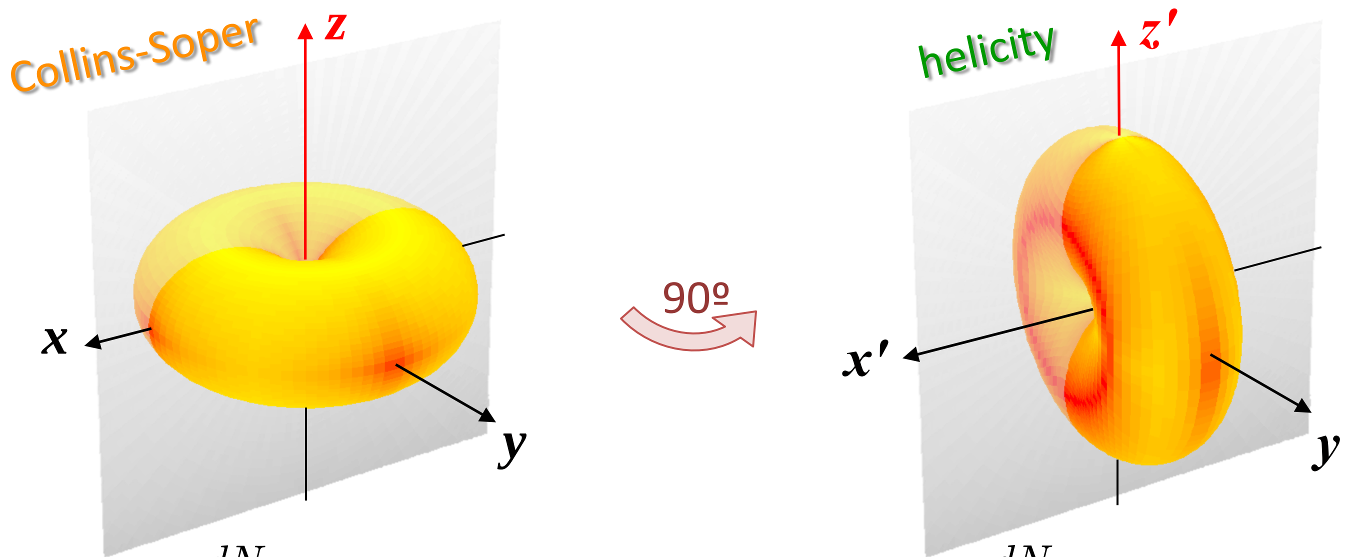
The observed polarization depends on the frame

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

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

(pure state)

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

"transverse"

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

(mixed state)

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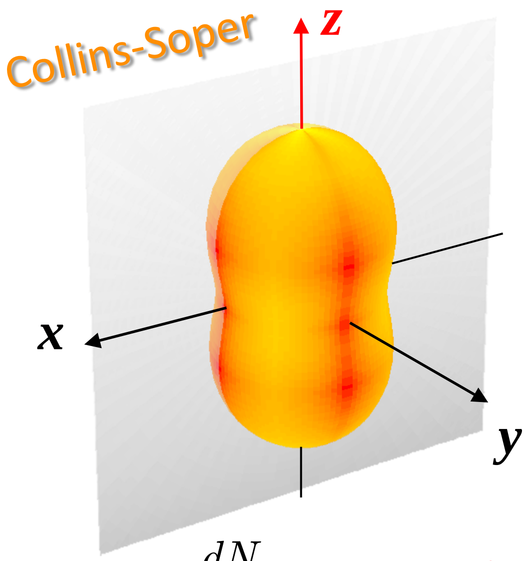

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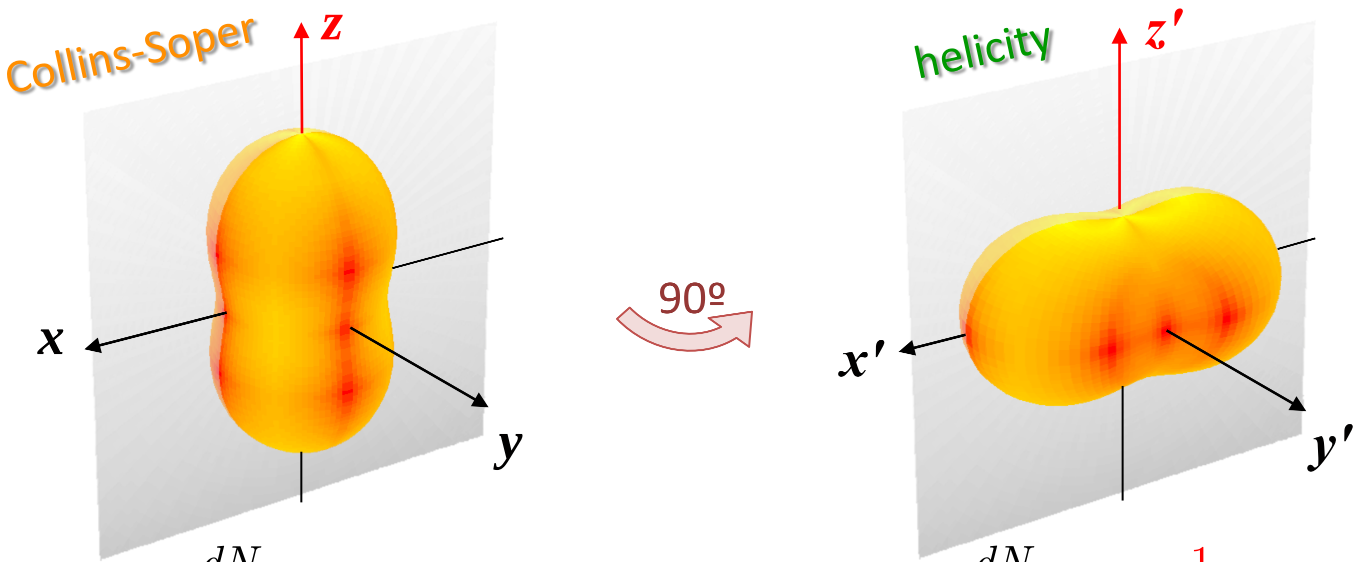

$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta$$

transverse

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

moderately "longitudinal"

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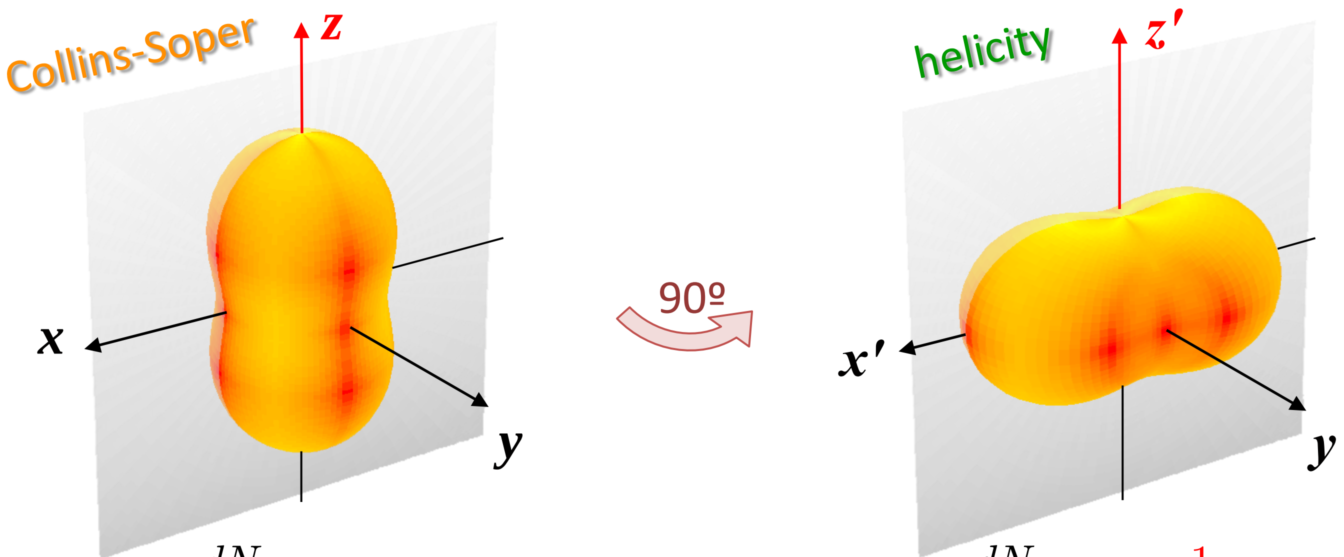

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moderately “longitudinal”

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

(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 $\Upsilon(1S)$ mass
  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^-	$\lvert y \rvert < 0.9$
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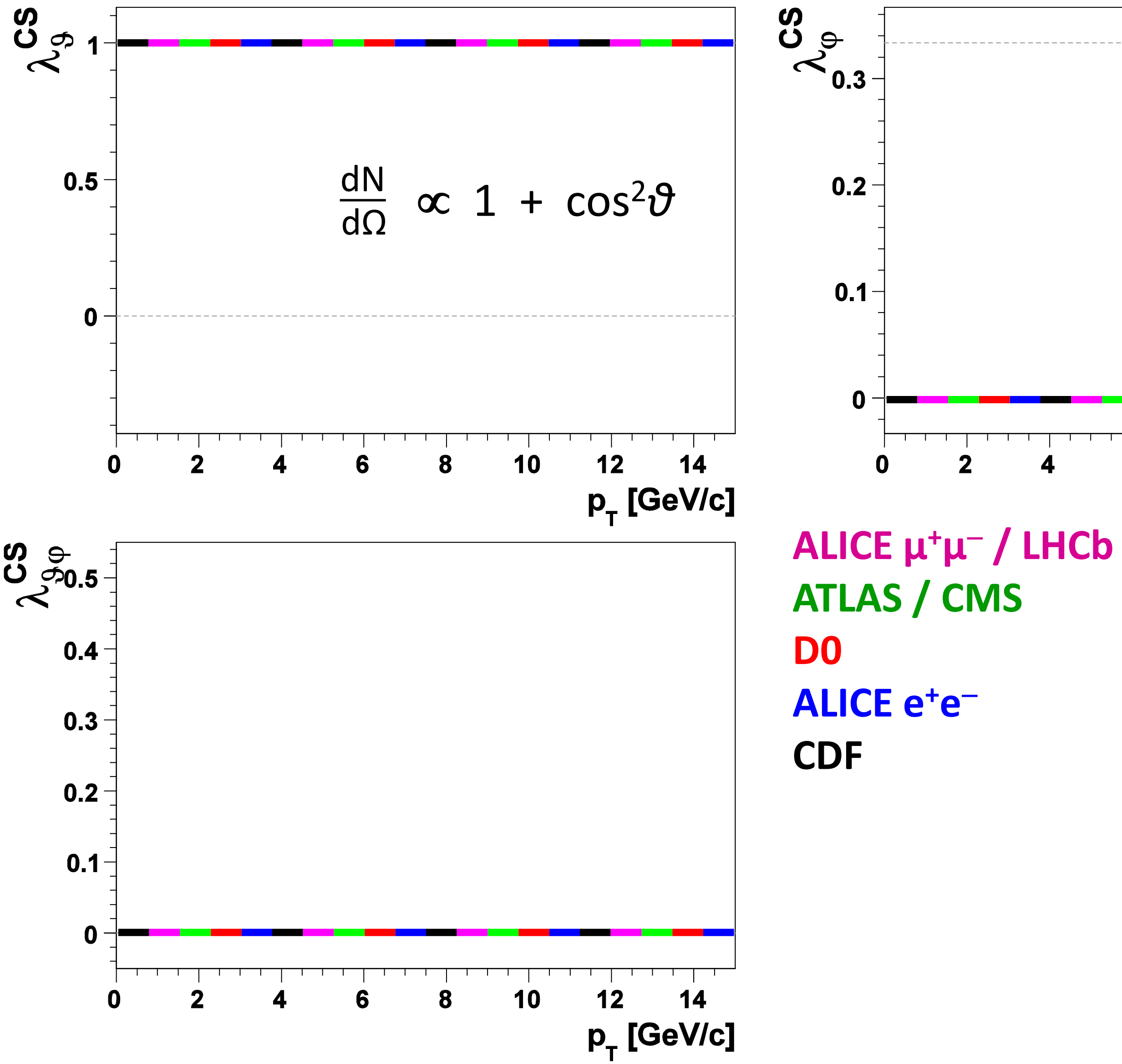
LHCb	$2 < y < 4.5$

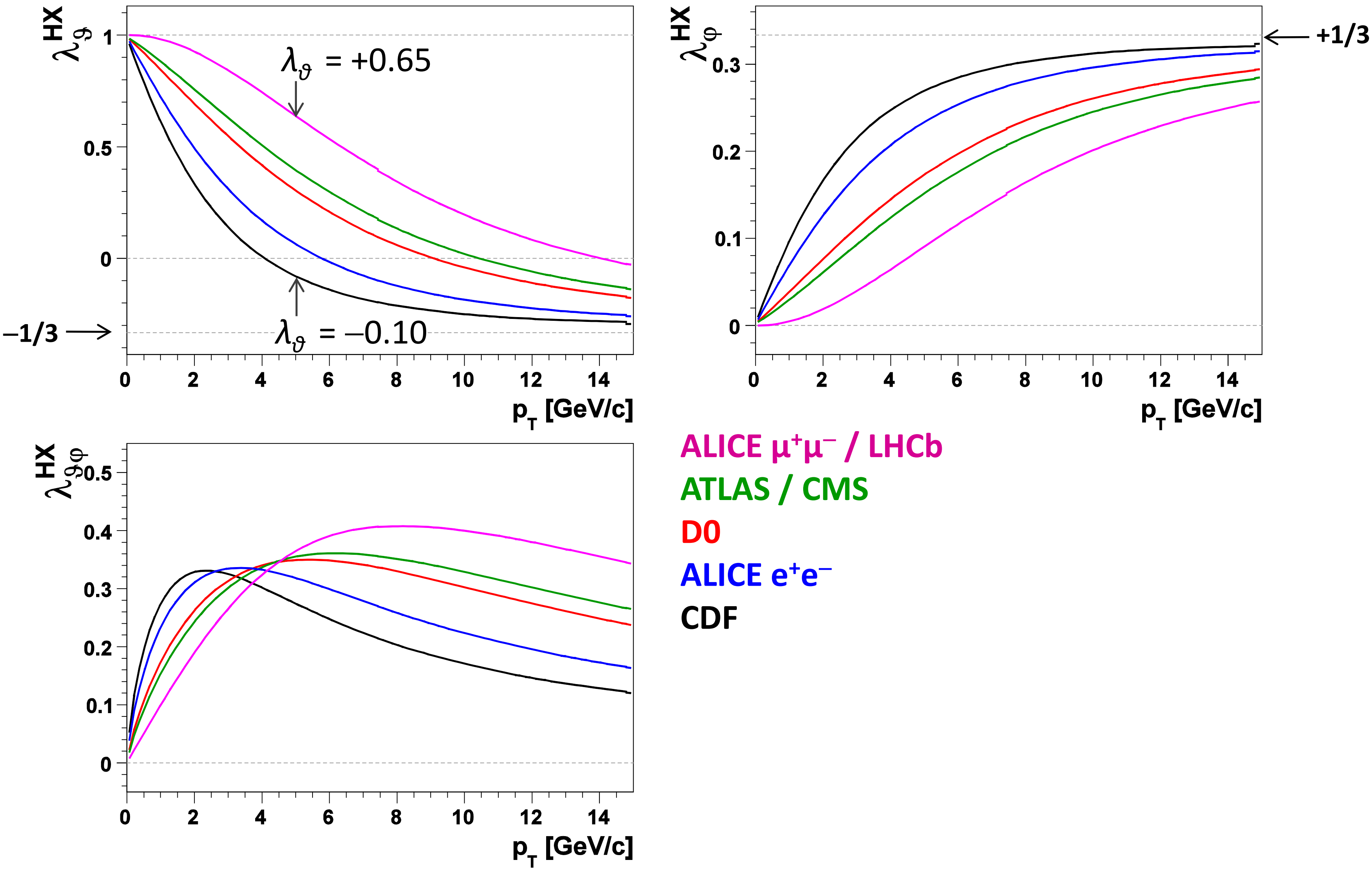
The lucky frame choice

(CS in this case)



Less lucky choice

(HX in this case)



Less lucky choice

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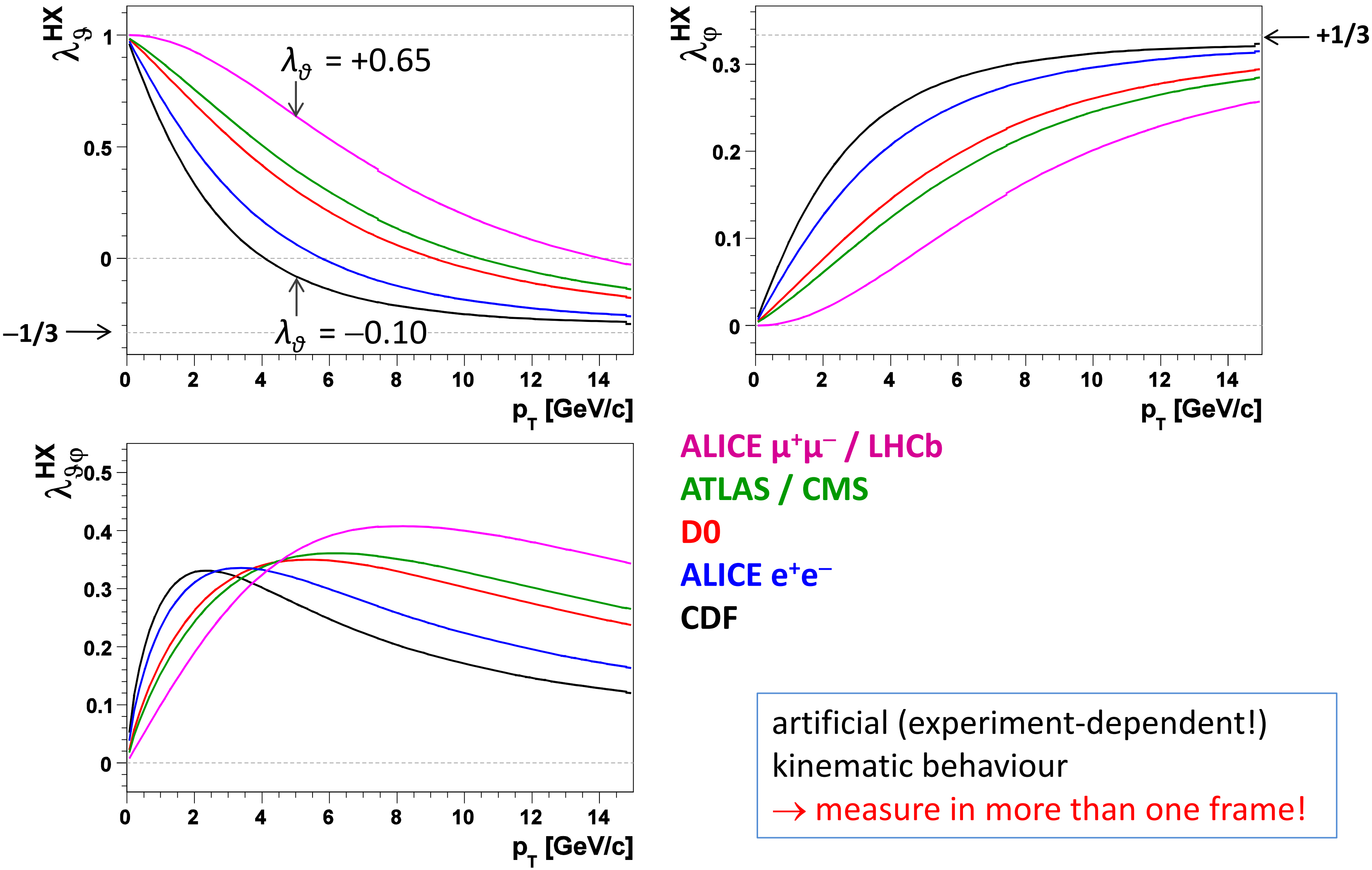
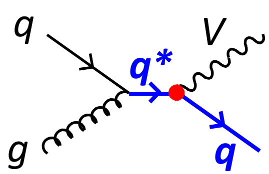


artificial (experiment-dependent!) kinematic behaviour

→ measure in more than one frame!

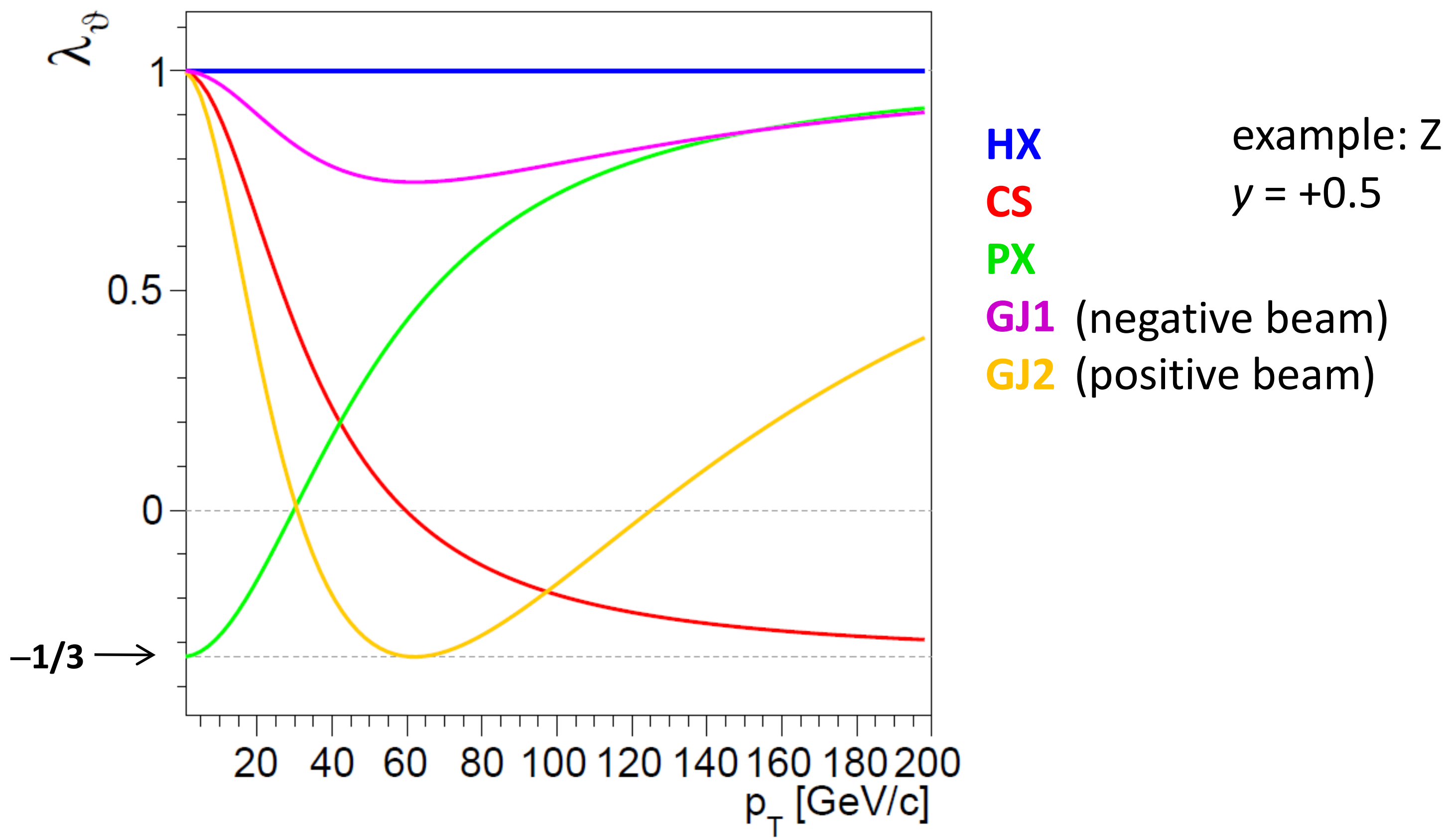
"Optimal" frames for Drell-Yan, *Z* and *W* polarizations

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!)



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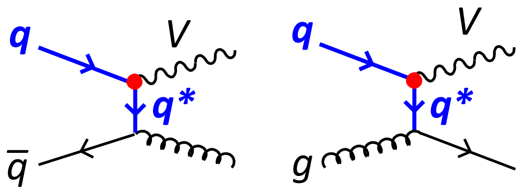
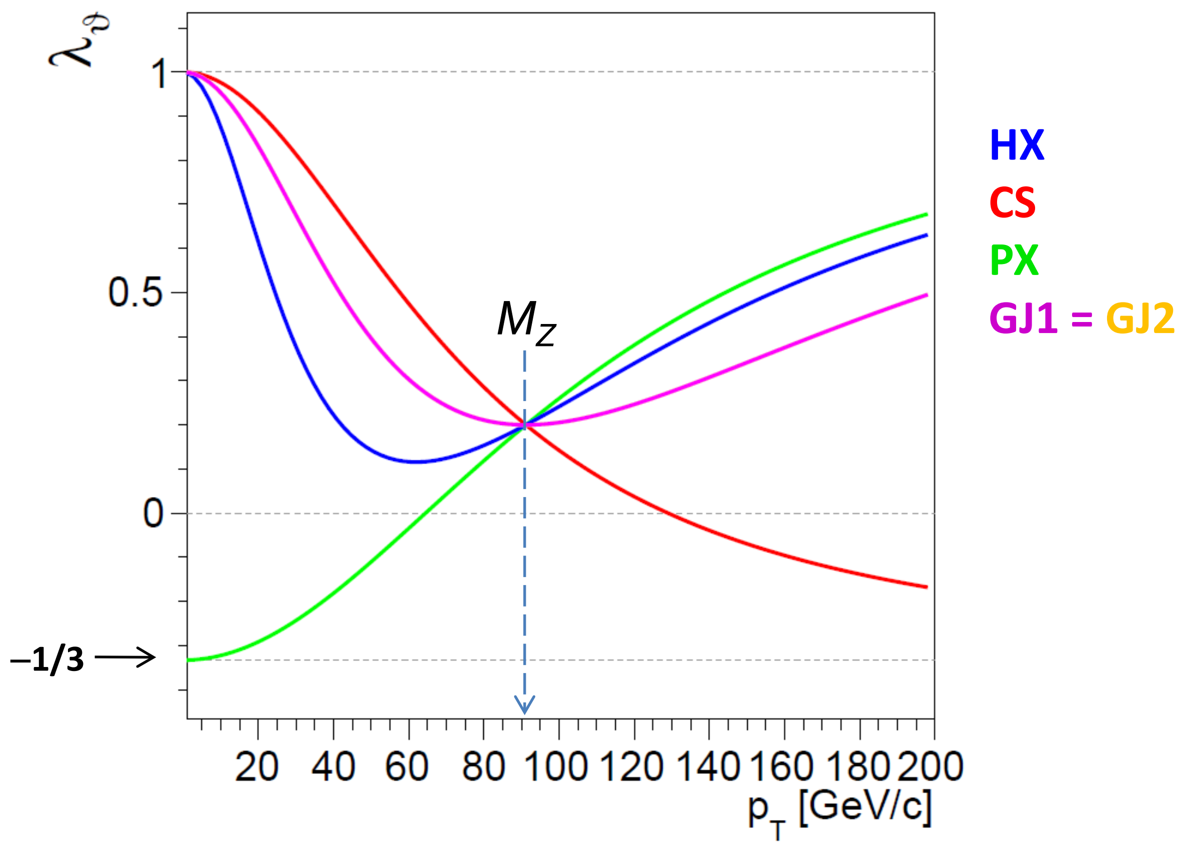


For ***t*- and *u*-channel processes** the natural axis is the direction of either one or the other incoming parton (~ "Gottfried-Jackson" axes)

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



example: Z

y = +0.5

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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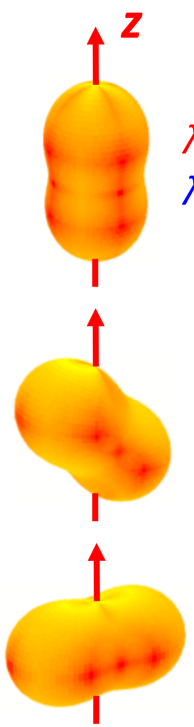

$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$

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

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

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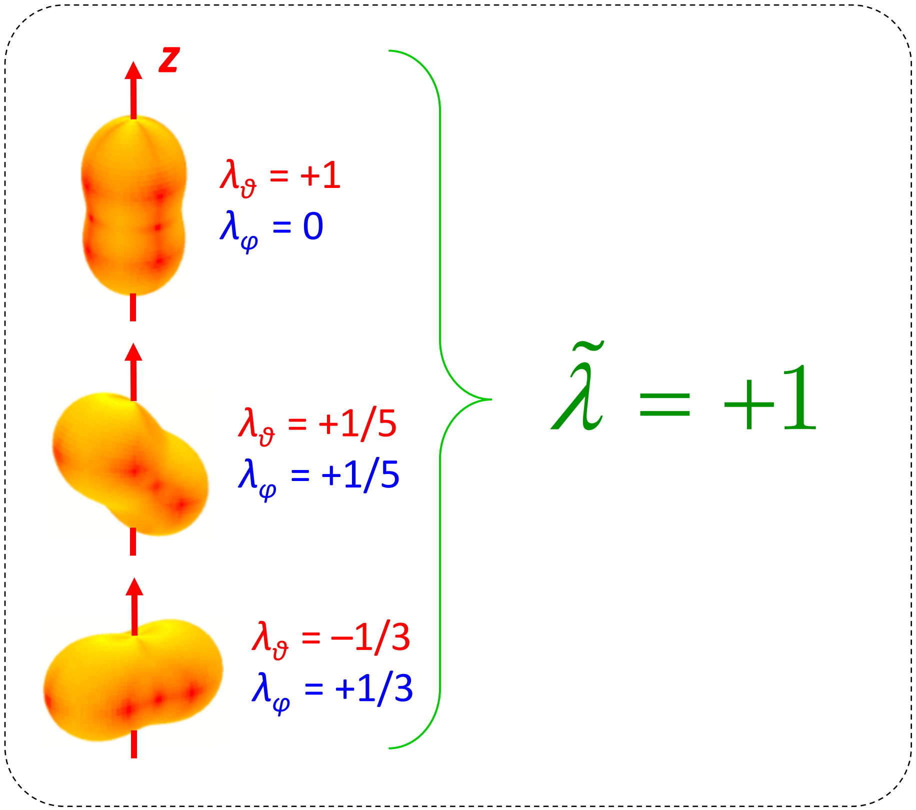

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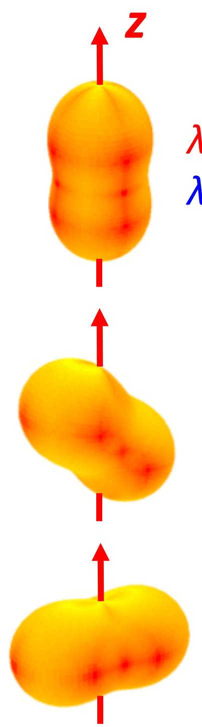
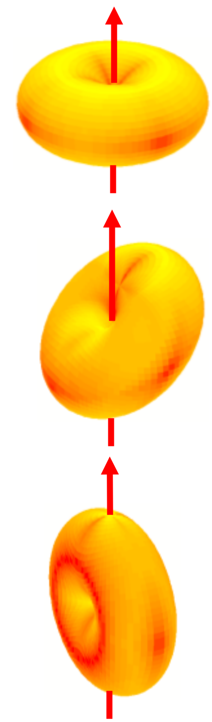


$$\tilde{\lambda} = +1$$



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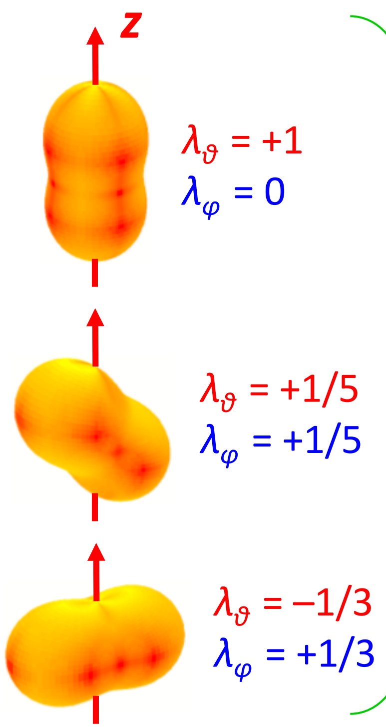

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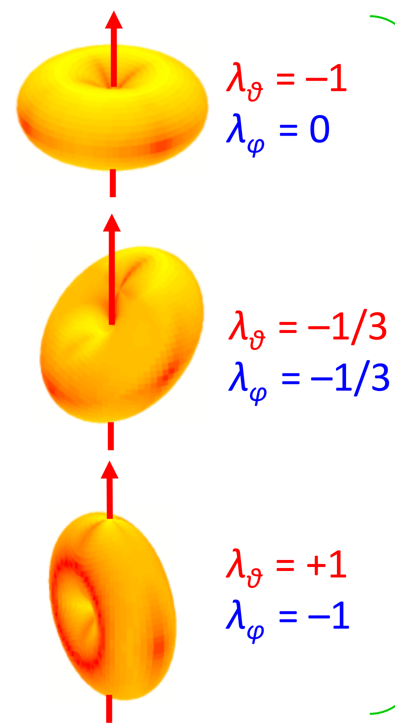

$$\tilde{\lambda} = -1$$

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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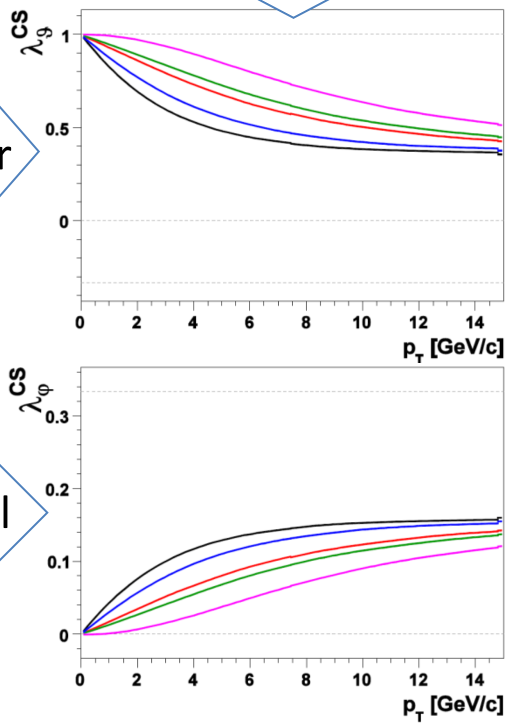
CS

polar

azimuthal



M = 10 GeV/c^2

CDF	**|y| < 0.6**
D0	**|y| < 1.8**
ATLAS/CMS	**|y| < 2.5**
ALICE e^+e^-	**|y| < 0.9**
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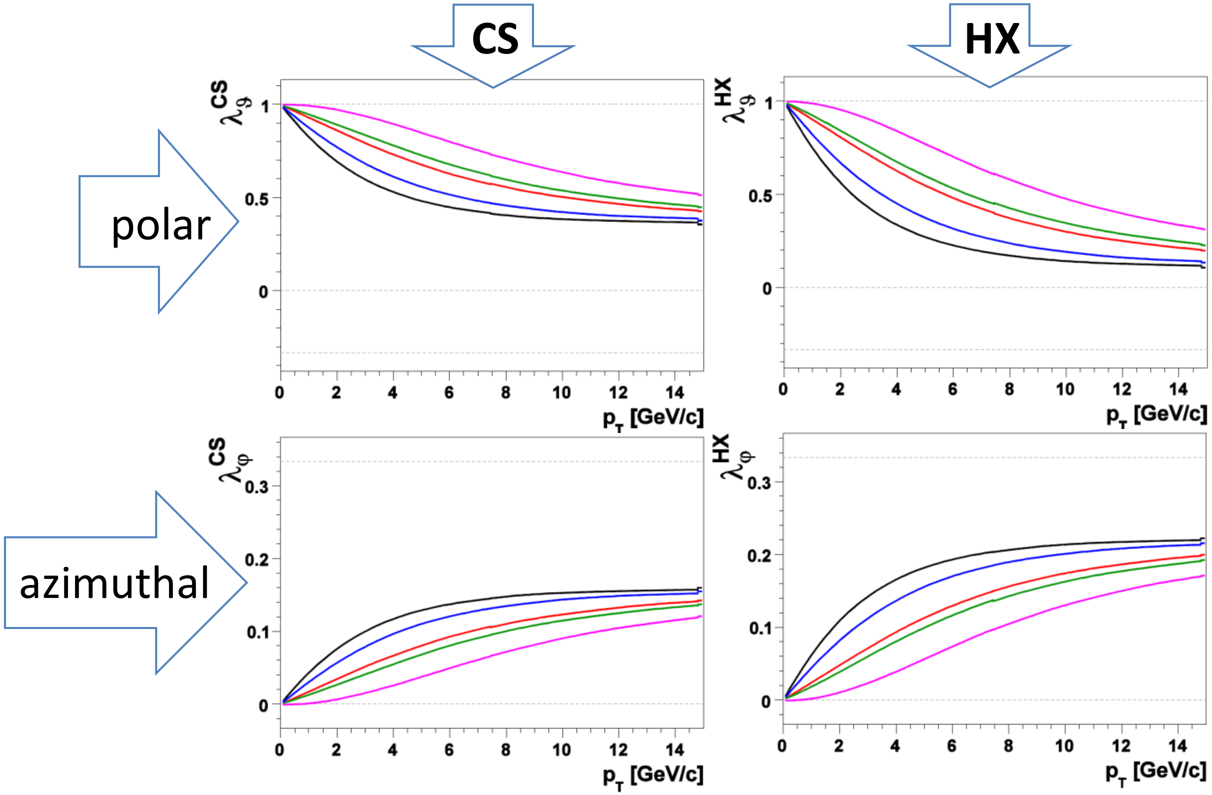

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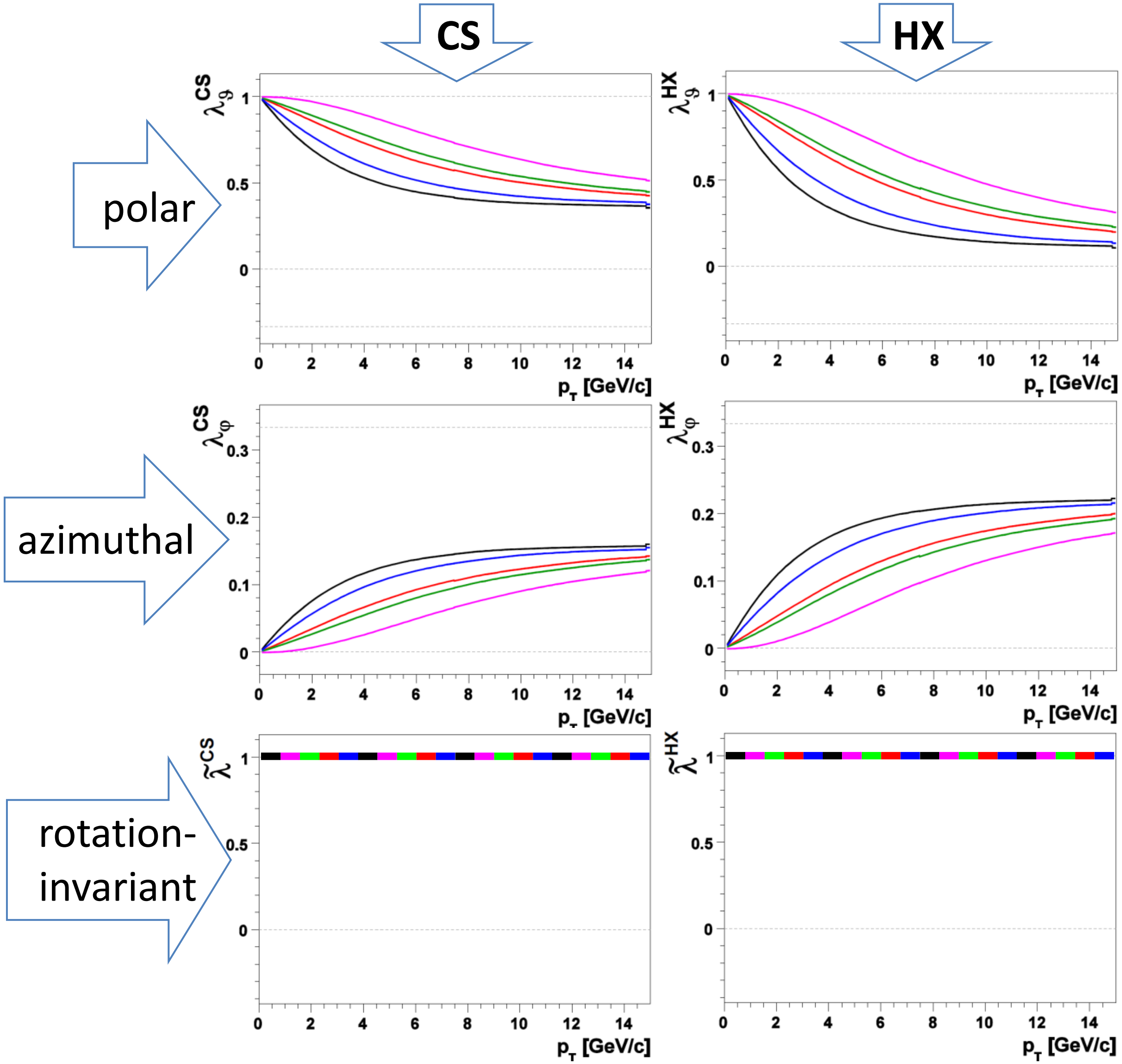

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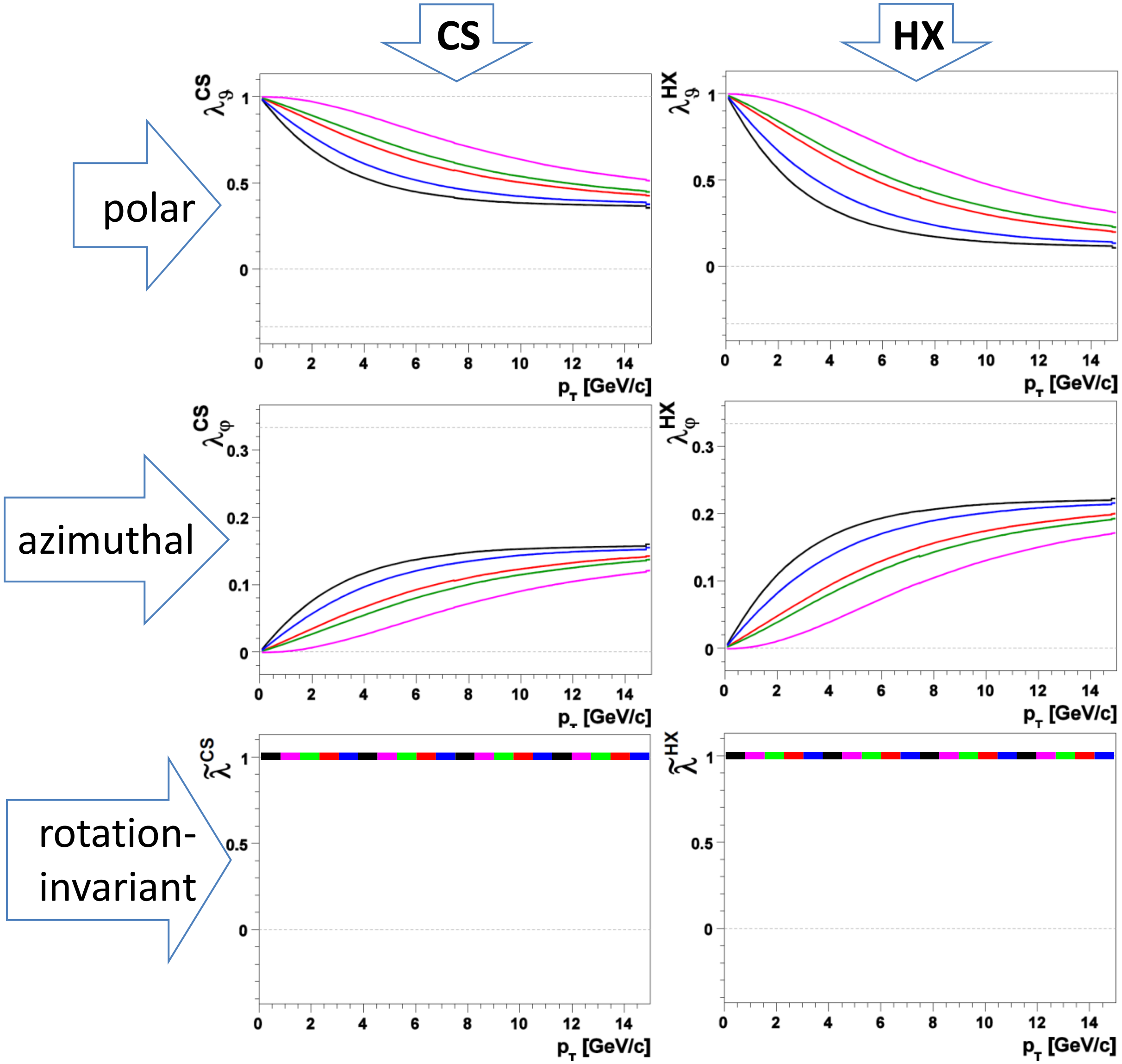

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- Immune to "extrinsic" kinematic dependencies

→ *less acceptance-dependent*

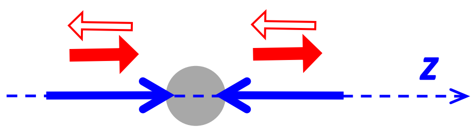
→ *facilitates comparisons*

- *useful as closure test*

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

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

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



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

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

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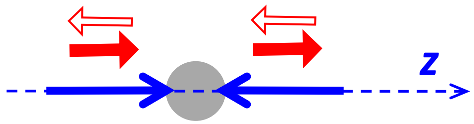

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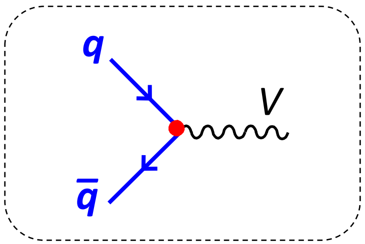
$O(\alpha_S^0) \longrightarrow$



"natural" z = relative dir. of *q* and *q*bar

$\rightarrow \lambda_\vartheta(\text{"CS"}) = +1$

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

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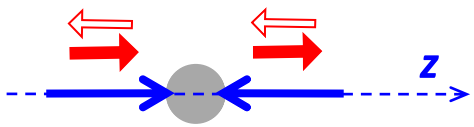

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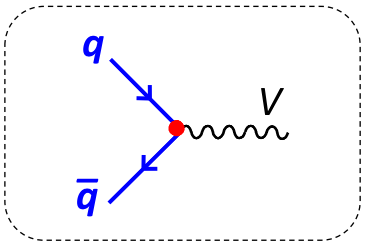
$O(\alpha_S^0)$



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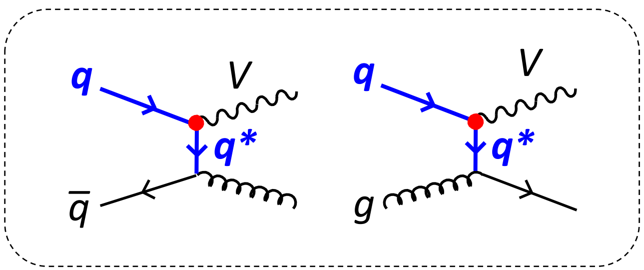

$O(\alpha_S^1)$

(LO) QCD corrections

z = dir. of *one* incoming quark

$\rightarrow \boldsymbol{\lambda_\vartheta}$**("GJ") = +1**

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

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

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

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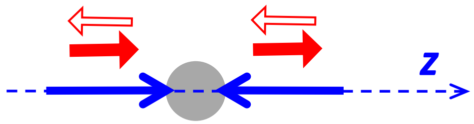

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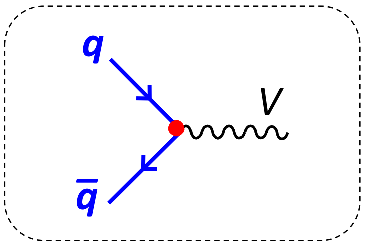
- ...but with respect to a ***subprocess-dependent quantization axis***

$O(\alpha_S^0)$ →



"natural" z = relative dir. of *q* and *q*bar
→ λ_ϑ("CS") = +1
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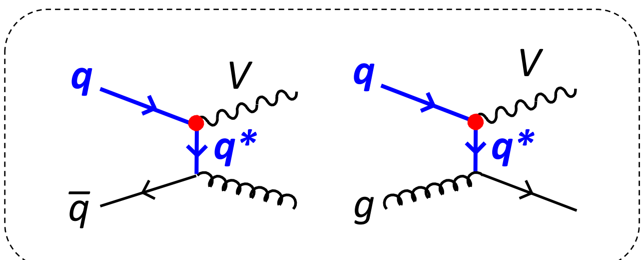
$O(\alpha_S^1)$
(LO) QCD corrections



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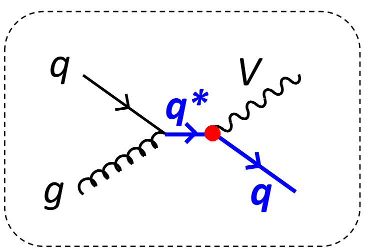


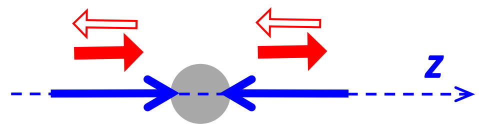
z = dir. of outgoing *q*
→ λ_ϑ("HX") = +1
$\tilde{\lambda} = +1$

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

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

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

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



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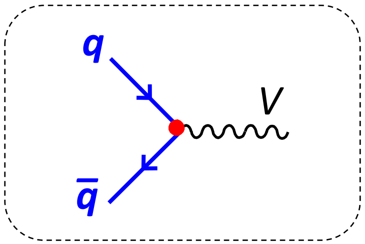
- ...but with respect to a ***subprocess-dependent quantization axis***

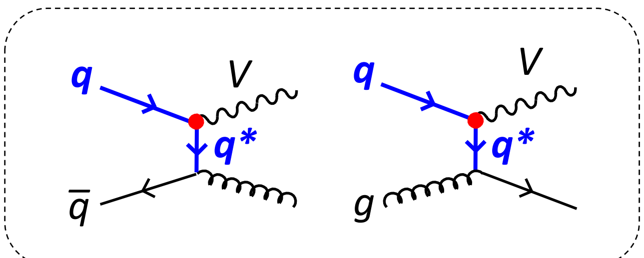
$O(\alpha_S^0)$ →



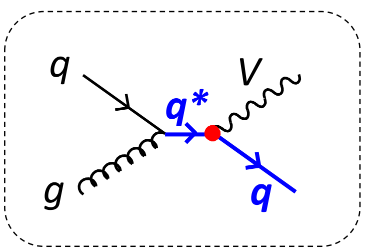
"natural" z = relative dir. of q and $q$bar
→ λ_ϑ("CS") = +1

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

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



z = dir. of *one* incoming quark
→ λ_ϑ("GJ") = +1
$\tilde{\lambda} = +1$



z = dir. of outgoing q
→ λ_ϑ("HX") = +1
$\tilde{\lambda} = +1$

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

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

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

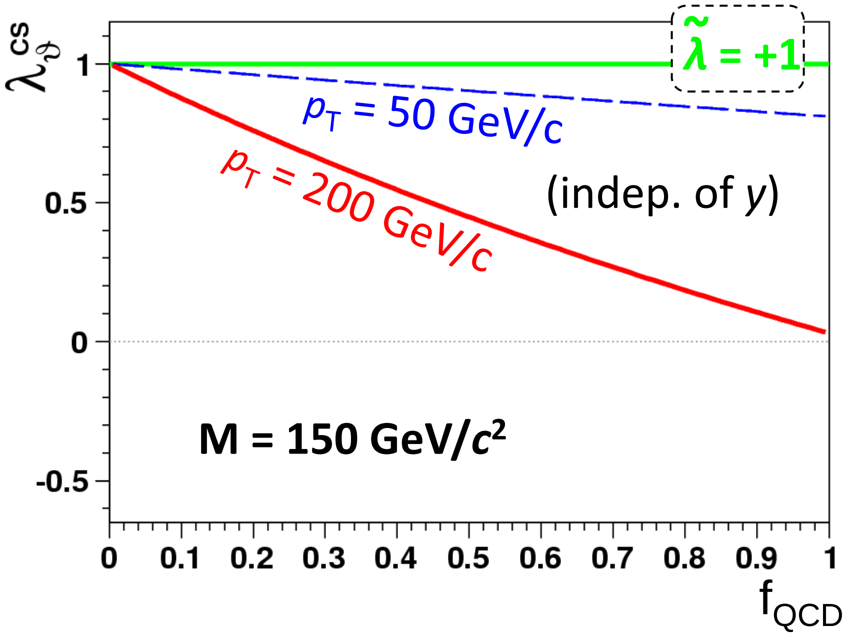
λ_ϑ vs $\tilde{\lambda}$

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

λ_ϑ vs $\tilde{\lambda}$

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

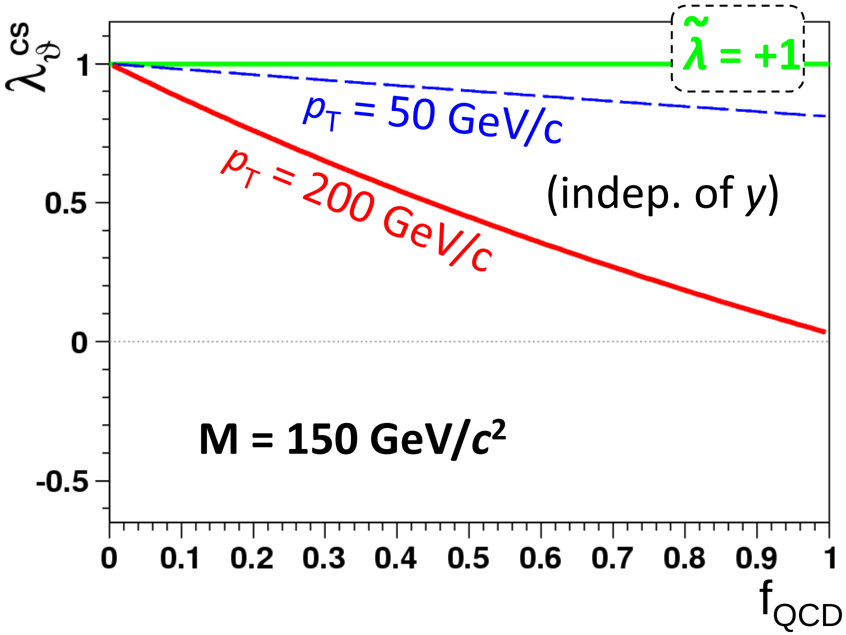
Case 1: dominating ***q-q*bar** QCD corrections



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



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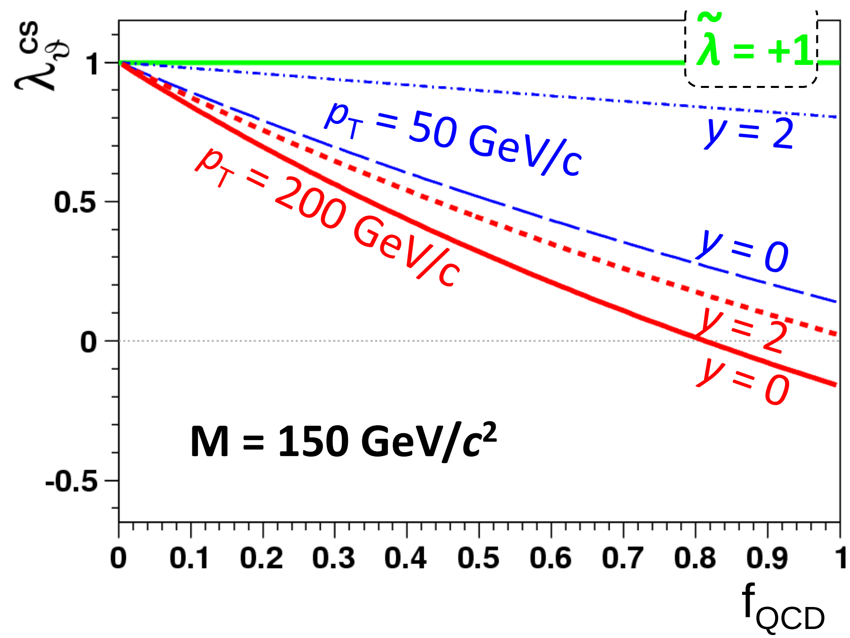

λ_ϑ vs $\tilde{\lambda}$

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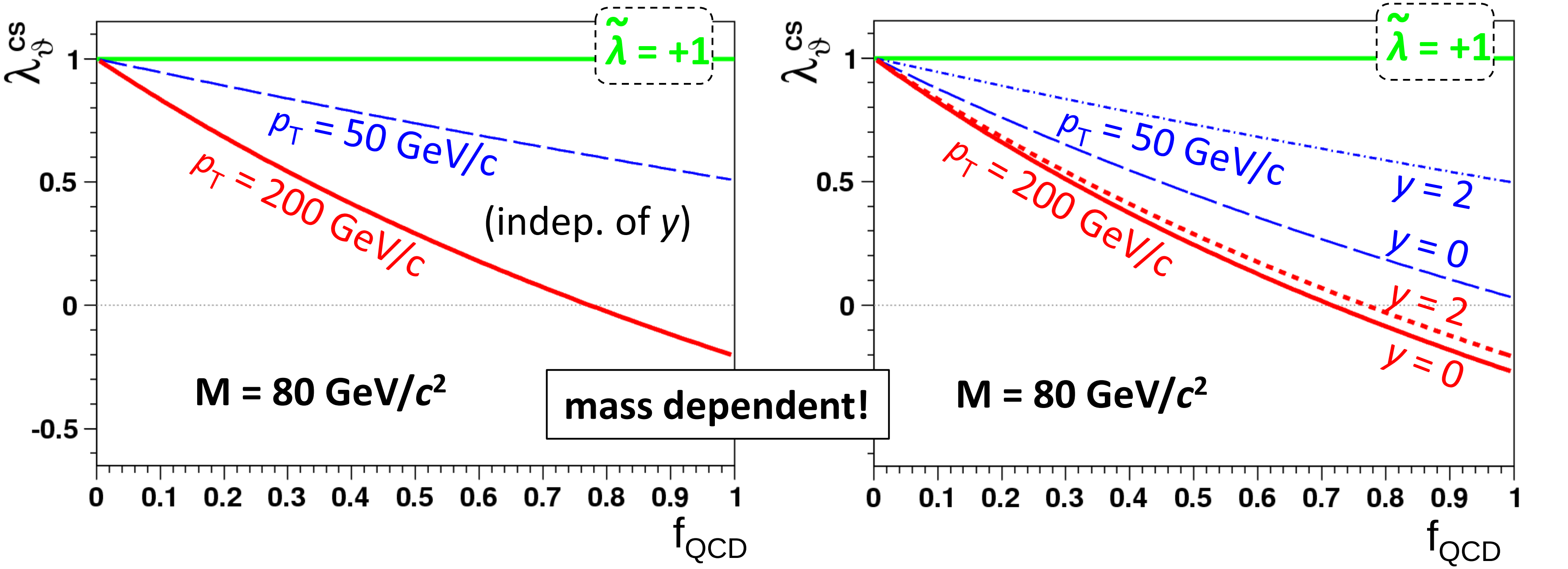

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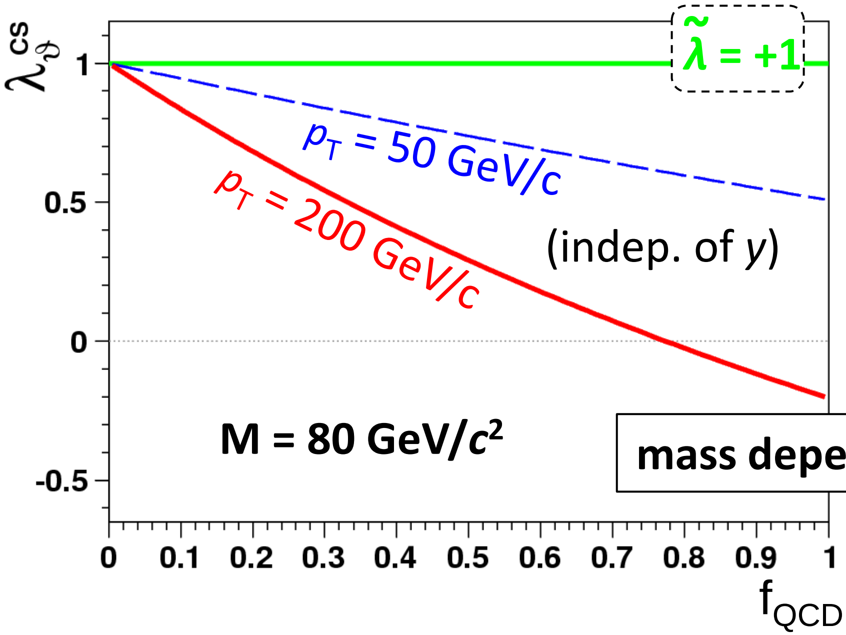

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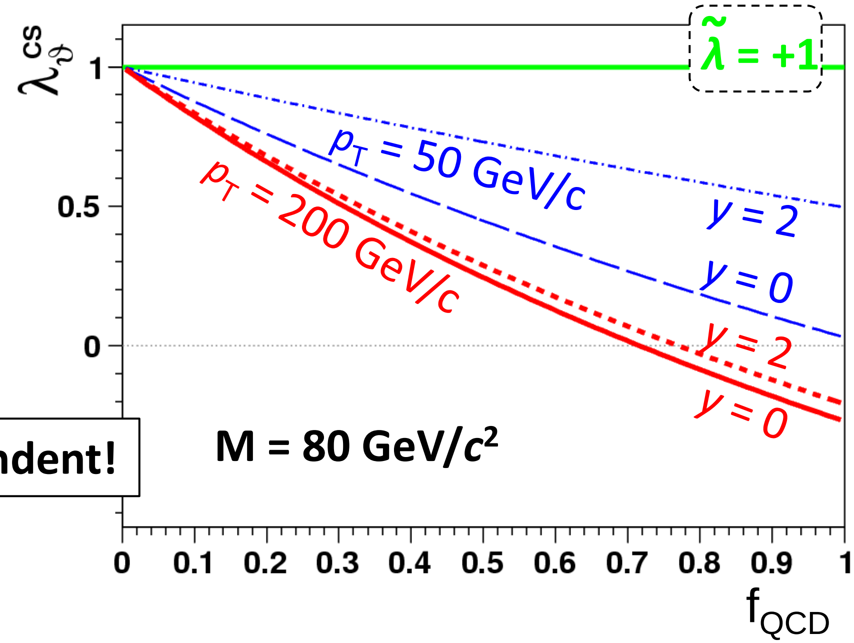
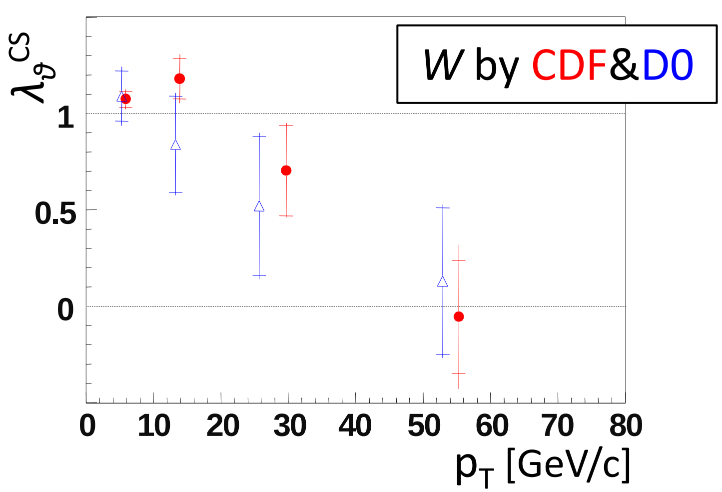


mass dependent!



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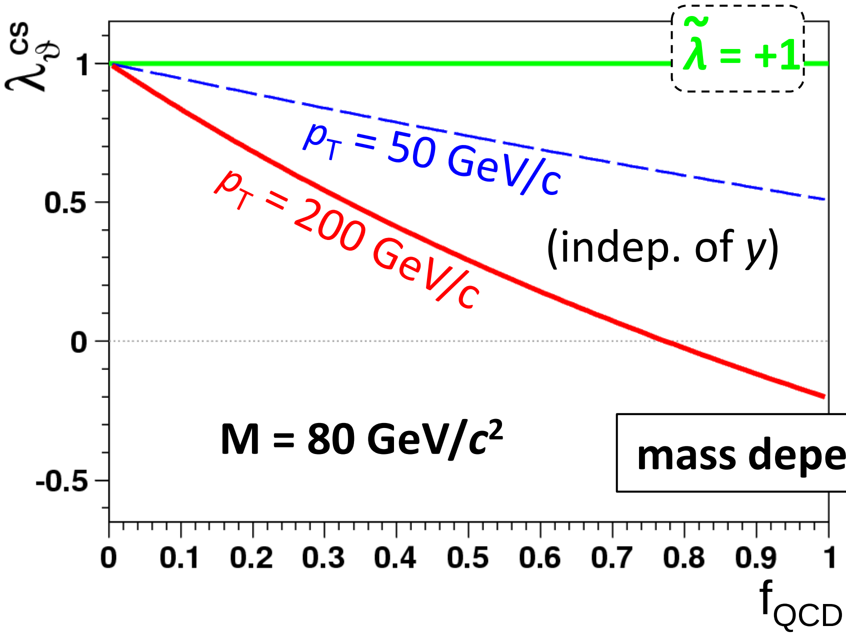

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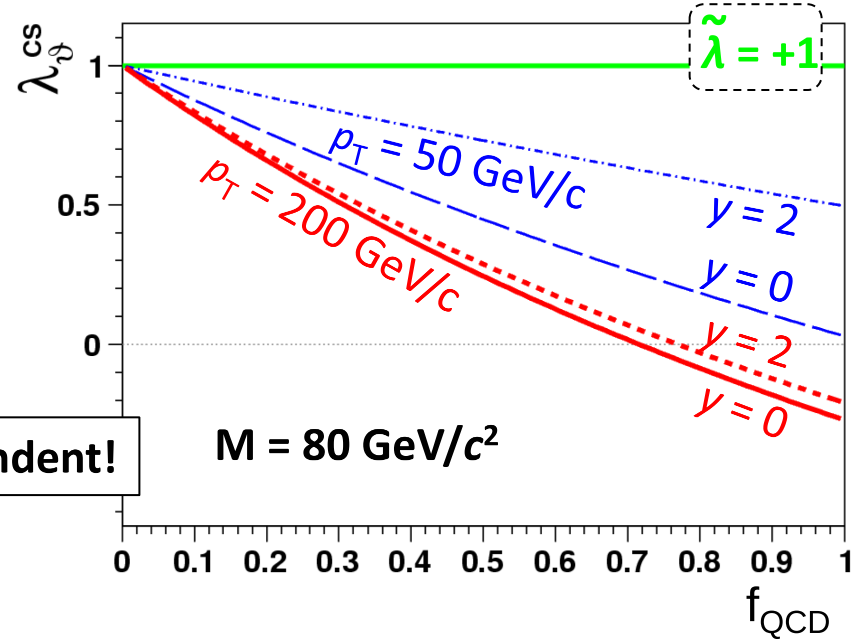

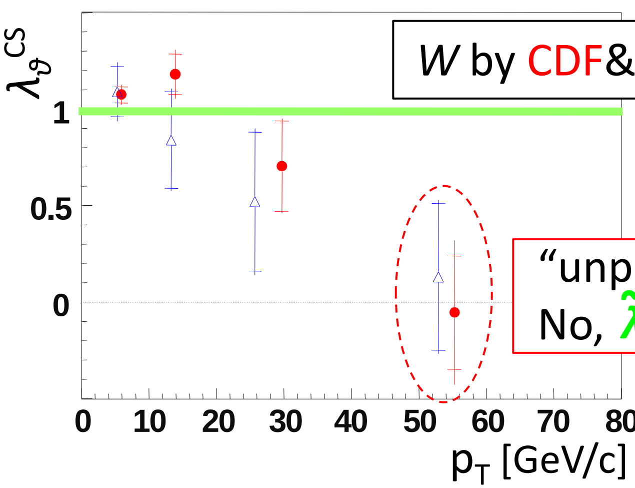

"unpolarized"?
No, $\tilde{\lambda}$ = +1 !

λ_ϑ vs $\tilde{\lambda}$

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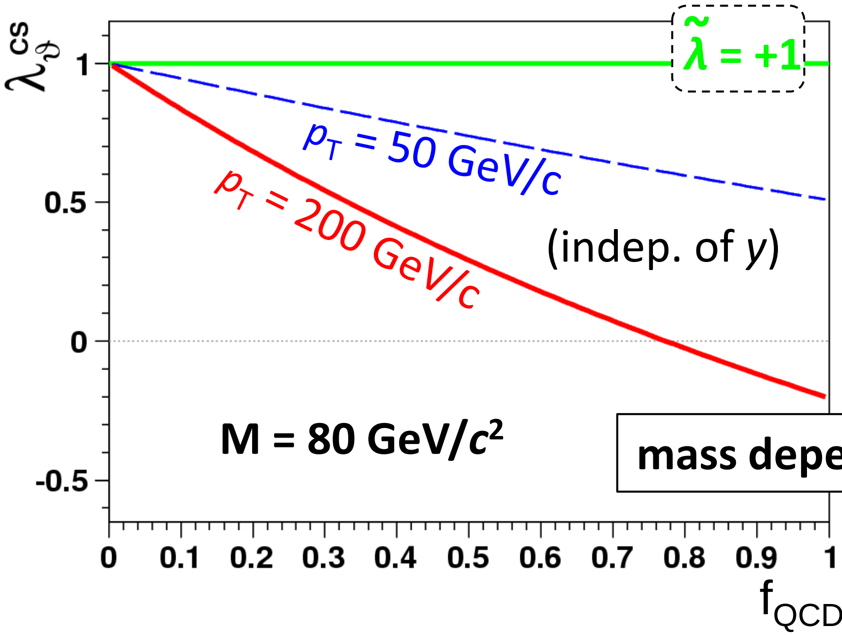

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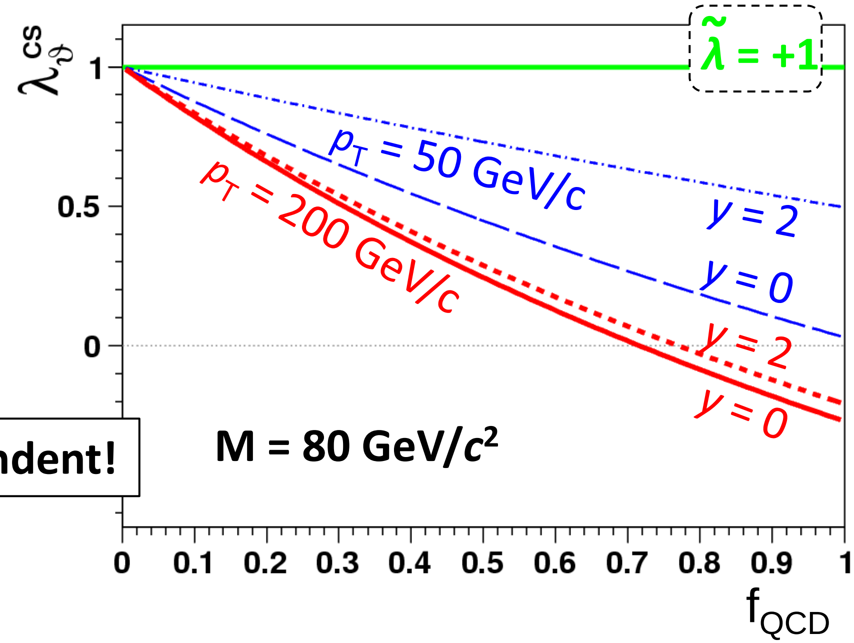

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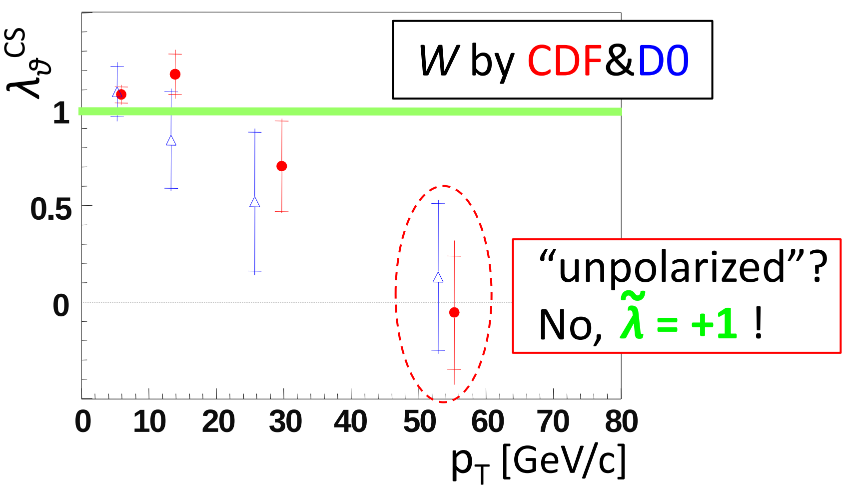

λ_ϑ

- 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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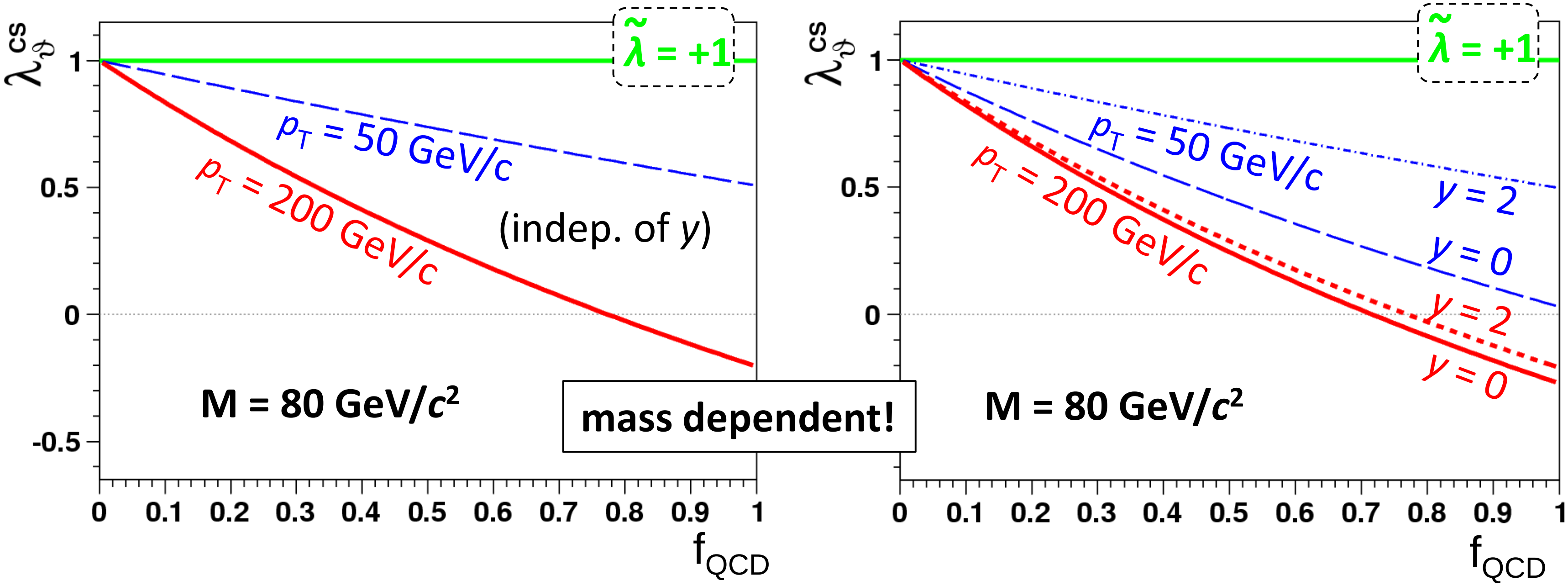

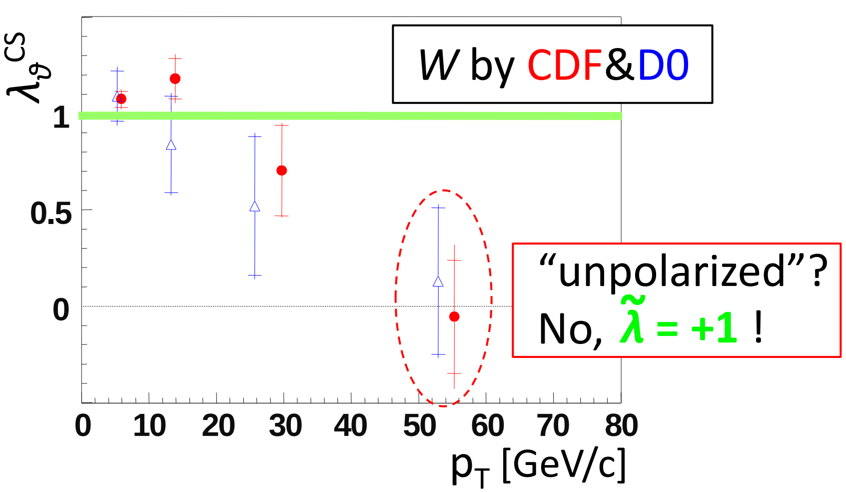

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$\tilde{\lambda}$ is constant, maximal and independent of process admixture

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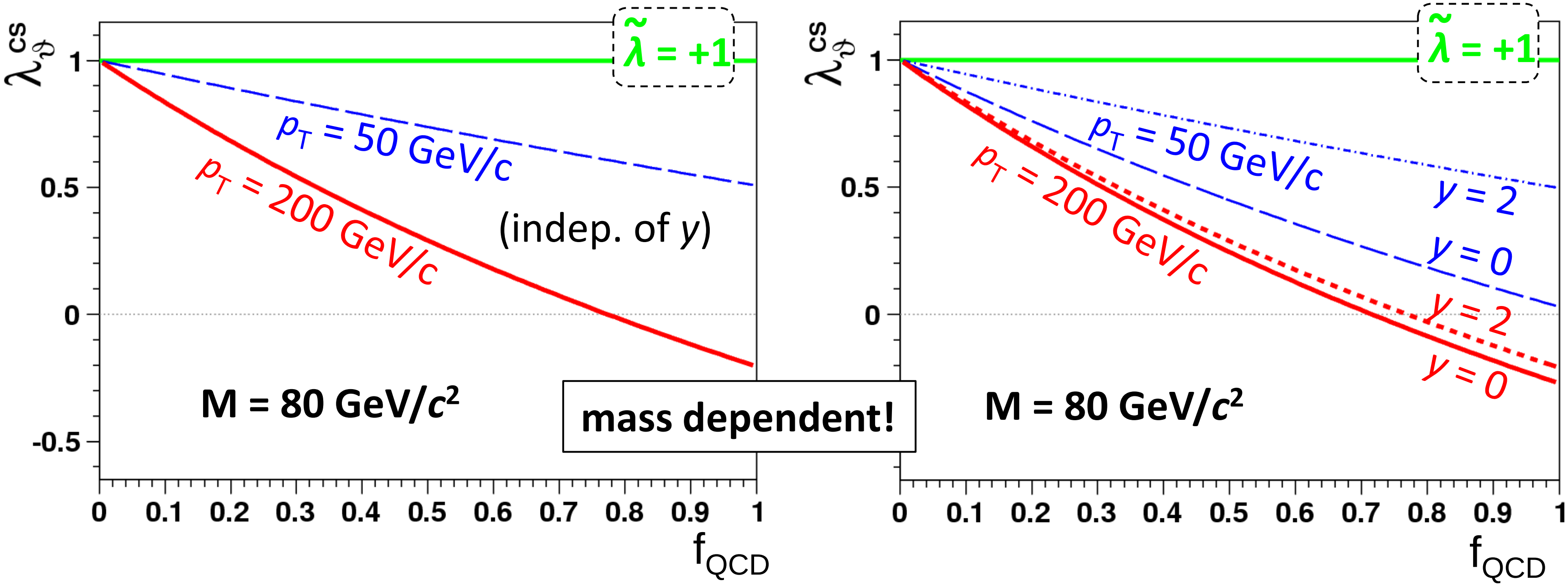

On the other hand, $\tilde{\lambda}$ forgets about the direction of the quantization axis.
This information is crucial if we want to **disentangle the *qg* contribution**,
the only one resulting in a ***rapidity-dependent λ_ϑ***

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

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

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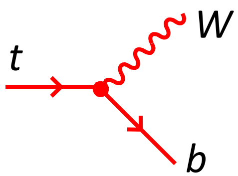
longitudinally polarized:

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

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

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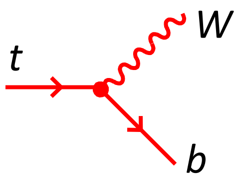
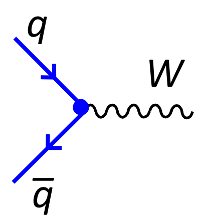


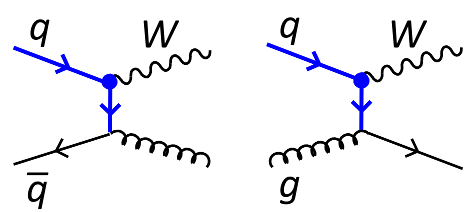
independently of top production mechanism

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

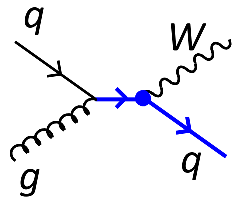
transversely polarized,
$\lambda_{\vartheta} = +1$ & $\lambda_{\varphi} = 0$ *wrt 3 different axes:*



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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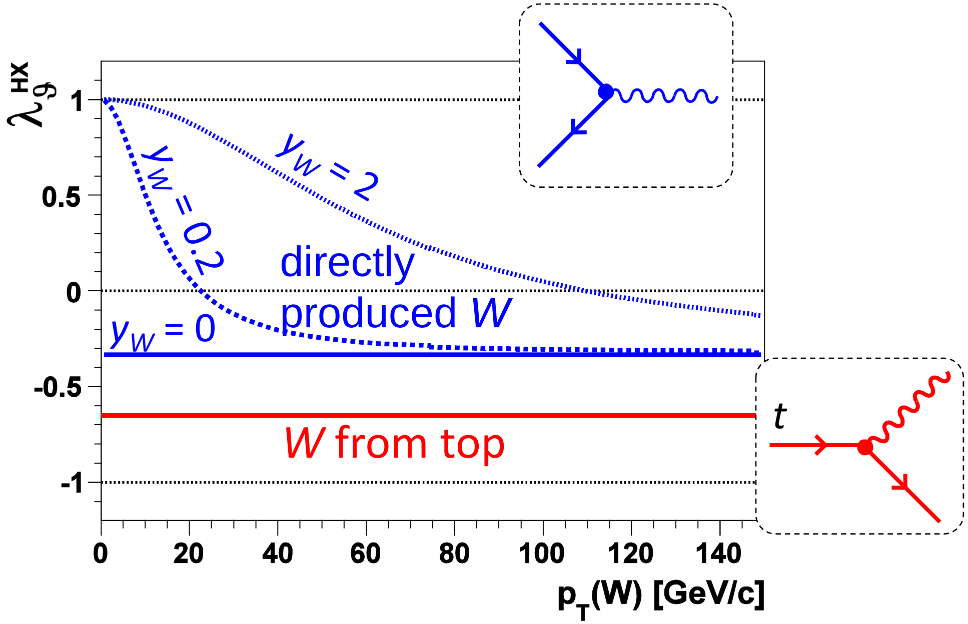

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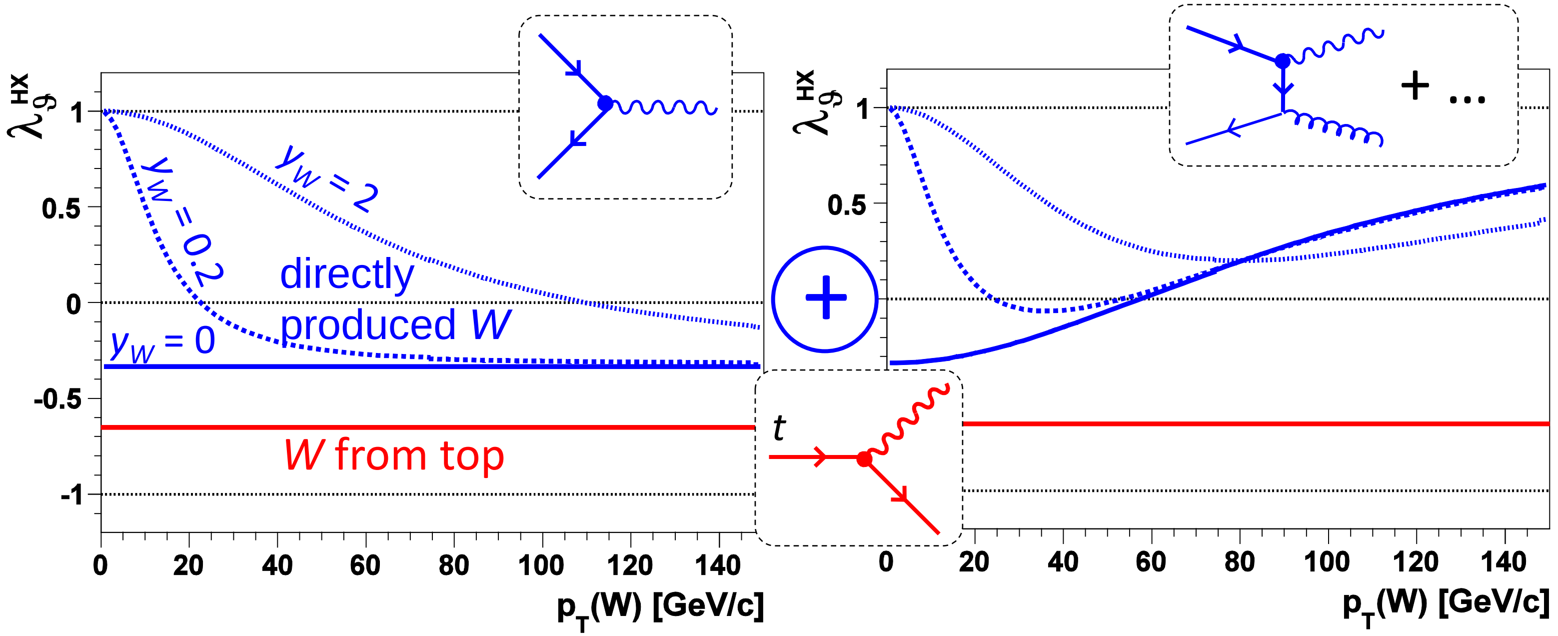

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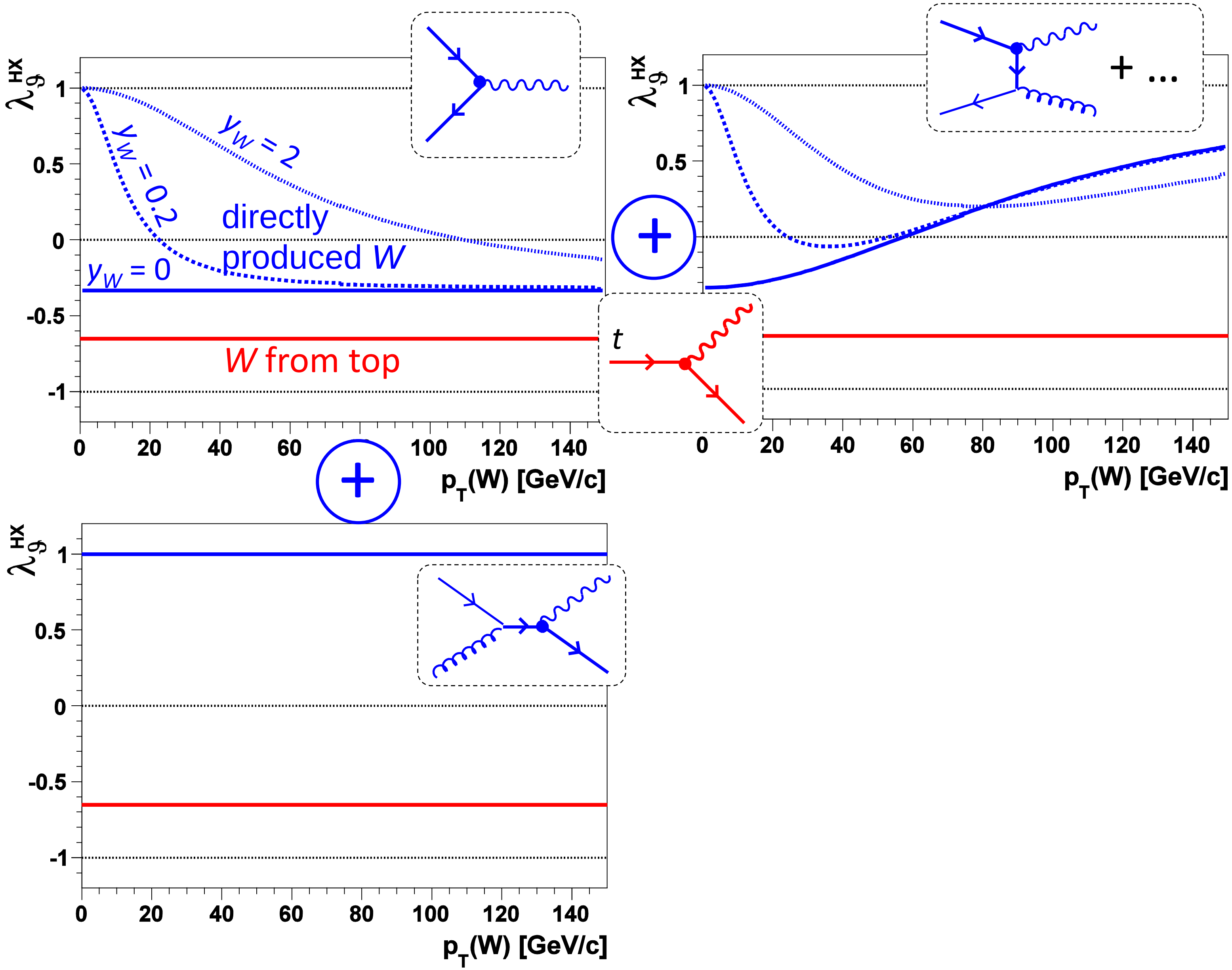

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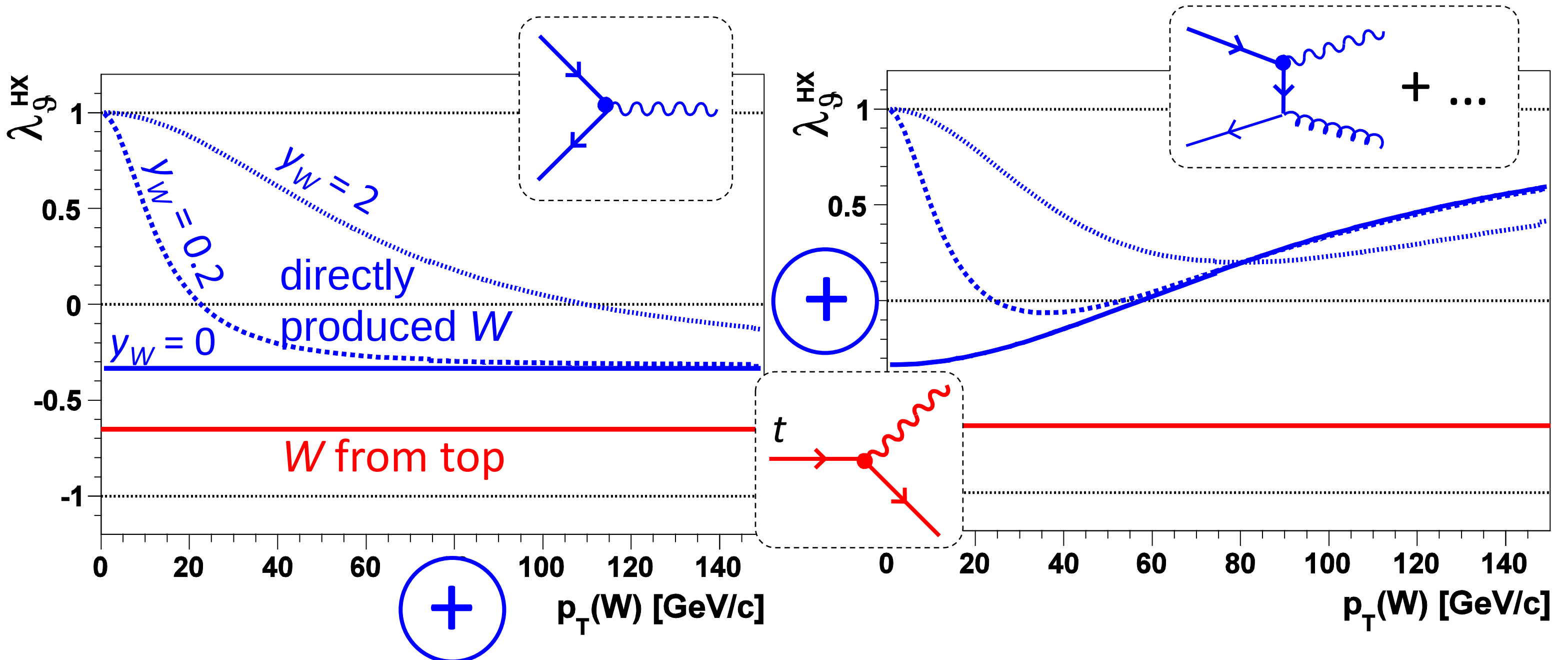
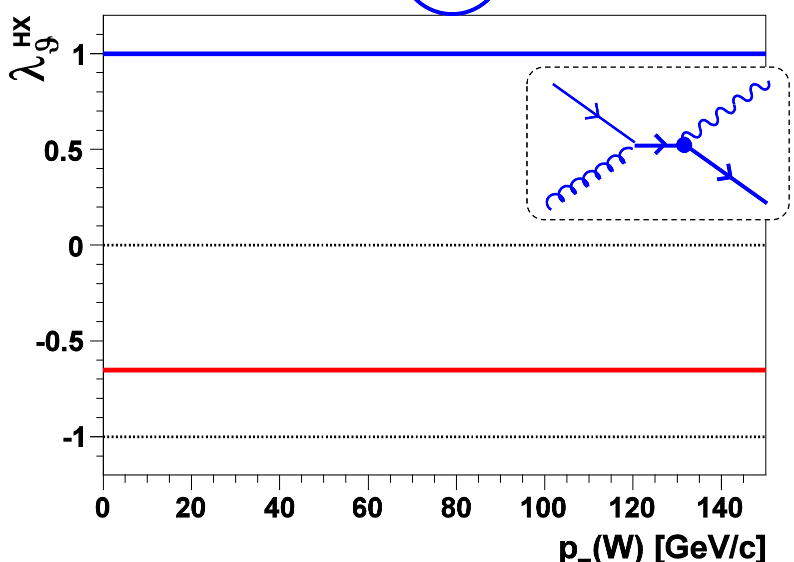
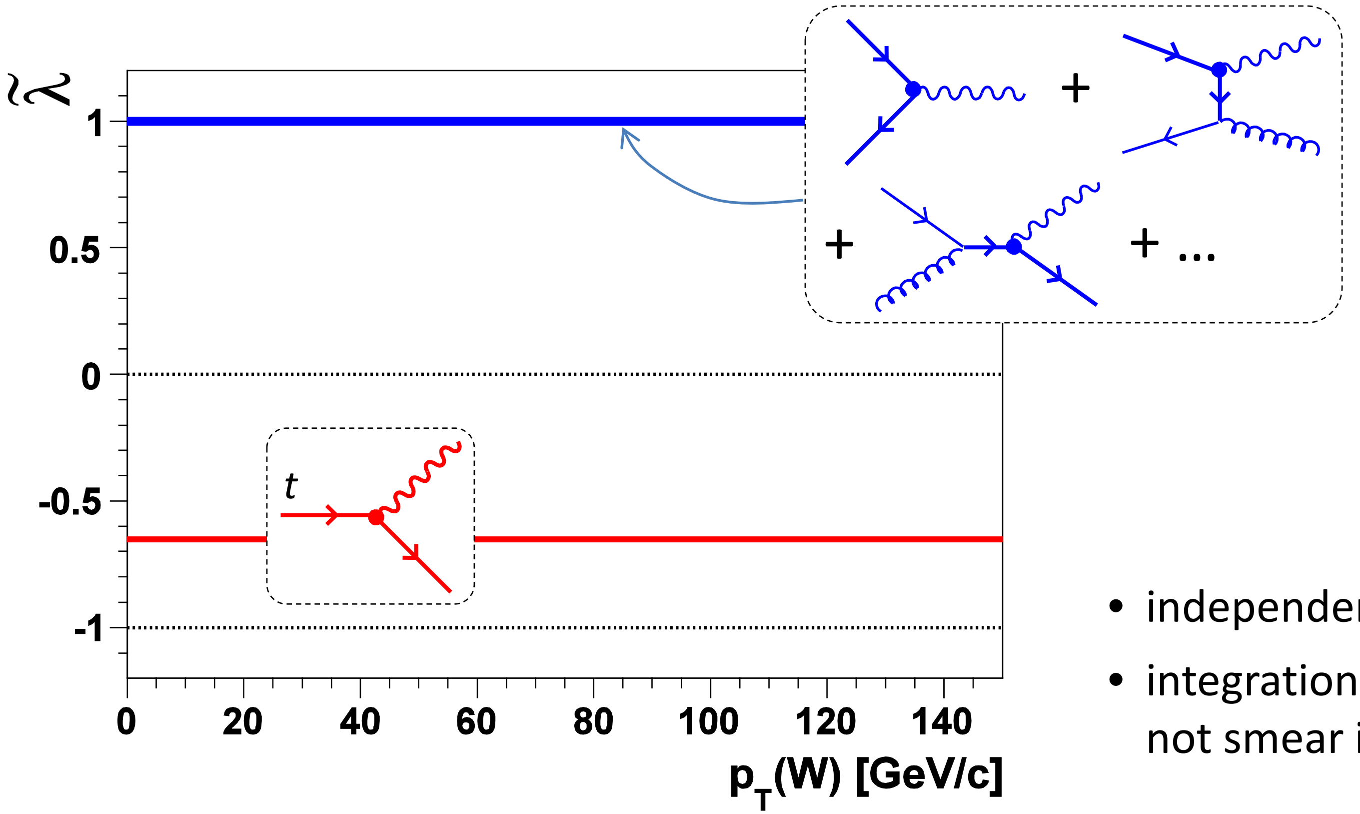




The polarization of *W from q-qbar / q-g*

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

b) Rotation-invariant approach



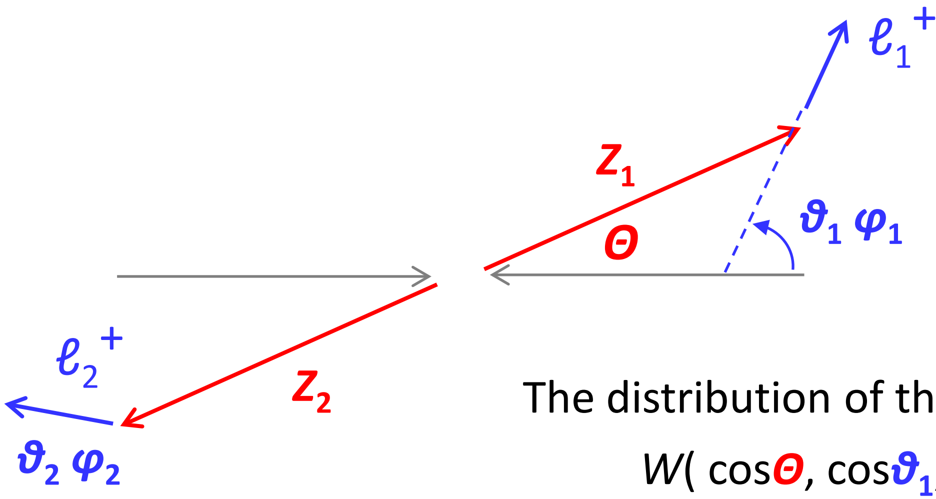
The *invariant* polarization of *W* from *q-qbar* / *q-g* is **constant** and fully **transverse**

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

Example: the *q*-*q*bar $\rightarrow$ *ZZ* continuum background

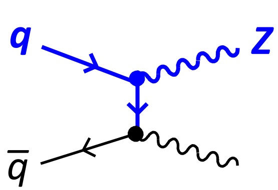
dominant Standard Model background for new-signal searches
in the $ZZ \rightarrow 4\ell$ channel with $m(ZZ) > 200$ GeV/c^2

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

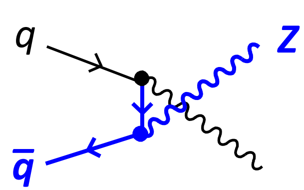


The distribution of the **5 angles** depends on the **kinematics**

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



t-channel

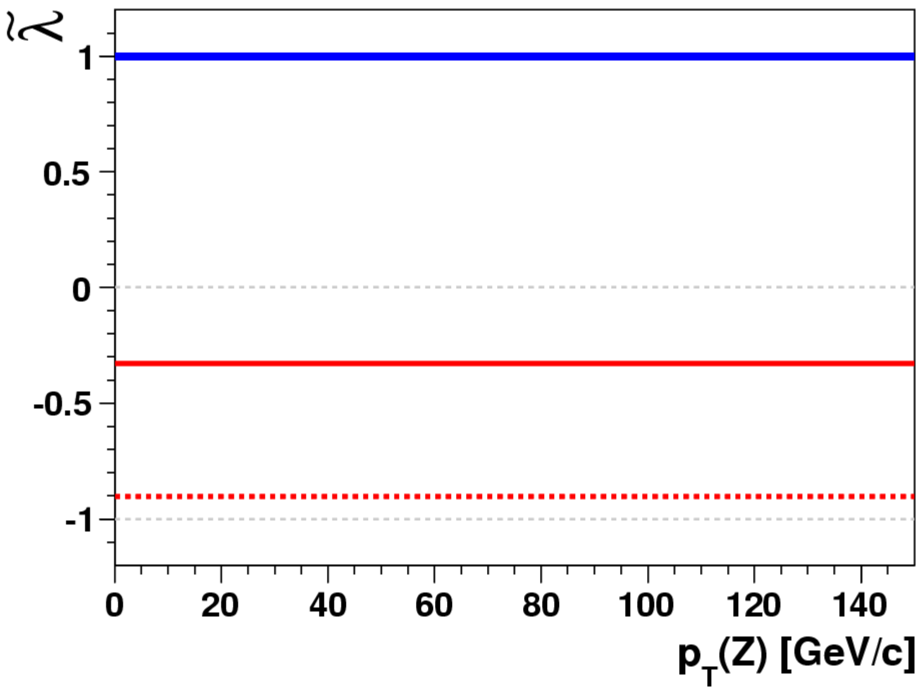


u-channel

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

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

Discriminant nº1: ***Z* polarization**



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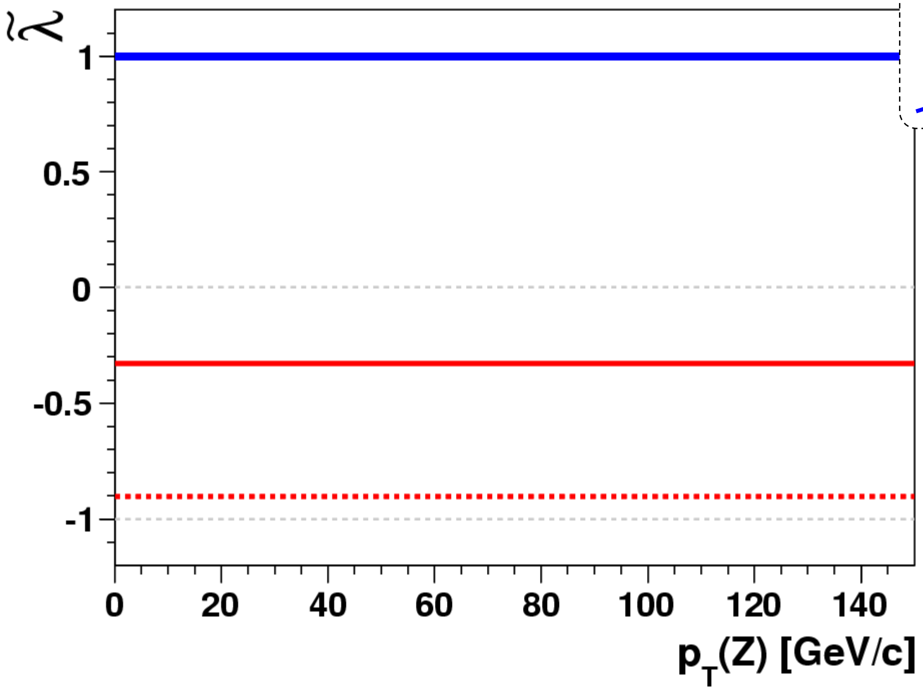

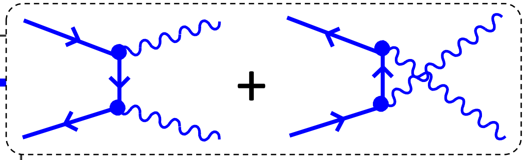

The *invariant* polarization of *Z* from *q*-*q*bar is fully **transverse**

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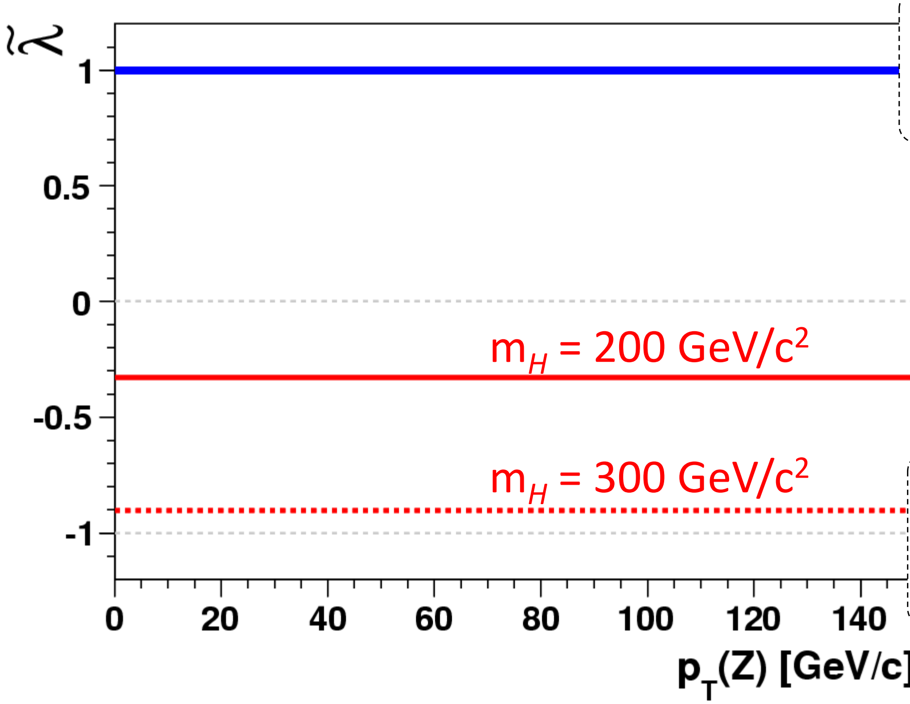

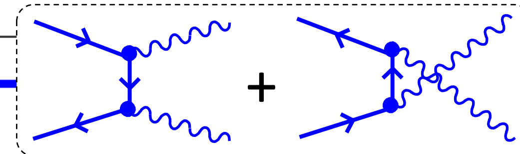

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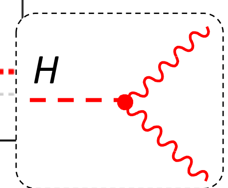
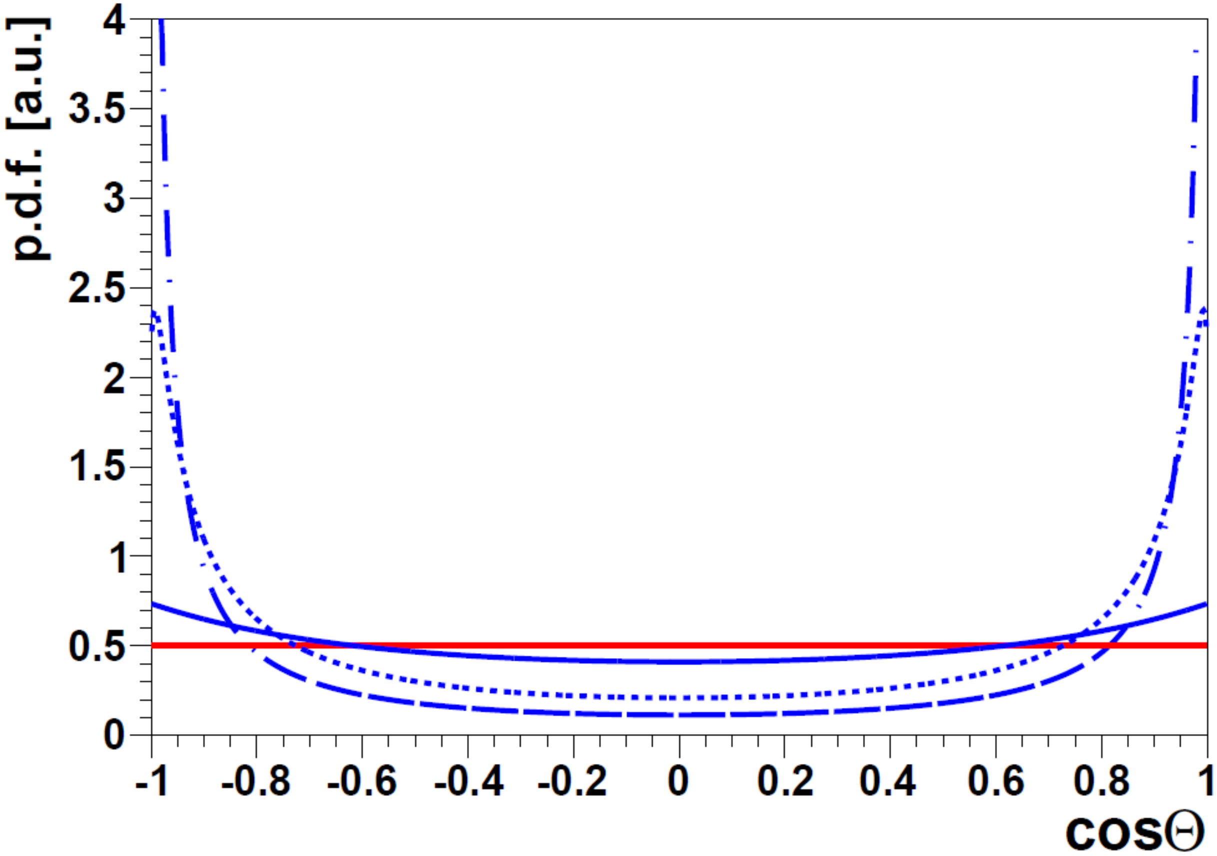


Z bosons from *H* → *ZZ* are **longitudinally** polarized (stronger polarization for heavier *H*)

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

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



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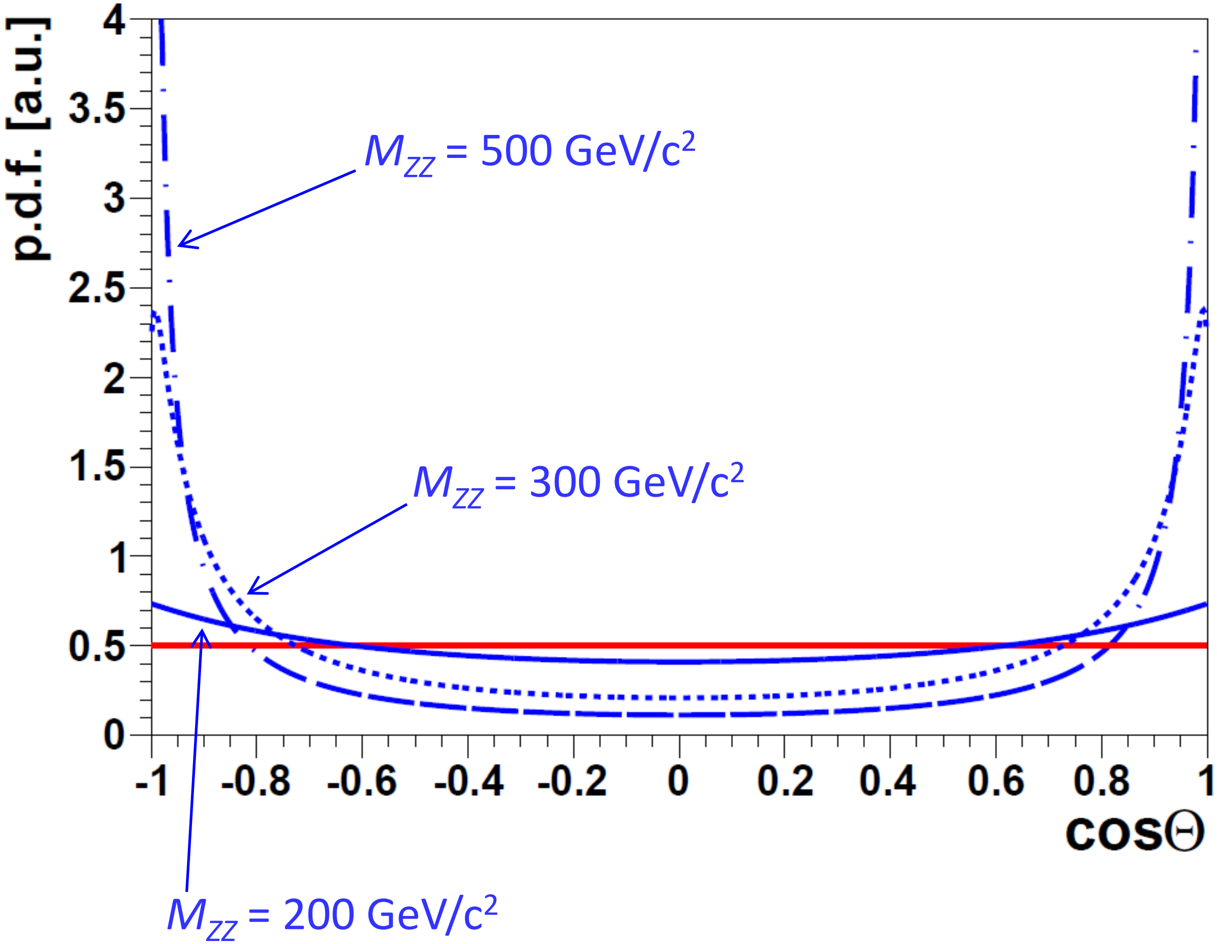

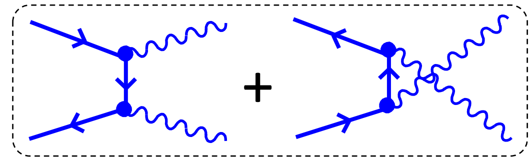

Z from *q*-*q*bar is emitted mainly close to the beam if M_{ZZ}/M_Z is large

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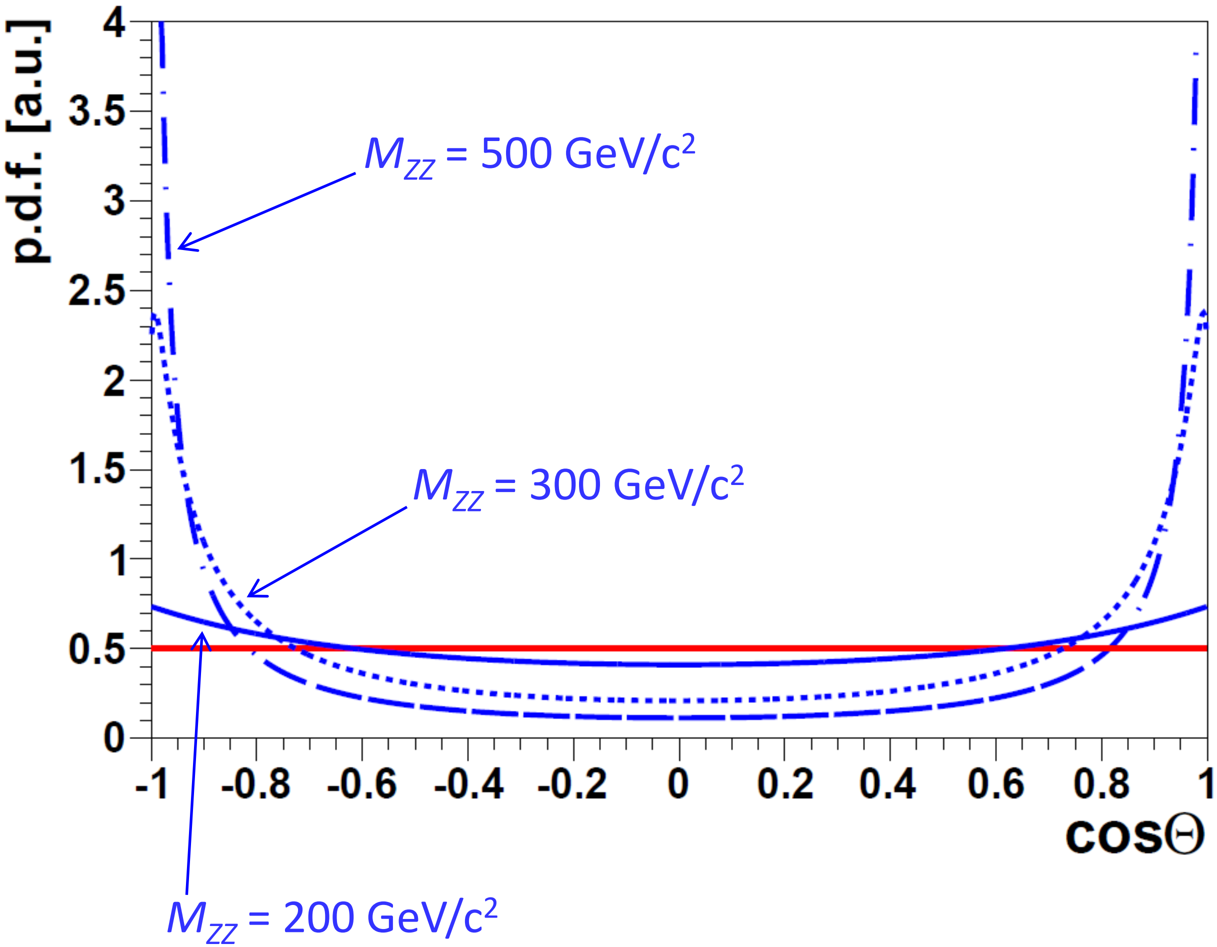

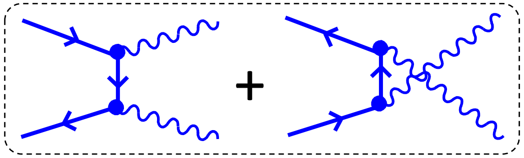

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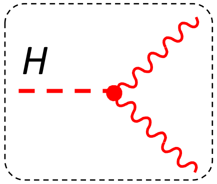

Z bosons from *H* decay are emitted isotropically

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

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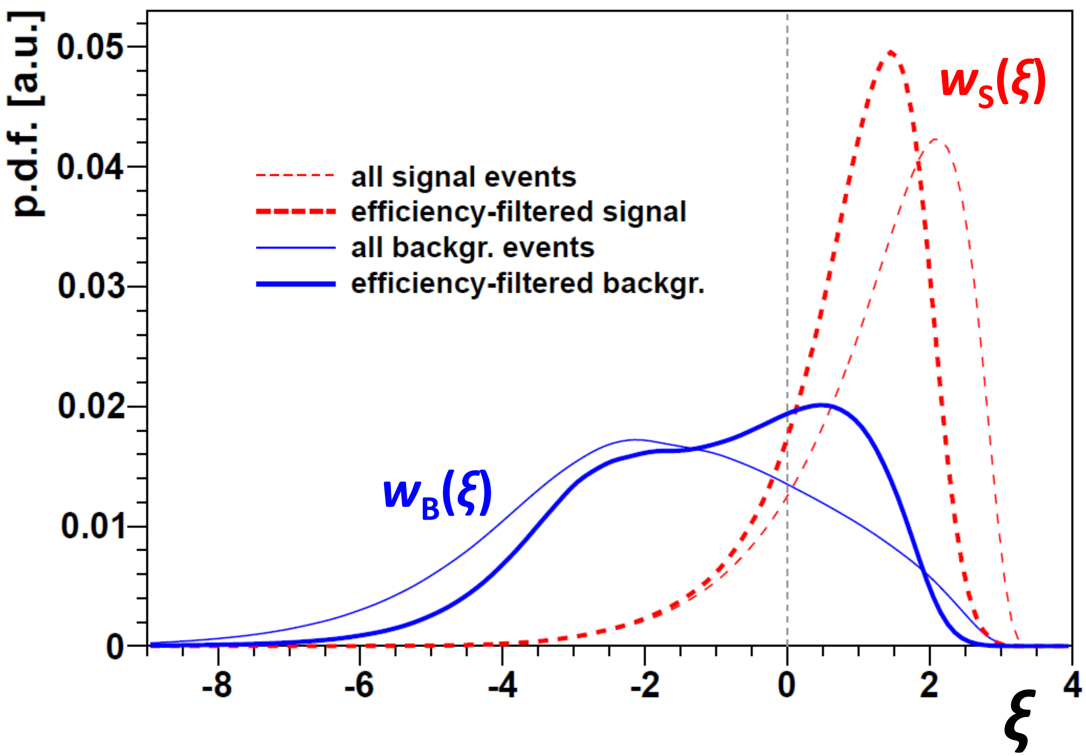

$\sqrt{s}$ = 14 TeV
$500 < M_{ZZ} < 900$ GeV/c^2
M_H = 700 GeV/c^2
$|y_{ZZ}| < 2.5$

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

β = ratio of observed / expected signal events

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$\beta < 1 \rightarrow$ 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

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

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

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

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

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

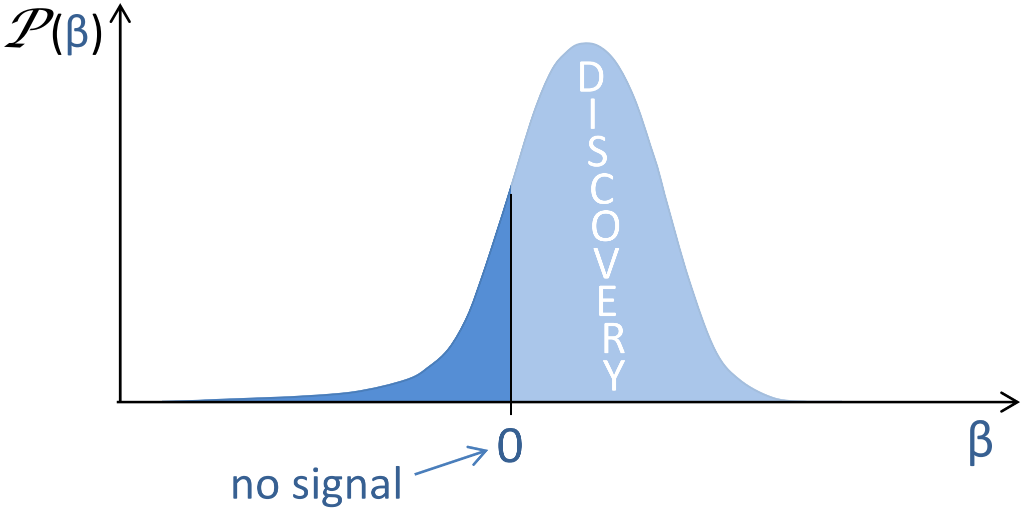
*in*dependent of luminosity and cross-section uncertainties!

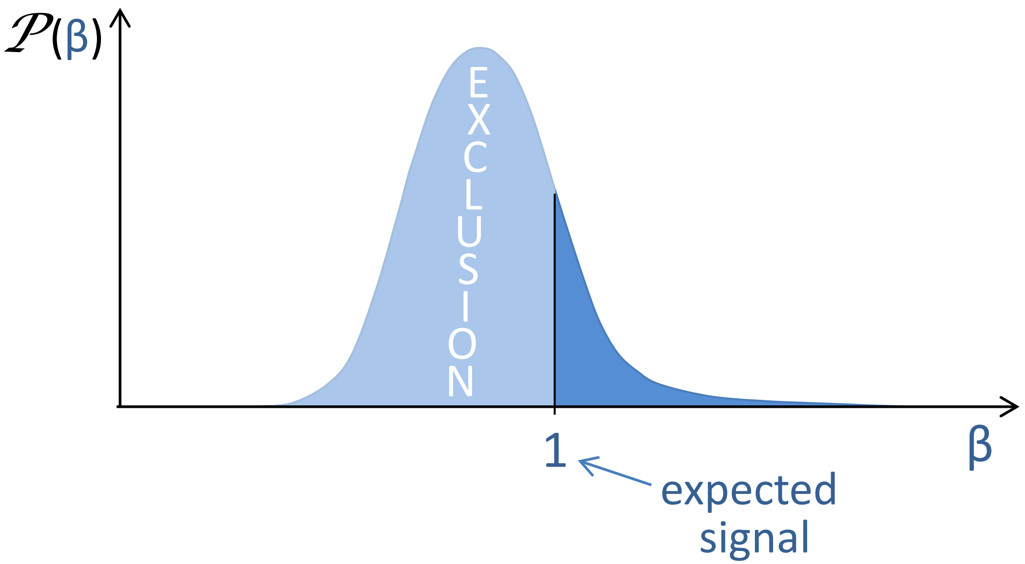
3) $$\mathcal{P}_{\text{tot}}(\boldsymbol{\beta}) = \mathcal{P}_{\text{angular}}(\boldsymbol{\beta}) \times \mathcal{P}_{\text{BGnorm}}(\boldsymbol{\beta})$$

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

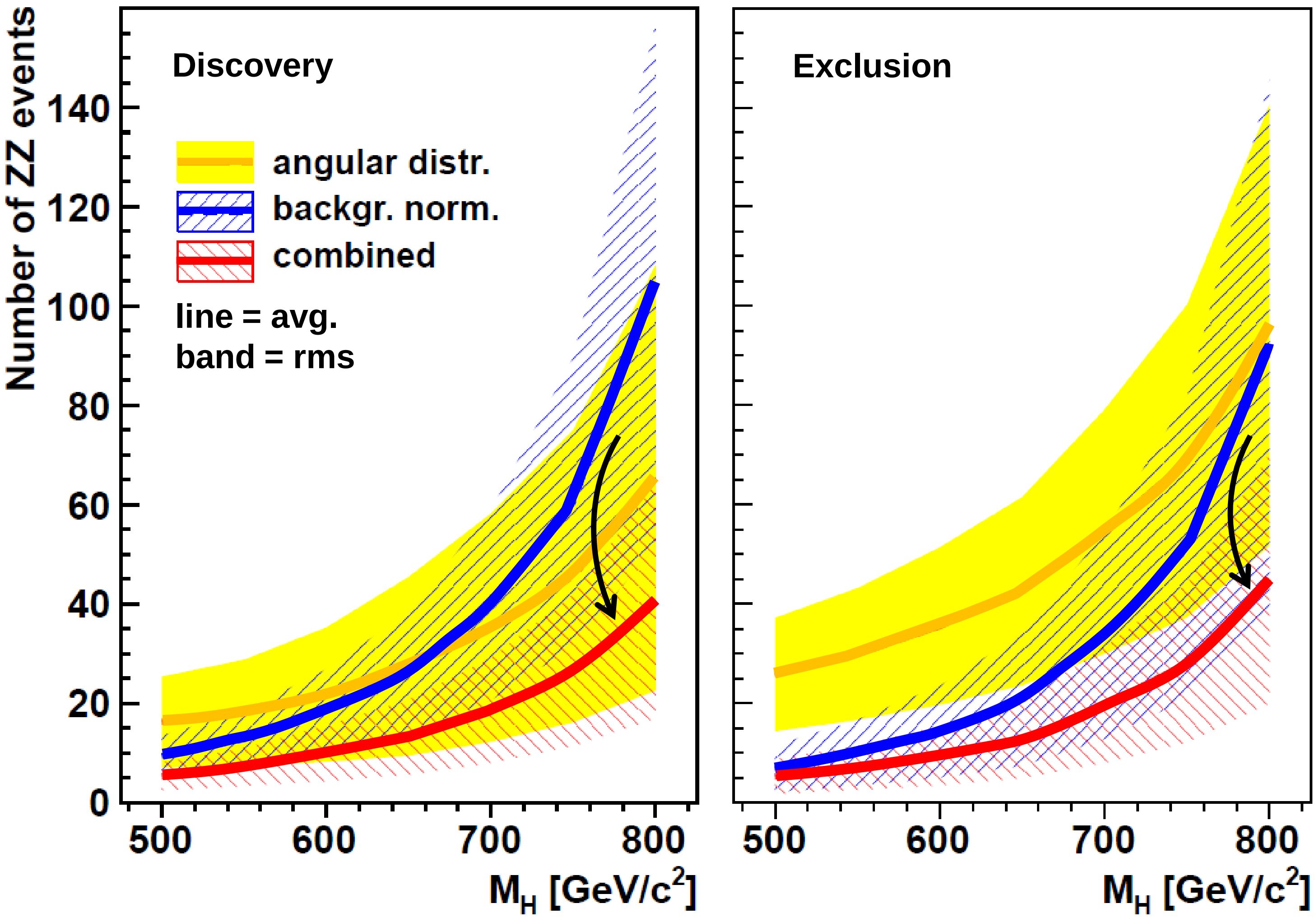
Confidence levels





Limits vs m_H

“3σ” level



Variation with mass essentially due to varying BG level:

30% for m_H = 500 GeV/c^2 → 70% for m_H = 800 GeV/c^2

Angular method more advantageous with higher BG levels

Further reading

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- P. Faccioli, *Questions and prospects in quarkonium polarization measurements from proton-proton to nucleus-nucleus collisions*, invited “brief review”, Mod. Phys. Lett. A Vol. 27 N. 23, 1230022 (2012)
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