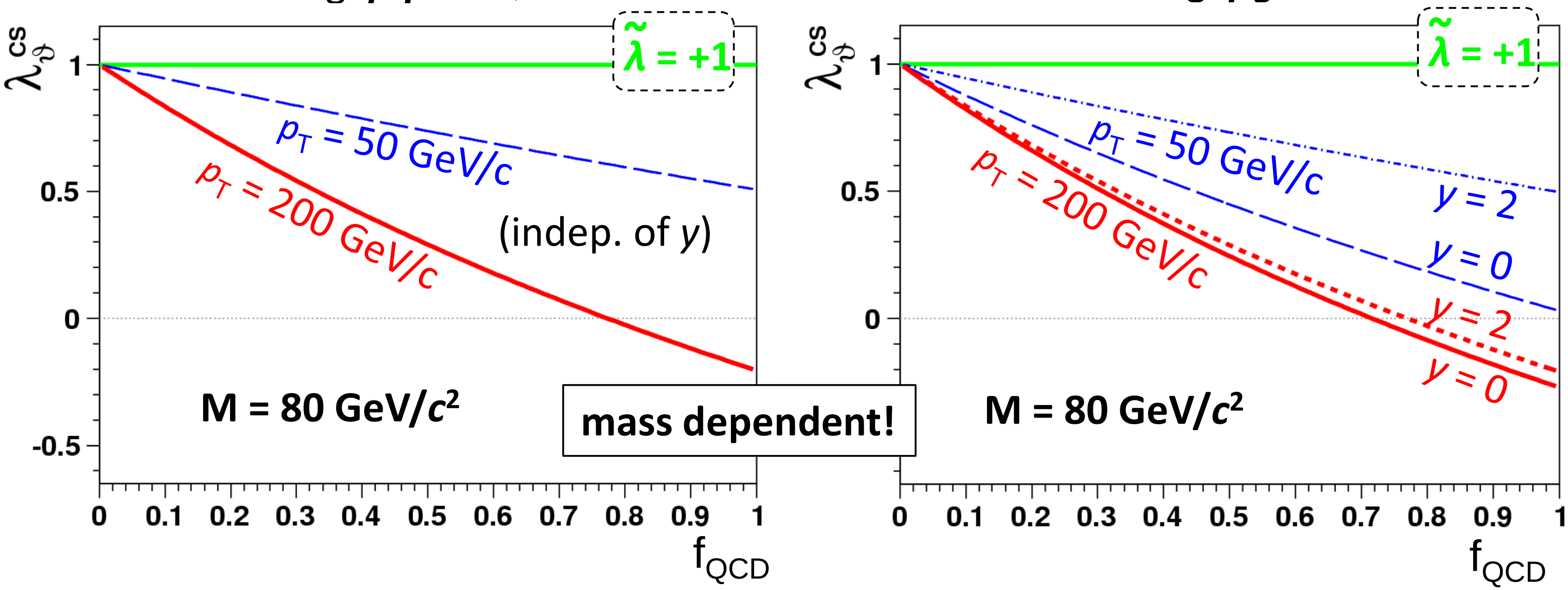

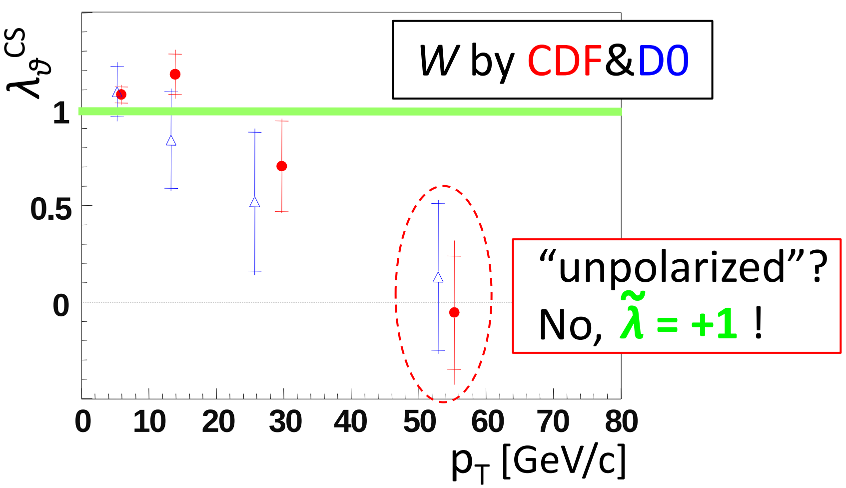

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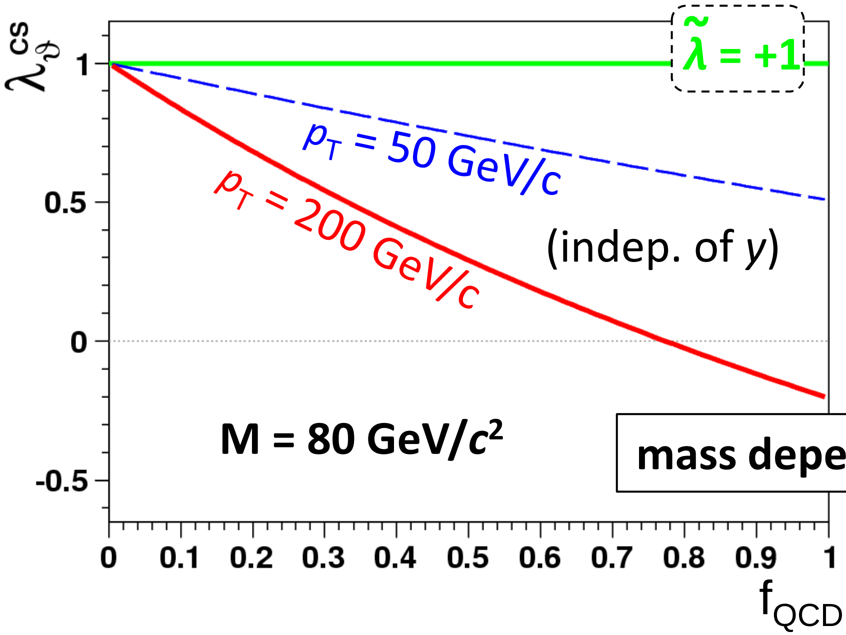

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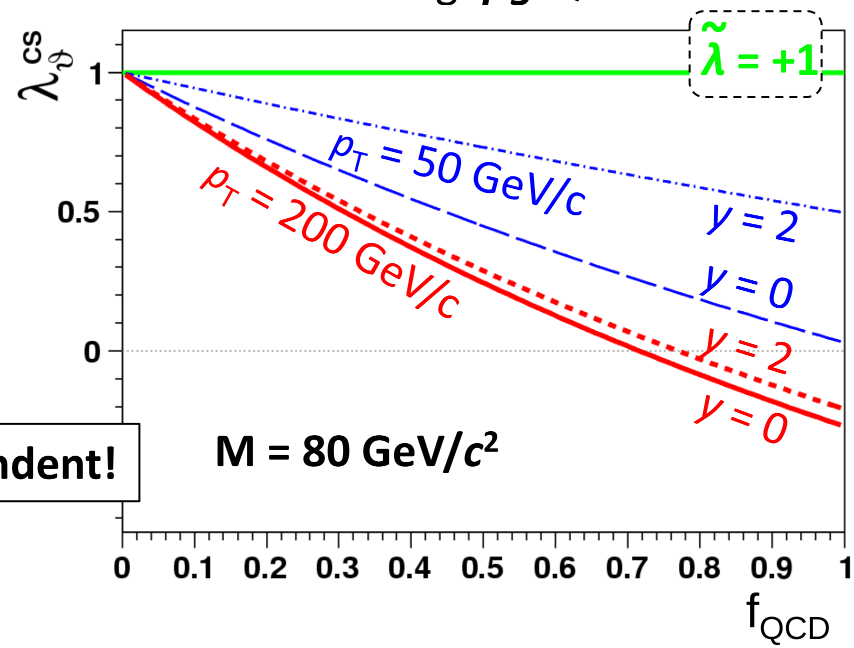

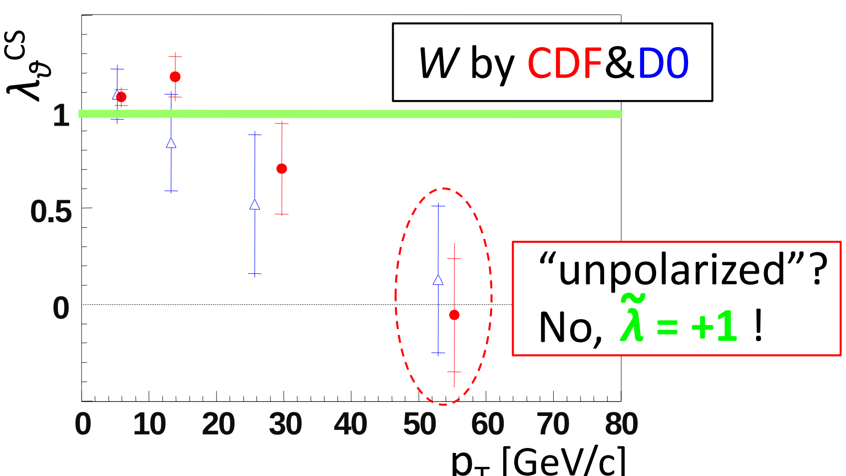

λ_ϑ

- 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

λ_ϑ vs $\tilde{\lambda}$

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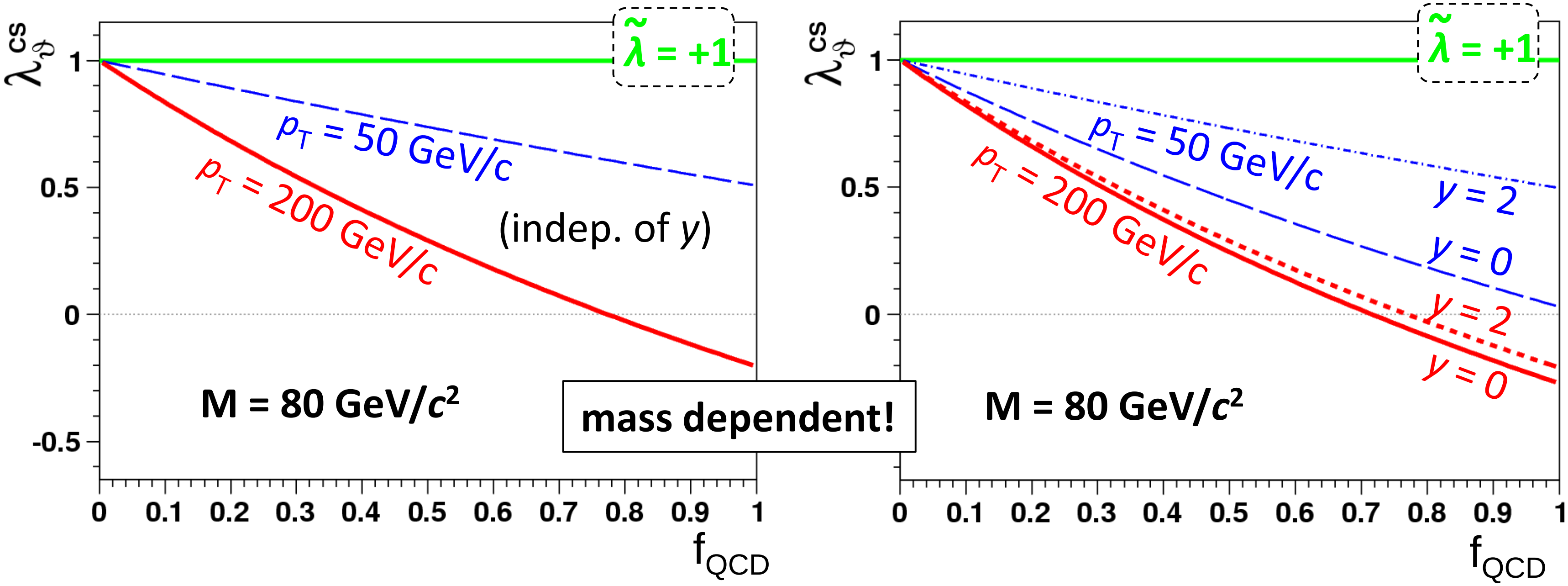

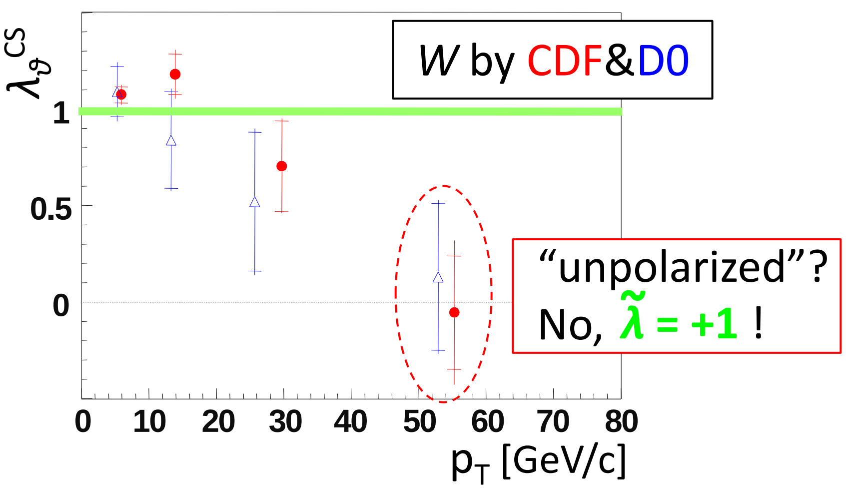

λ_ϑ:

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

λ_ϑ vs $\tilde{\lambda}$

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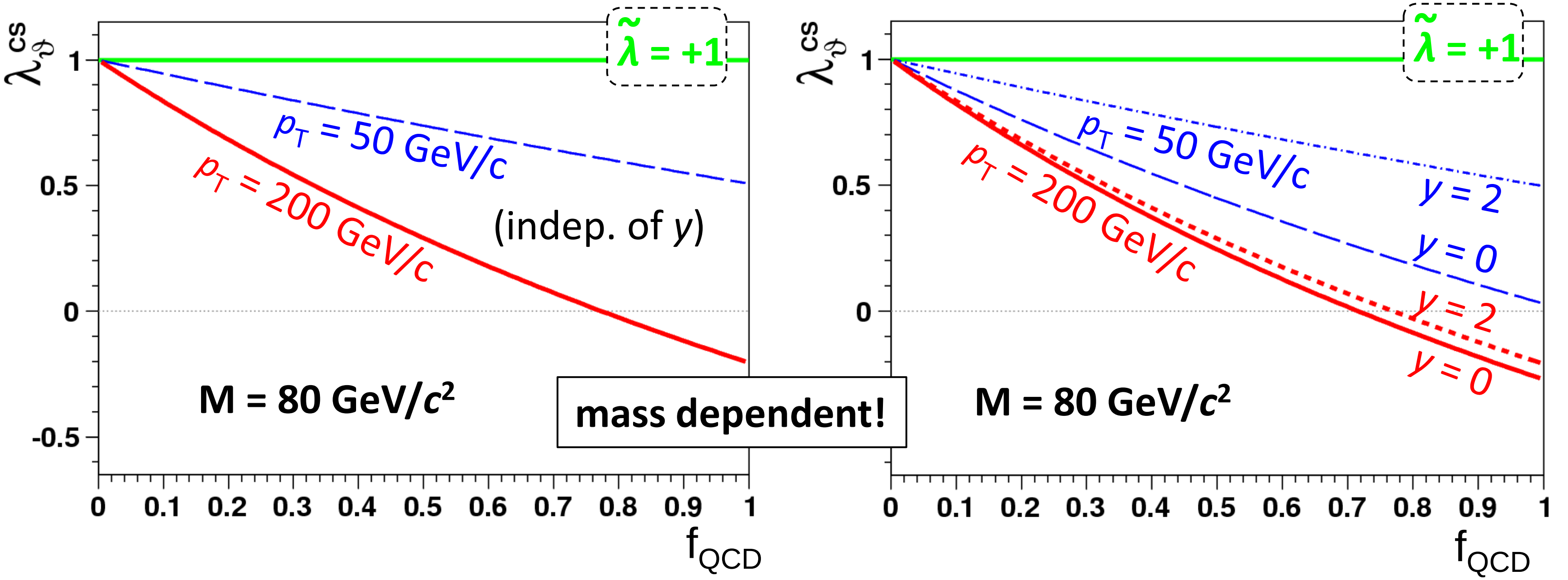
Case 1: dominating ***q-qbar*** QCD corrections   Case 2: dominating ***q-g*** QCD corrections



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

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)

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

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→ 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…)

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***

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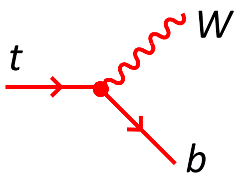
longitudinally polarized:

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

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

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

longitudinally polarized:

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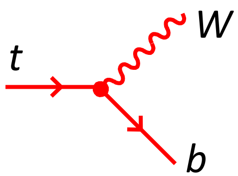
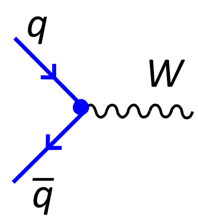


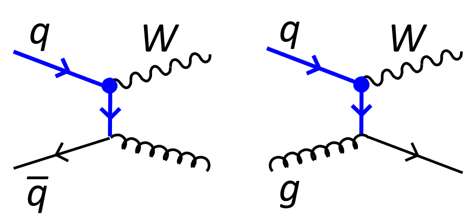
independently of top production mechanism

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

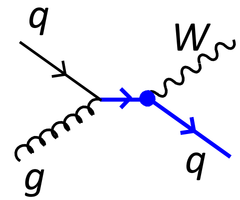
transversely polarized,
$\lambda_{\vartheta} = +1$ & $\lambda_{\varphi} = 0$ *wrt 3 different axes:*



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

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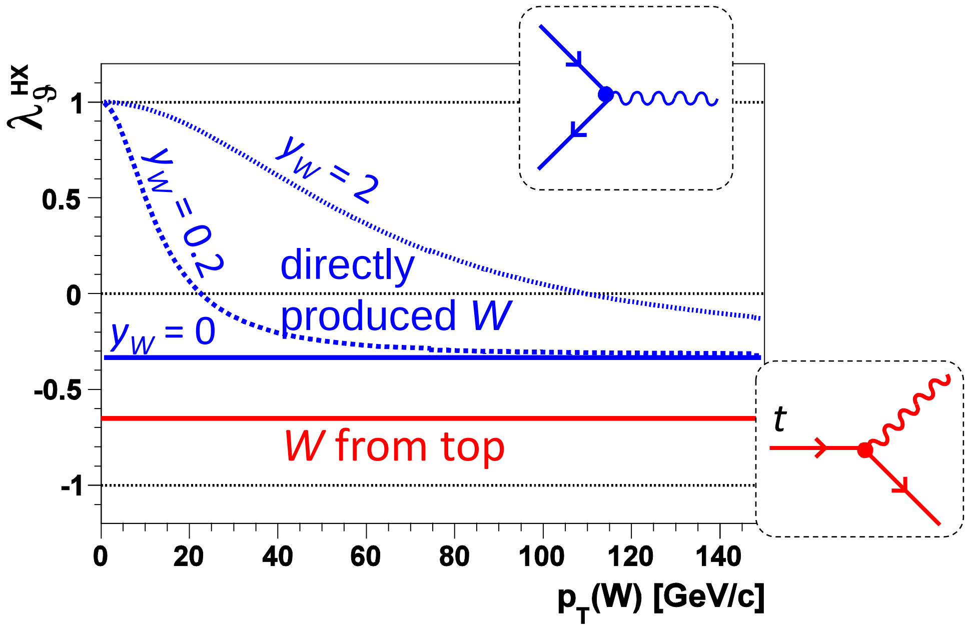

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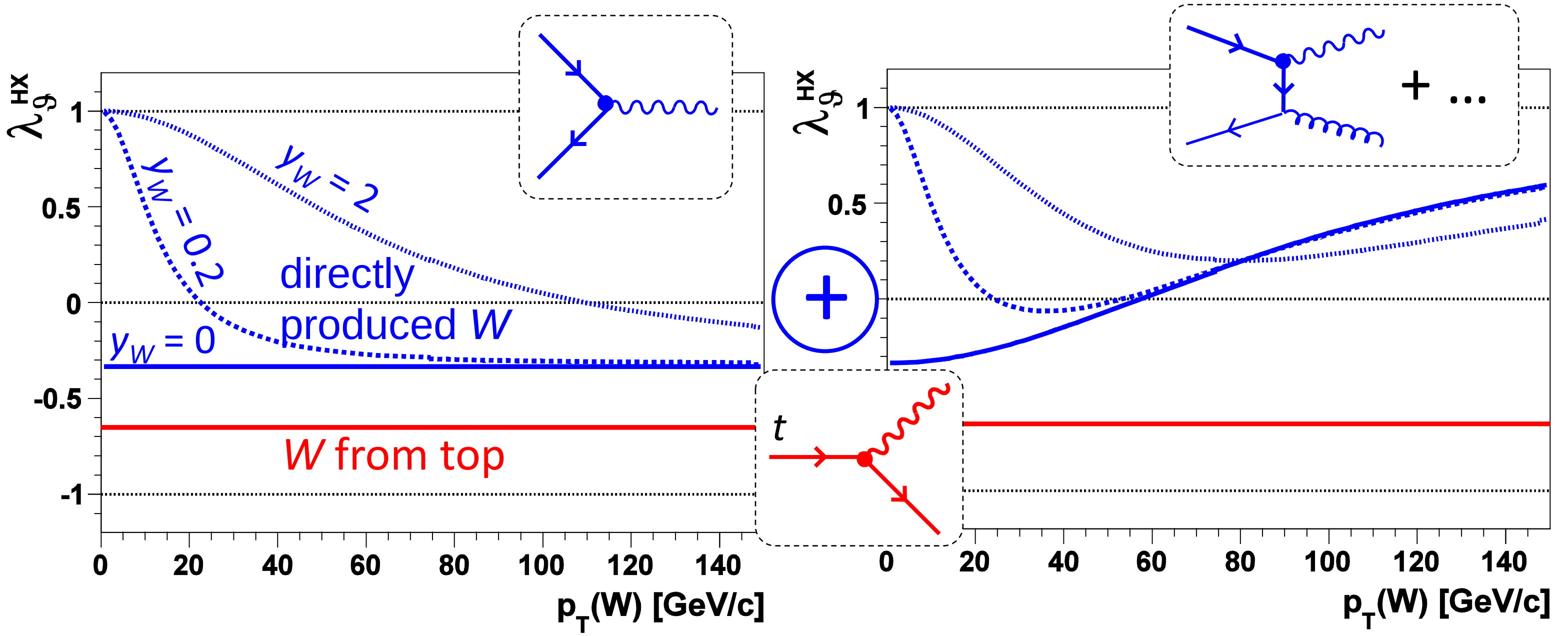

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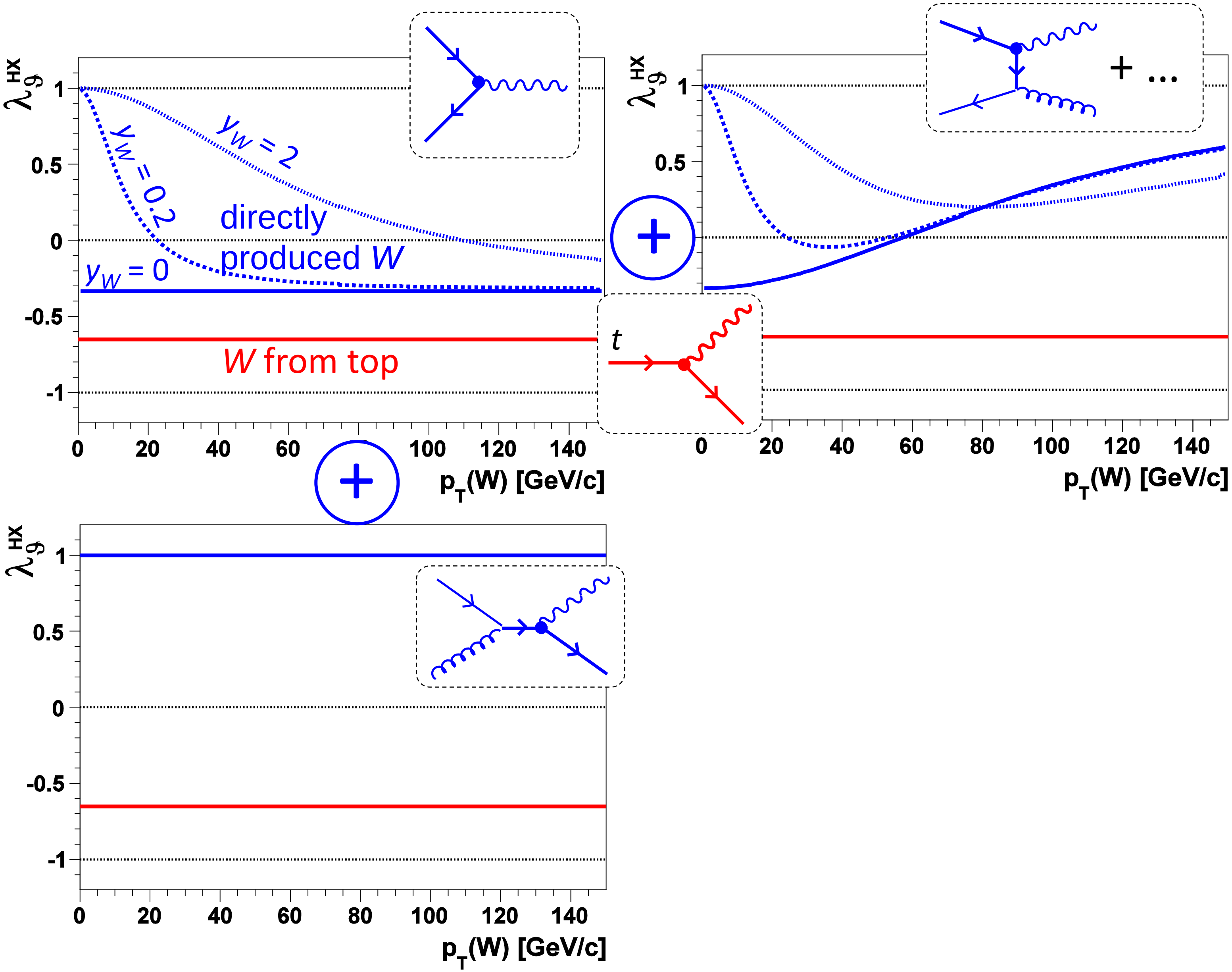

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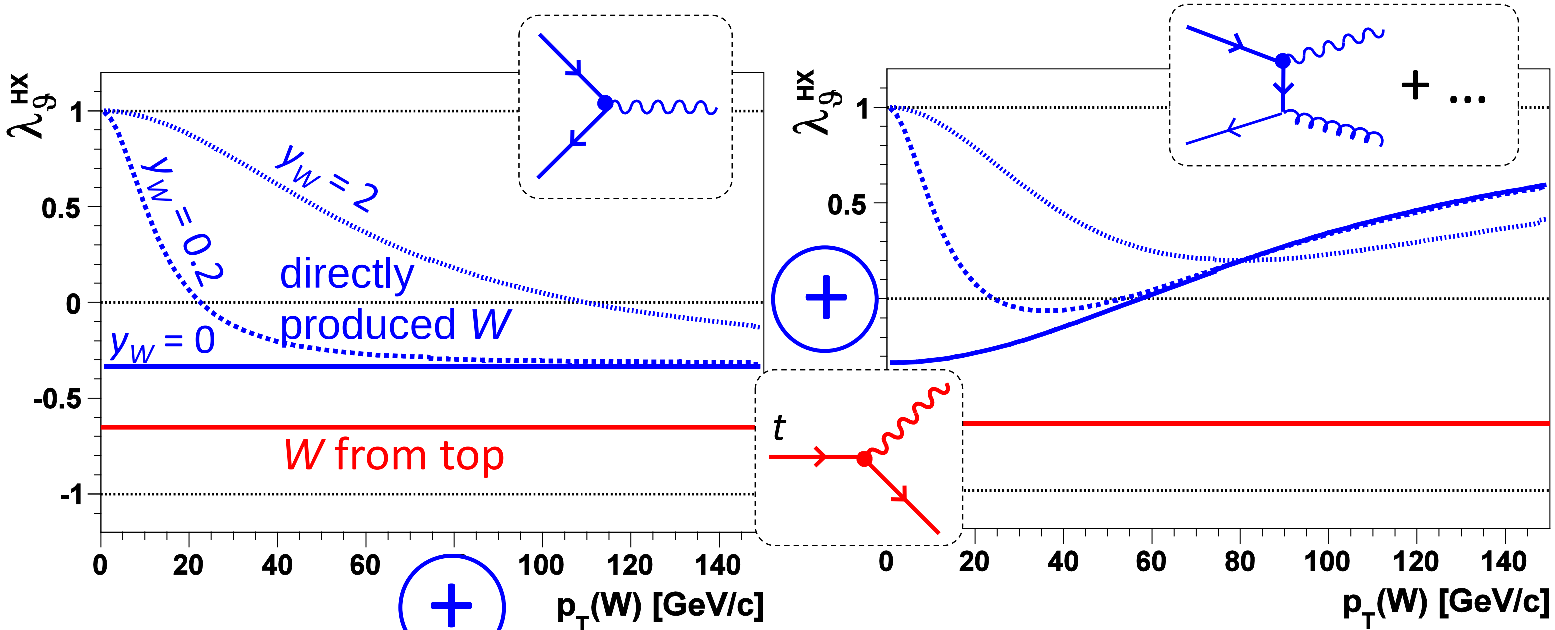
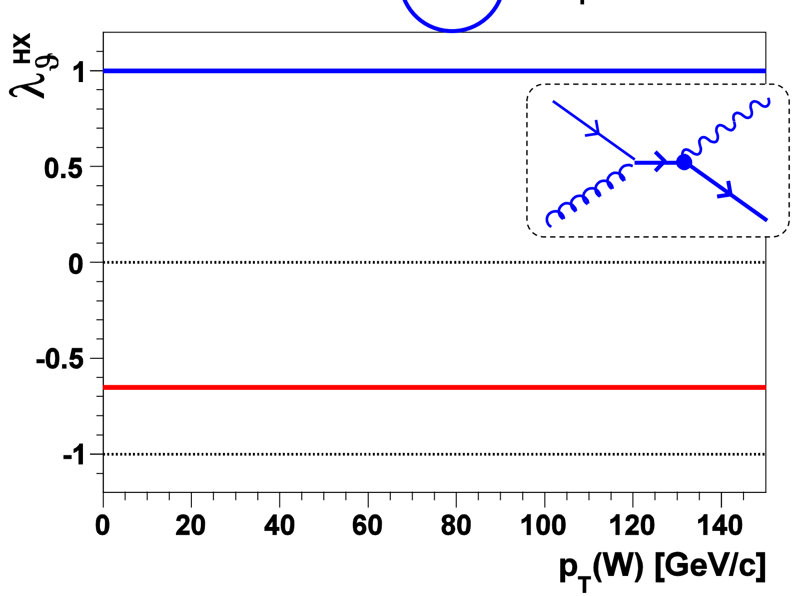
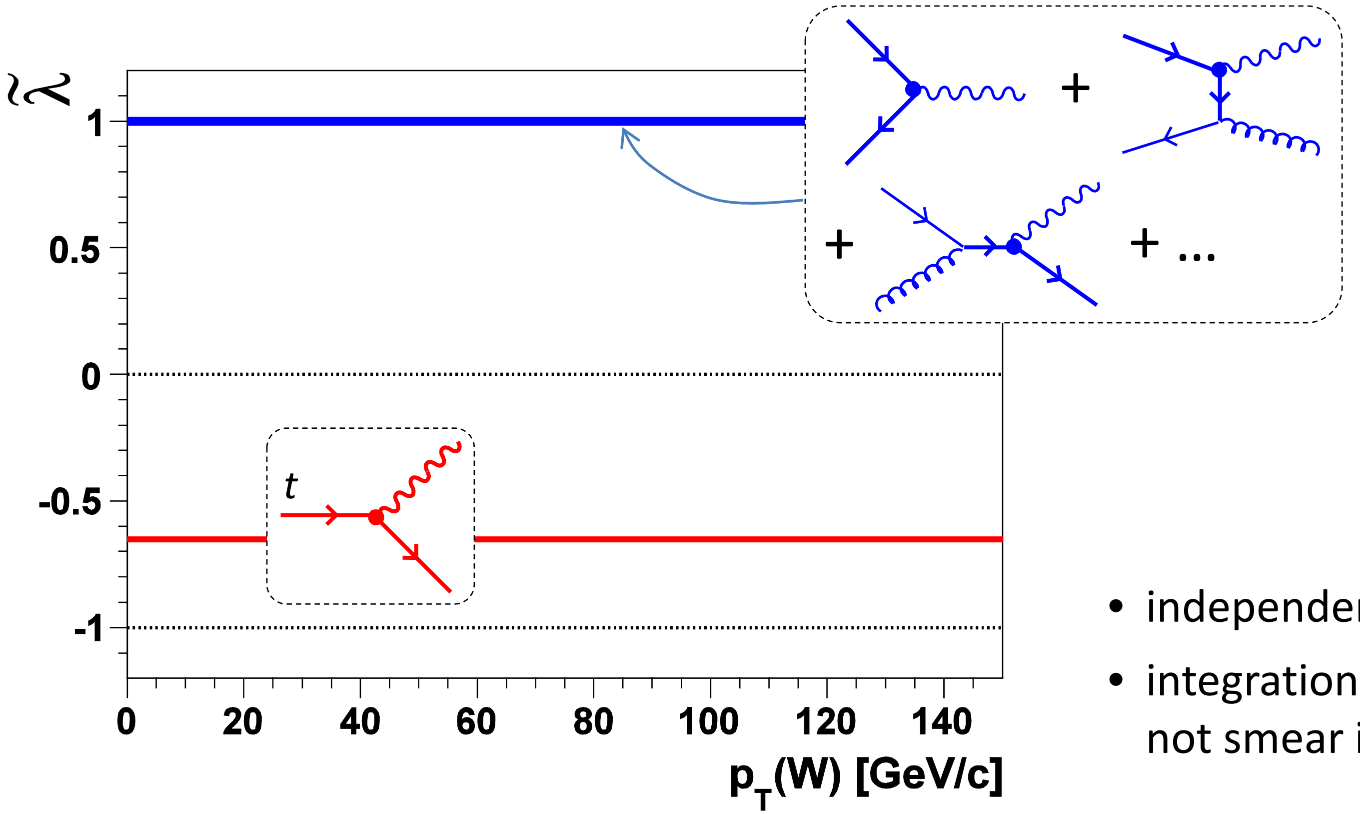




The polarization of *W* from *q-qbar* / *q-g*

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

b) Rotation-invariant approach



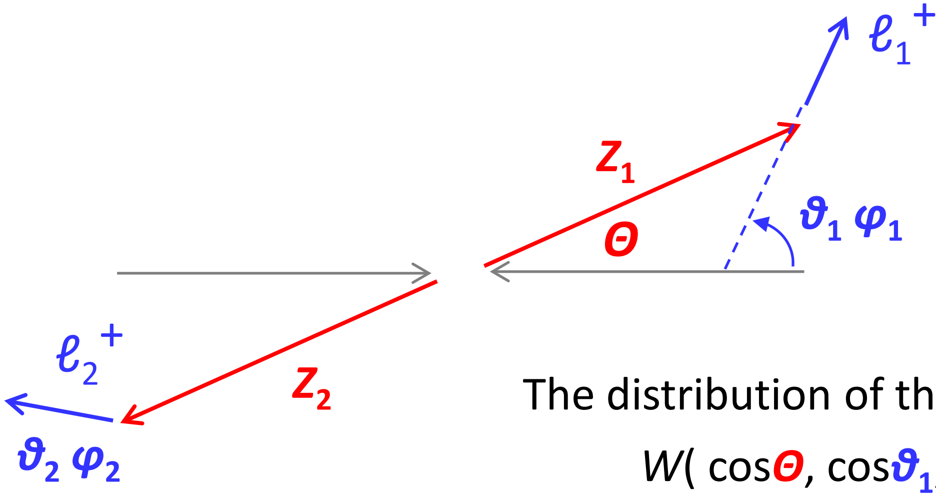
The *invariant* polarization of *W* from *q-qbar* / *q-g* is **constant** and fully **transverse**

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

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

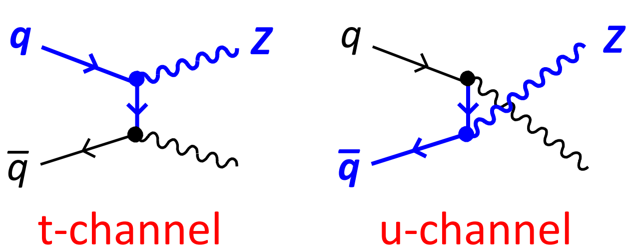
dominant Standard Model background for new-signal searches in the $ZZ \to 4\ell$ channel with $m(ZZ) > 200$ GeV/c^2

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



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

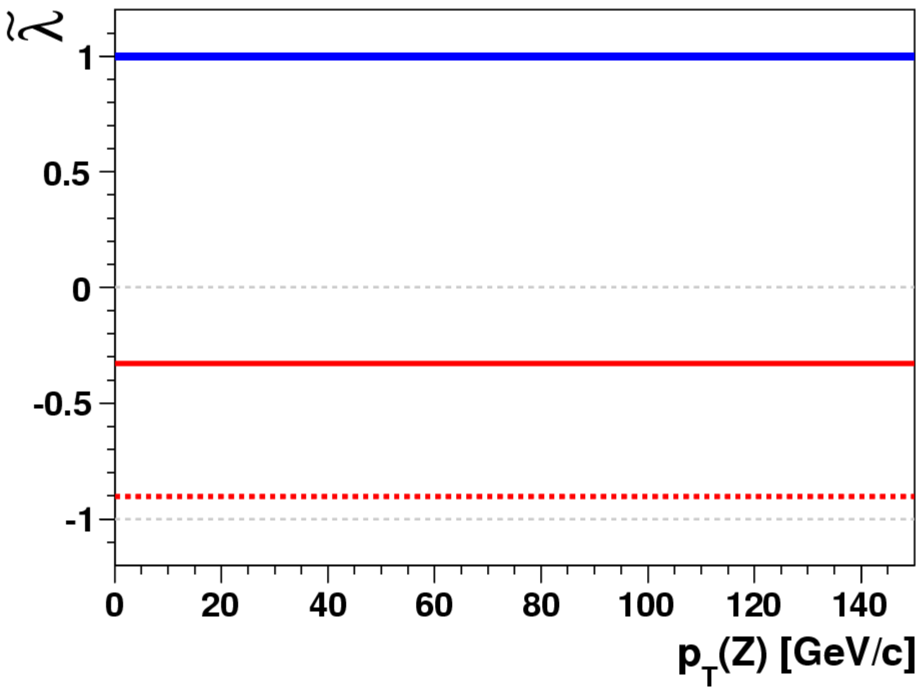
$$W(\cos\Theta, \cos\vartheta_1, \varphi_1, \cos\vartheta_2, \varphi_2 \mid M_{ZZ}, \vec{p}(Z_1), \vec{p}(Z_2))$$



- 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 $M_Z/M_{ZZ} \to 0$

ZZ from Higgs ↔ ZZ from q-$q$bar

Discriminant nº1: ***Z* polarization**



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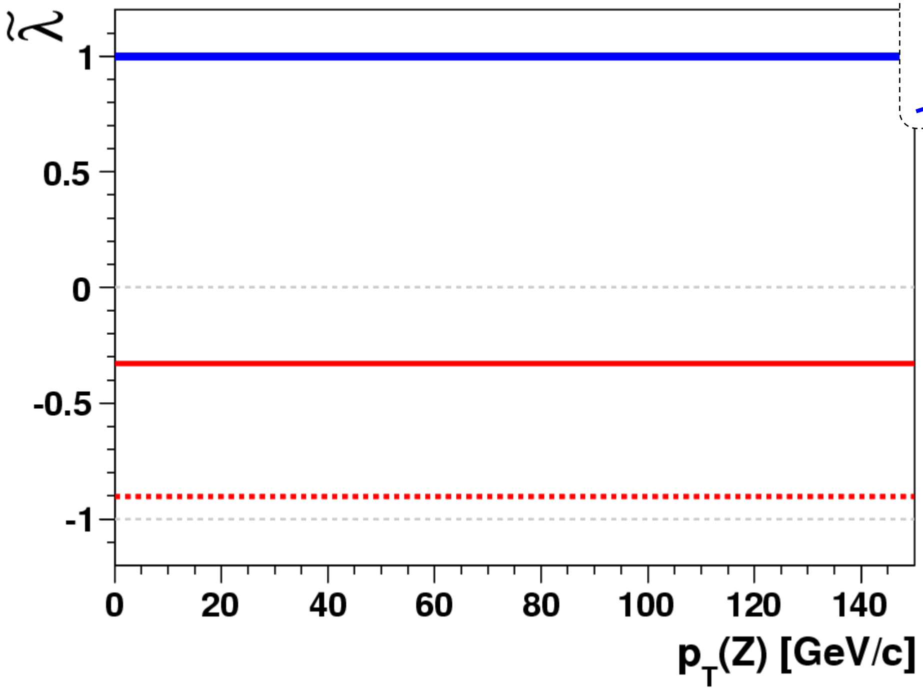
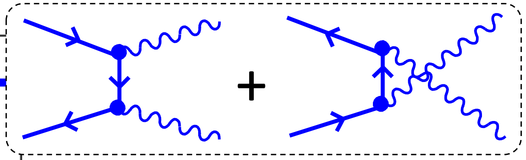
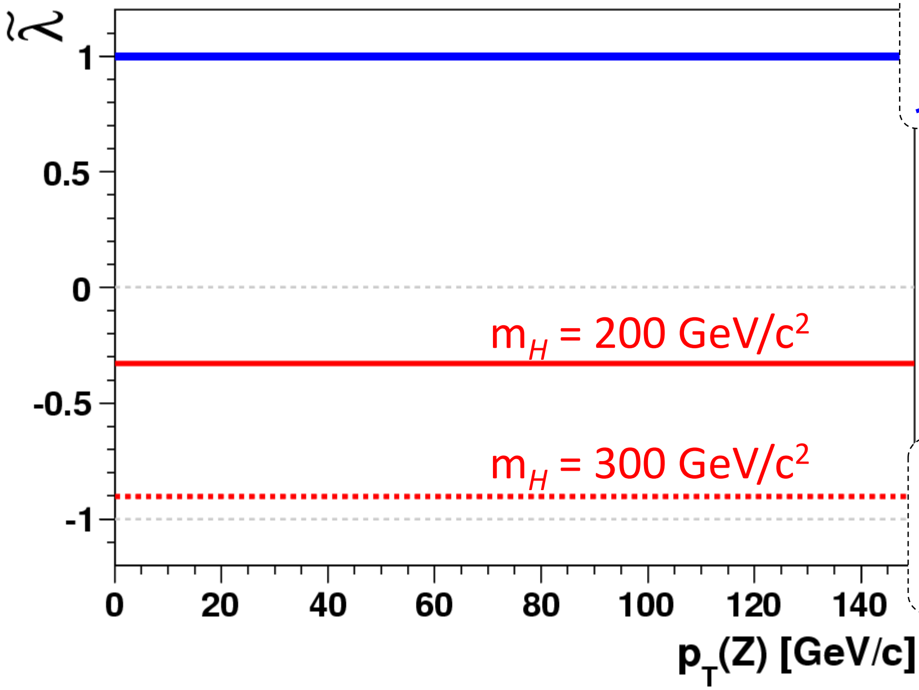


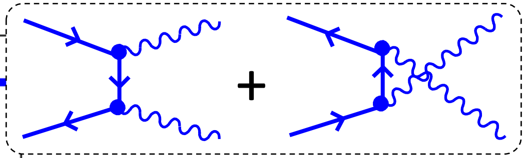


The *invariant* polarization of *Z* from *q*-*q*bar is fully **transverse**

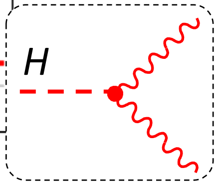
Z Z from Higgs ↔ Z Z from q-qbar

Discriminant nº1: ***Z* polarization**





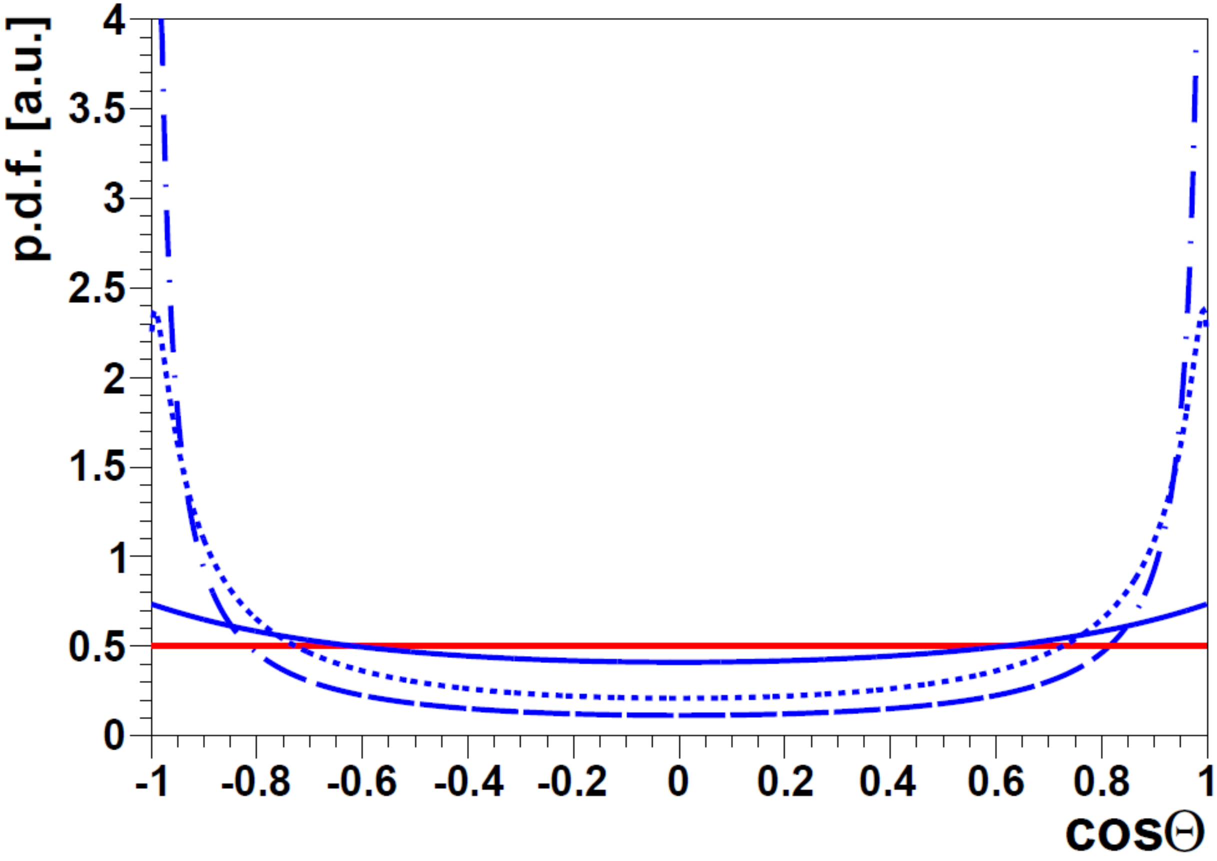
The *invariant* polarization of *Z* from *q*-*q*bar is fully **transverse**



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

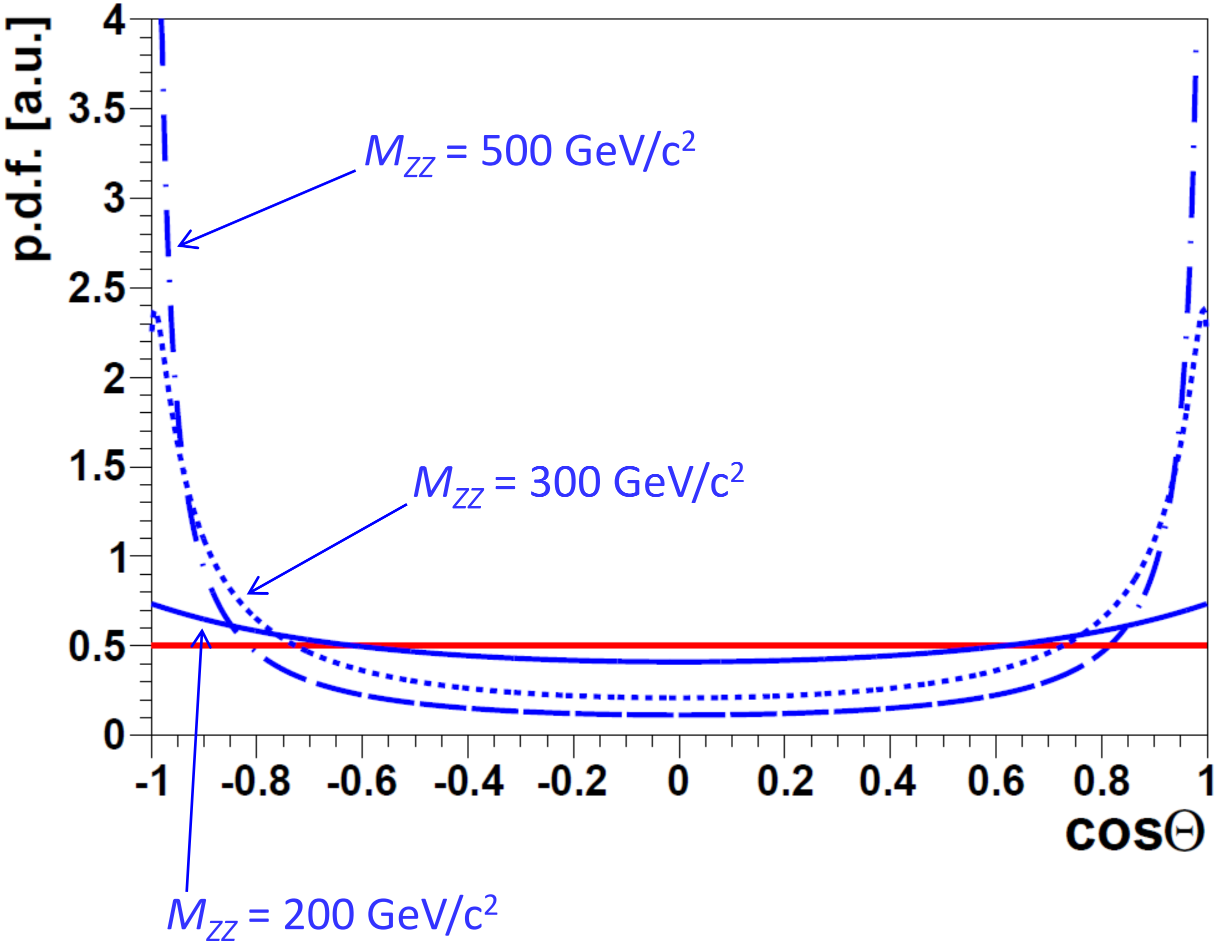
Z Z from Higgs ↔ *Z Z* from *q*-*q*bar

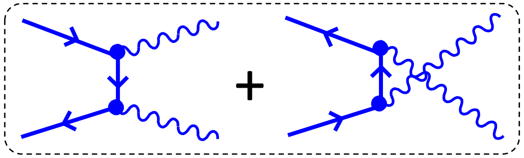
Discriminant nº2: ***Z* emission direction**



Z Z from Higgs ↔ Z Z from q-qbar

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

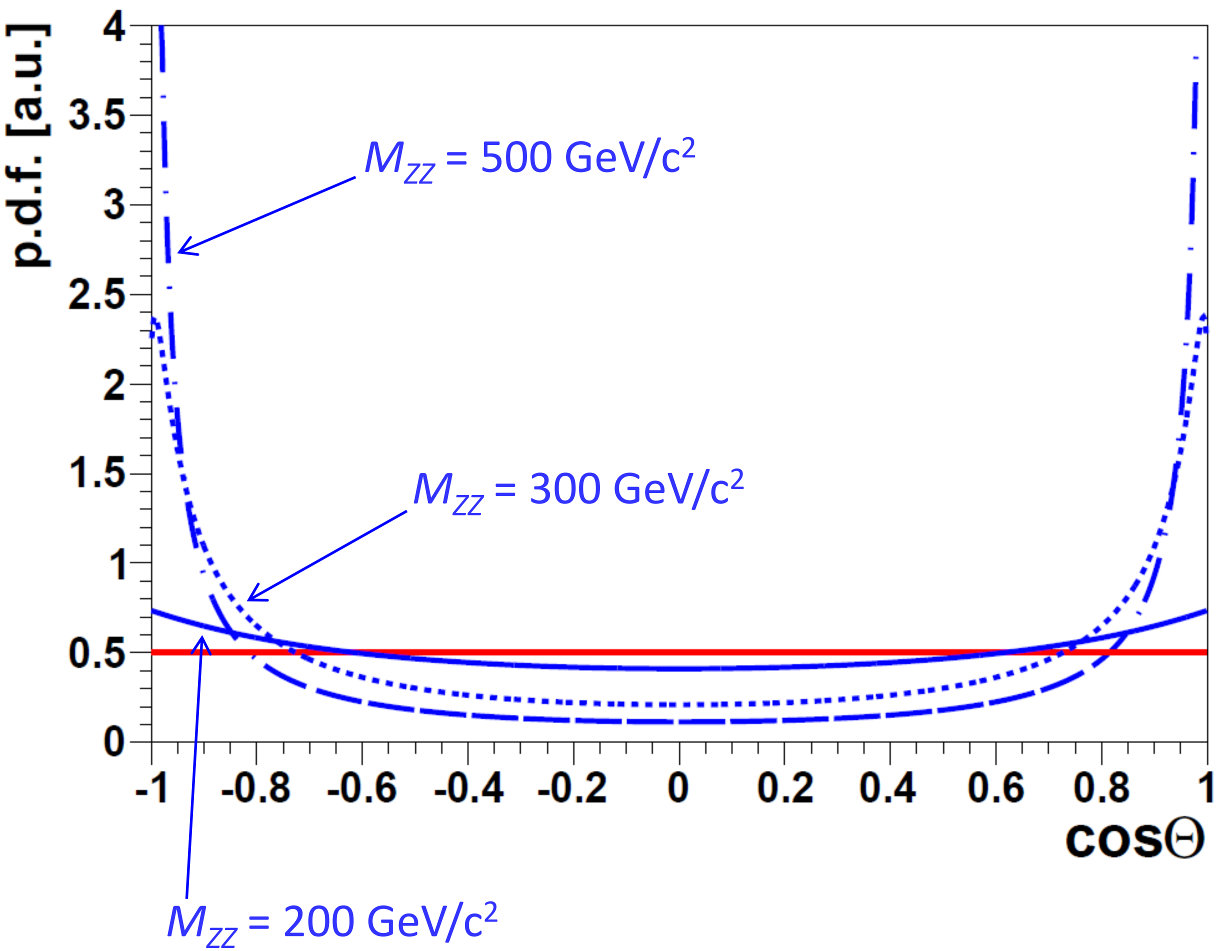


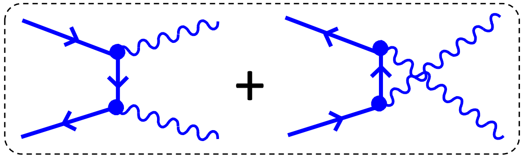


Z from *q*-*q*bar is emitted mainly close to the beam if M_{ZZ}/M_Z is large

Z Z from Higgs ↔ *Z Z* from *q*-*q*bar

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





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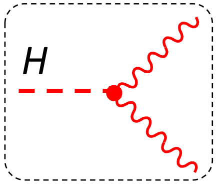

Z bosons from *H* decay
are emitted isotropically

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: $\xi = \ln \frac{\mathcal{P}_{H\to ZZ}}{\mathcal{P}_{q\bar{q}\to ZZ}}$

← event probabilities, including detector acceptance and efficiency effects

Putting everything together

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5 kinematic variables (M_{ZZ}, $p_T(Z_1)$, $y(Z_1)$, $p_T(Z_2)$, $y(Z_2)$)

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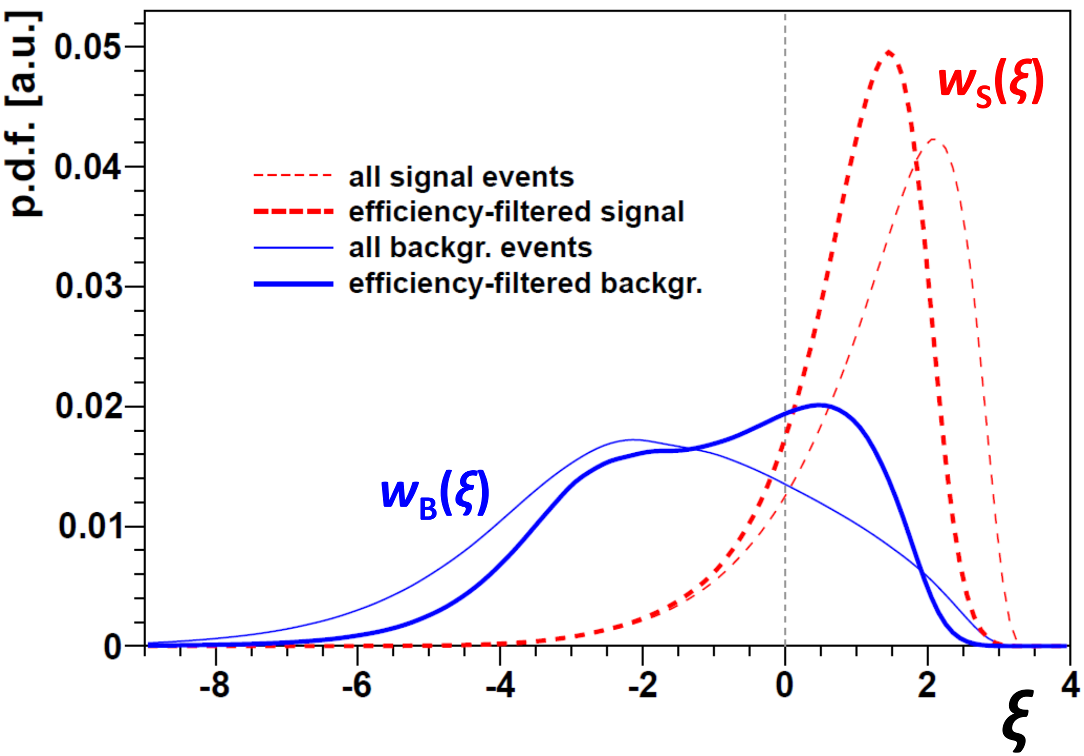

$\sqrt{s}$ = 14 TeV
$500 < M_{ZZ} < 900$ GeV/c^2
M_H = 700 GeV/c^2
$|y_{ZZ}| < 2.5$

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

β = ratio of observed / expected signal events

$\beta > 0 \rightarrow$ observation of something new

$\beta < 1 \rightarrow$ exclusion of expected hypothetical signal

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“integrated yield” constraint: signal = excess yield wrt expected **number of BG events**

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

crucially dependent on the expected BG normalization

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

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

N = total number of events in the sample

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constraint from angular distribution:
signal = deviation from the ***shape* of the BG angular distribution**

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

*in*dependent of luminosity and cross-section uncertainties!

μ_B = avg. number of BG events expected for the given luminosity
μ_S = avg. number of Higgs events expected for the given luminosity
N = total number of events in the sample

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*in*dependent of luminosity and cross-section uncertainties!

3) $$\mathcal{P}_{\mathrm{tot}}(\boldsymbol{\beta}) = \mathcal{P}_{\mathrm{angular}}(\boldsymbol{\beta}) \times \mathcal{P}_{\mathrm{BGnorm}}(\boldsymbol{\beta})$$

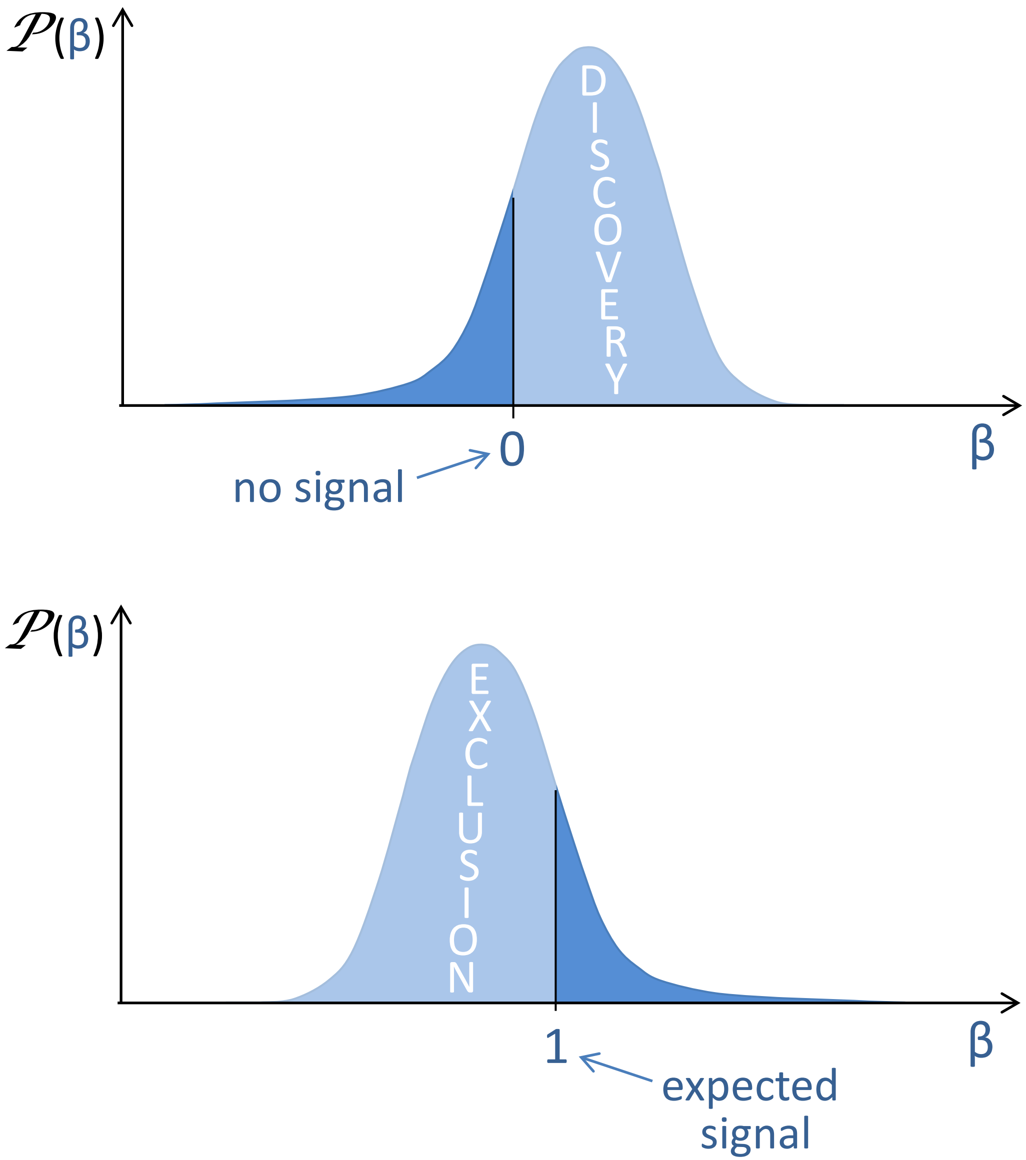
combination of the two methods

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

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

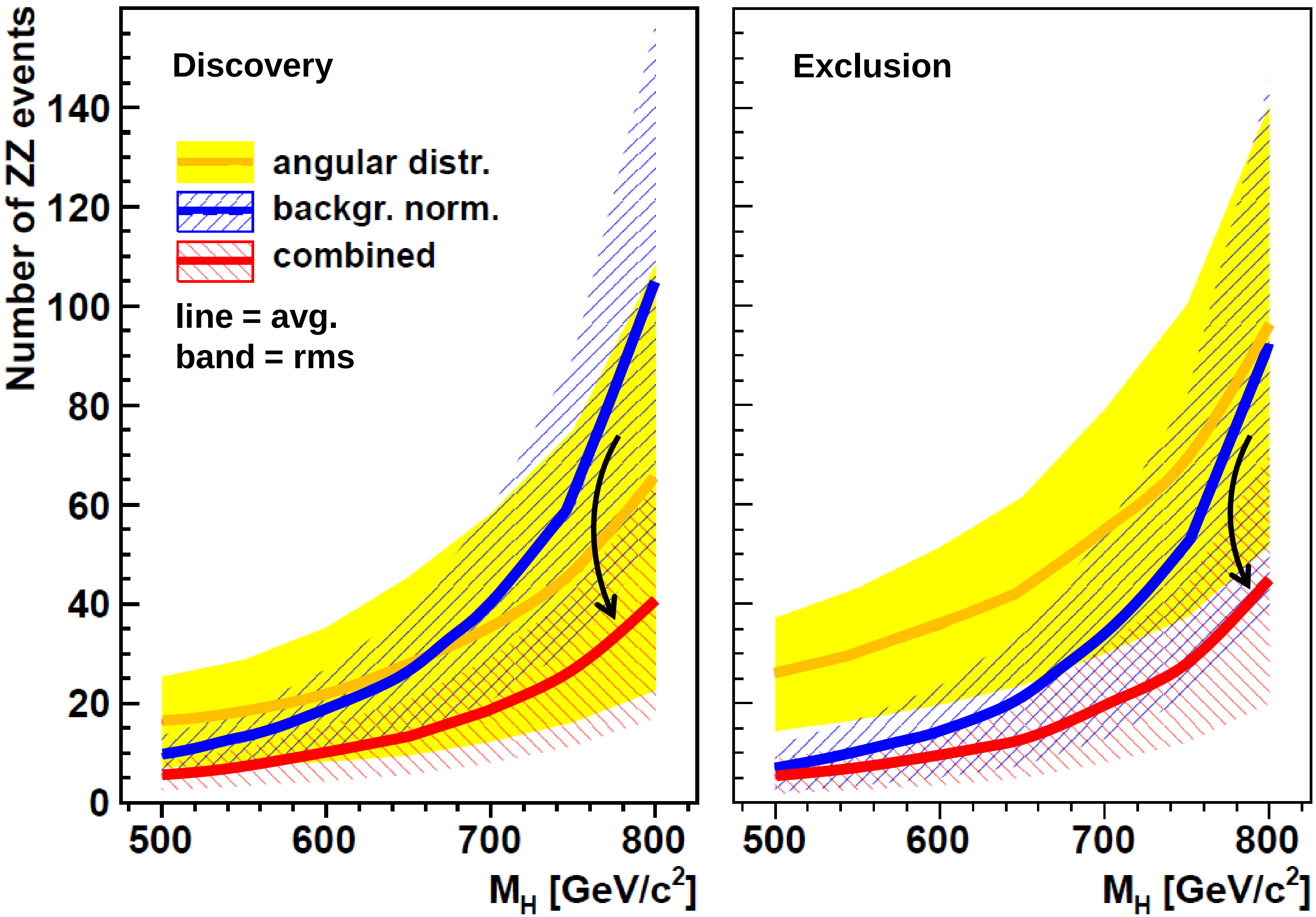
N = total number of events in the sample

Confidence levels



Limits vs m_H

"3σ" level



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

Further reading

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