$H \to ZZ$ as a double-slit experiment

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Quantum observables for collider physics 2025
Florence, April 7th 2025

Project PID2022-142545NB-C21 funded by
MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
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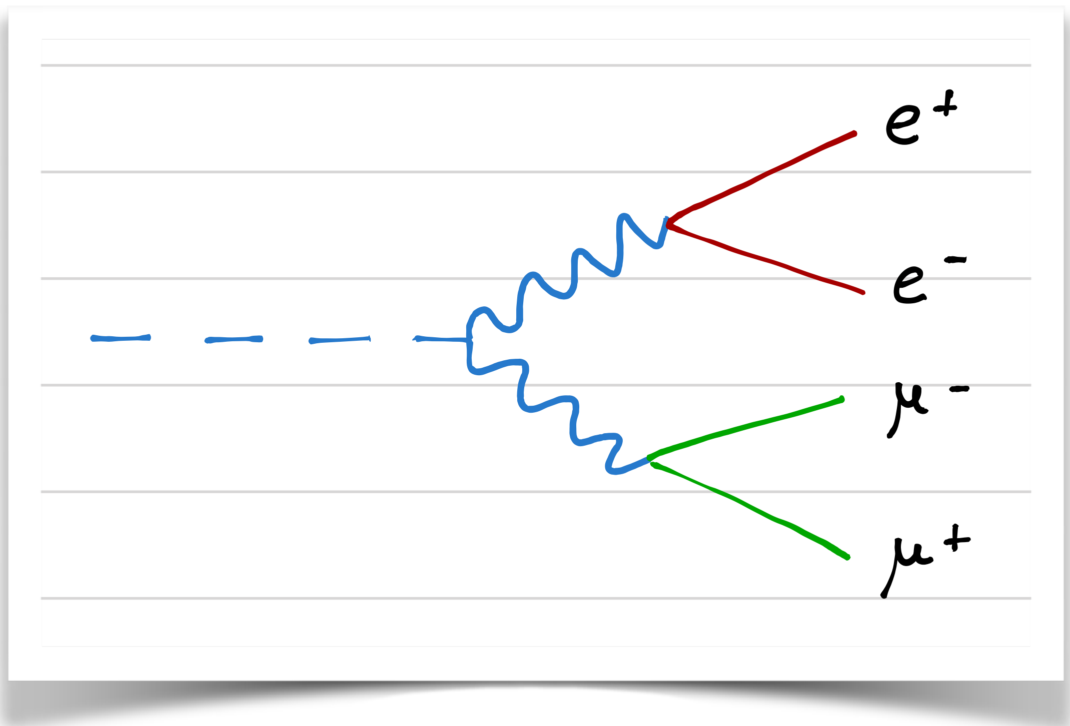
$H \to ZZ$

entanglement

$H \to ZZ$ entanglement

In the eeμμ final state it is clear that we have two intermediate Z bosons, of which we can measure entanglement, etc.

JAAS, Bernal, Casas,Moreno, 2209.13441

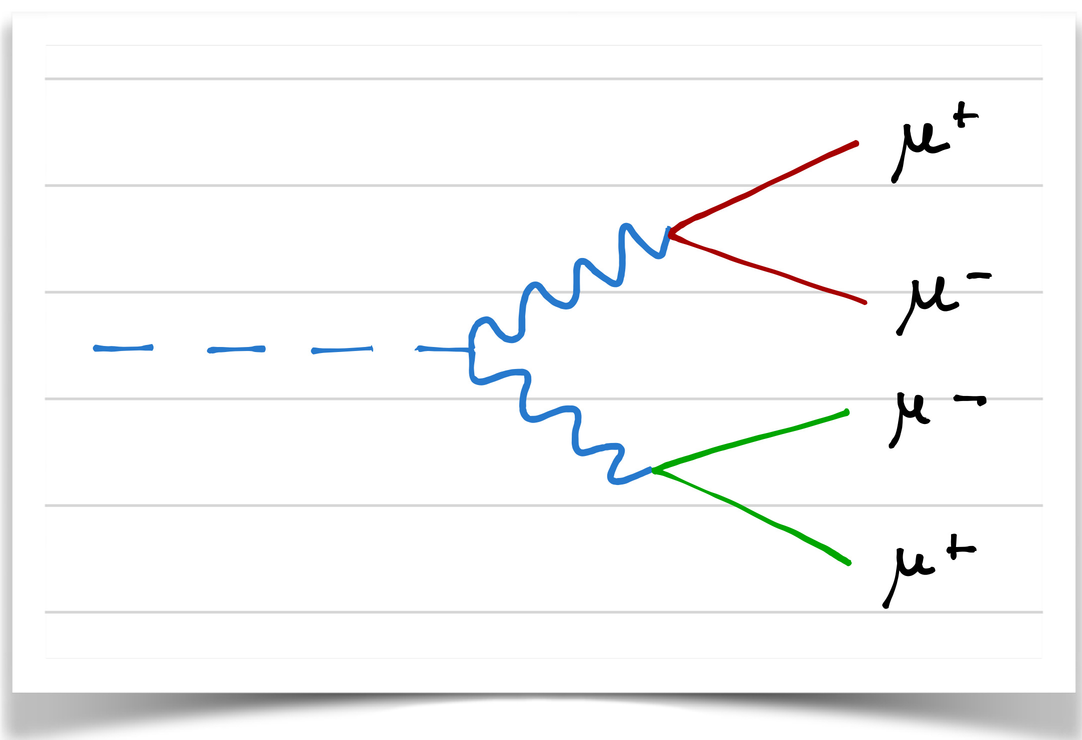


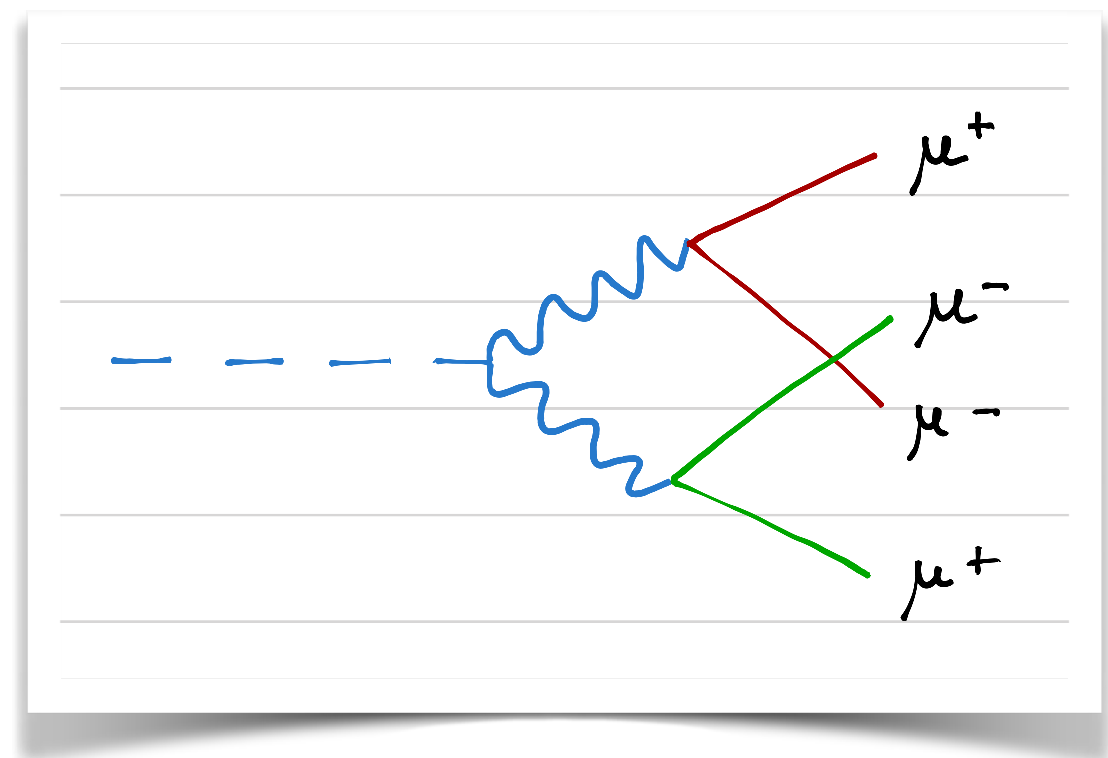
flavour pairing

One of the Z´s is virtual but that doesn't matter since it is decaying to light leptons

$H \to ZZ$ entanglement

If we want to use 4e / 4μ final states too [double statistics] we have two possibilities for the intermediate Z´s



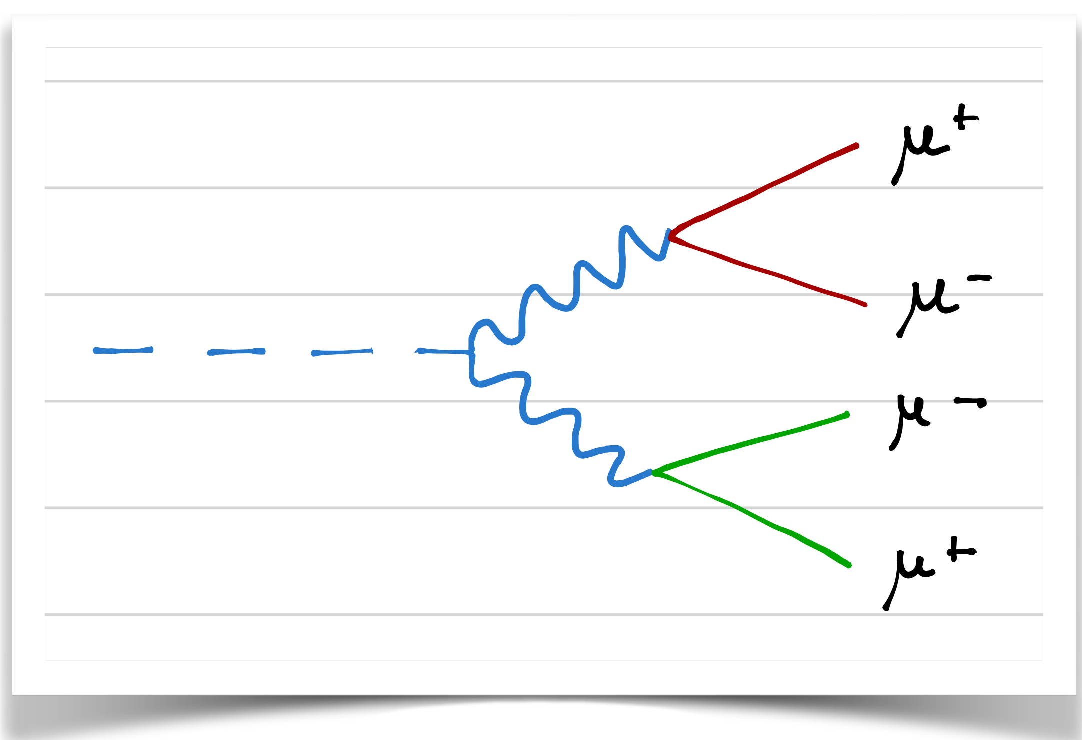


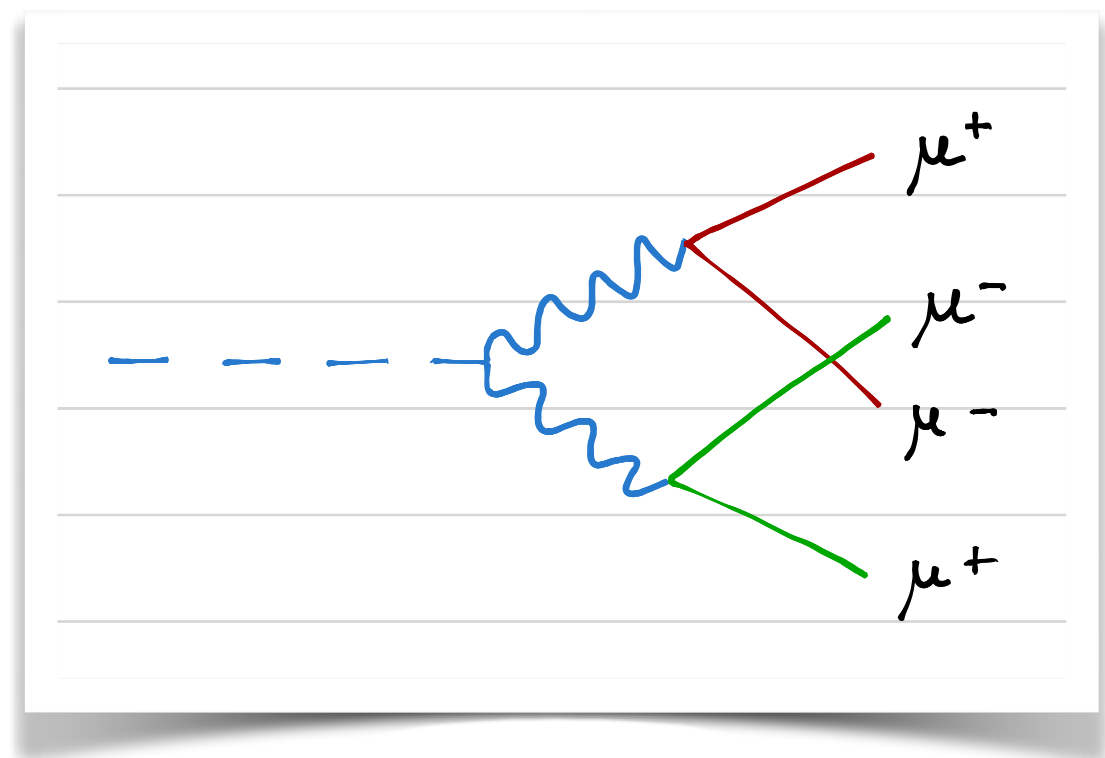
For each event [set of momenta], is there a dominant diagram?
Reasonable hypothesis: one of the Z´s will be nearly on-shell

We can try to guess the dominant diagram, if any, by checking invariant masses

$H \to ZZ$ entanglement

If we want to use 4e / 4μ final states too [double statistics] we have two possibilities for the intermediate Z´s





Pairing A → $m_{Z1}^{(A)}$, $m_{Z2}^{(A)}$

Pairing B → $m_{Z1}^{(B)}$, $m_{Z2}^{(B)}$

[m_{Z1} is the largest m_Z]

Select the pairing of opposite-sign leptons that gives largest m_Z among $m_{Z1}^{(A)}$, $m_{Z1}^{(B)}$

mass pairing

$H \to ZZ$ entanglement

… but this is not enough to make one diagram really dominant …

coefficients of spherical harmonics

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\Big[1 + a^1_{LM} Y^M_L(\Omega_1) + a^2_{LM} Y^M_L(\Omega_2) + c_{L_1 M_1 L_2 M_2} Y^{M_1}_{L_1}(\Omega_1) Y^{M_2}_{L_2}(\Omega_2)\Big]$$

angular coefficient	$e^+e^-\mu^+\mu^-$	4e / 4μ
$a_{20}^1 = B_2\, A_{20}^1$	-0.636	-0.706
$a_{20}^2 = B_2\, A_{20}^2$	-0.634	-0.706
$c_{111-1} = (B_1)^2\, C_{111-1}$	0.103	0.773
$c_{1010} = (B_1)^2\, C_{1010}$	-0.067	-0.857
$c_{222-2} = (B_2)^2\, C_{222-2}$	0.757	0.643
$c_{212-1} = (B_2)^2\, C_{212-1}$	-1.197	-1.091
$c_{2020} = (B_2)^2\, C_{2020}$	1.764	1.793

large contribution of *the other diagram*

spin interpretation only for eeμμ

proportional to $(B_1)^2 \simeq 0.1$

$H \to ZZ$ entanglement

However, a lower cut $m_{Zl} \geq 80$ GeV [eff = 0.77] does make one diagram dominant and 4e / 4μ similar to eeμμ for all practical purposes.

JAAS, 2403.13942

angular coefficient	$e^+e^-\mu^+\mu^-$	4e / 4μ	4e / 4μ cut	Δ_{stat} HL-LHC
$a_{20}^1 = B_2 A_{20}^1$	-0.636	-0.706	-0.639	0.05
$a_{20}^2 = B_2 A_{20}^2$	-0.634	-0.706	-0.640	0.05
$c_{111-1} = (B_1)^2 C_{111-1}$	0.103	0.773	0.210	0.15
$c_{1010} = (B_1)^2 C_{1010}$	-0.067	-0.857	-0.112	0.16
$c_{222-2} = (B_2)^2 C_{222-2}$	0.757	0.643	0.723	0.15
$c_{212-1} = (B_2)^2 C_{212-1}$	-1.197	-1.091	-1.159	0.12
$c_{2020} = (B_2)^2 C_{2020}$	1.764	1.793	1.707	0.17

$N = 0.843$ $N = 0.835$

spin interpretation also for 4e / 4μ with cut

entanglement measure

The silver lining:
identical particles

Identical particles

One can exploit the differences between eeμμ and 4e / 4μ to show that electrons and muons behave as identical particles!

JAAS, 2411.13464

angular coefficient	$e^+e^-\mu^+\mu^-$	4e / 4μ
a_{20}^1	-0.636	-0.706
a_{20}^2	-0.634	-0.706
c_{111-1}	0.103	0.773
c_{1010}	-0.067	-0.857
c_{222-2}	0.757	0.643
c_{212-1}	-1.197	-1.091
c_{2020}	1.764	1.793

However, in order to test identical-particle effects you have to compare apples to apples: use the same lepton pairing in all cases.

→ cannot pair leptons by flavour in eeμμ
and by invariant mass in 4e / 4μ !!!

Identical particles

We seek a flavour-blind criterion to pair leptons that reproduces flavour pairing for eeμμ as accurately as possible

→ so that $c_{111\text{-}1}$ and c_{1010} will remain small in eeμμ final state

[remember: $c_{111\text{-}1} = (B_l)^2\, C_{111\text{-}1}$; $c_{1010} = (B_l)^2\, C_{1010}$ with flavour pairing]

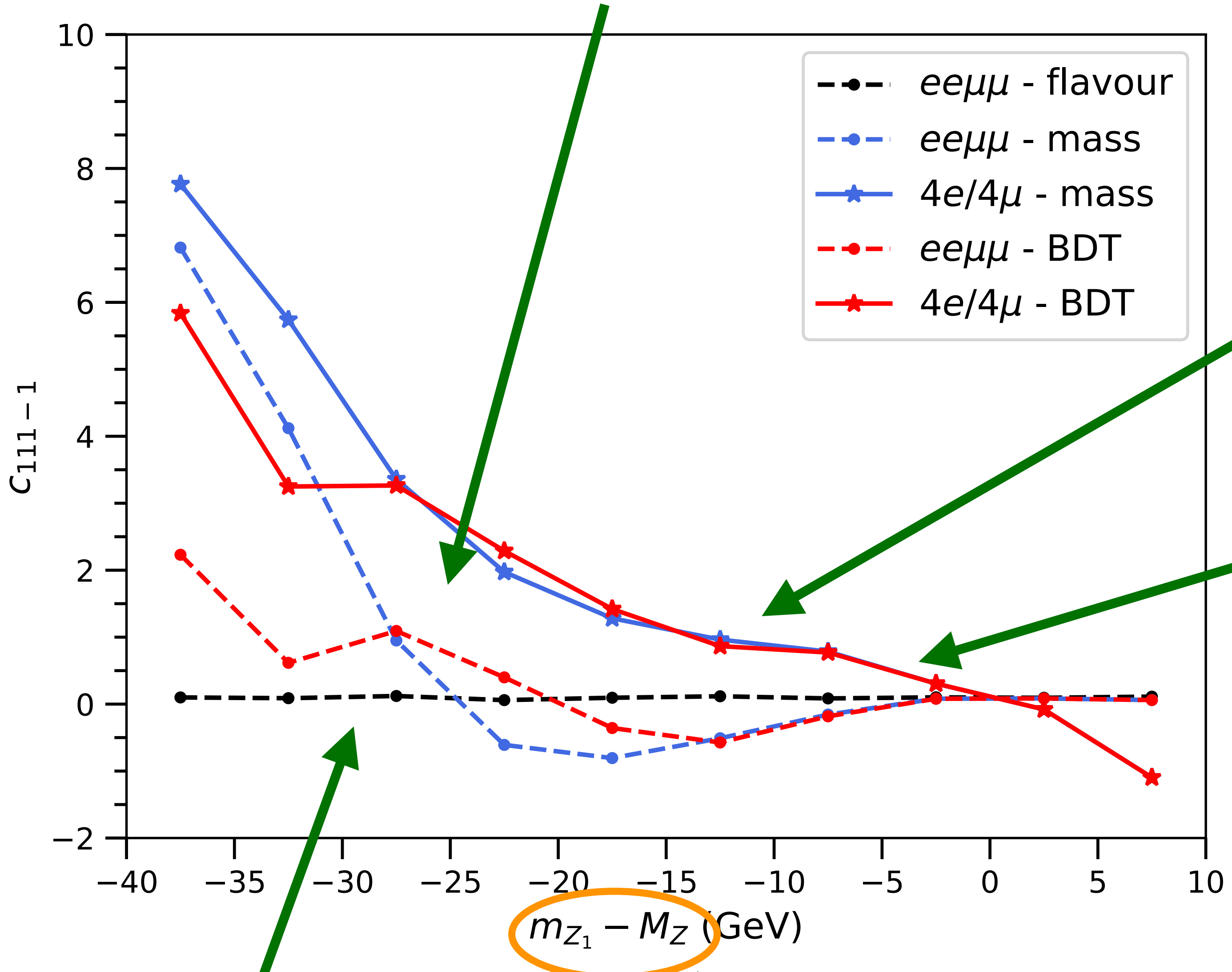
Options:

- Mass pairing
- do it smarter: feed $m_{Z1}^{(A,B)}$, $m_{Z2}^{(A,B)}$ and angles between leptons to a BDT — **BDT pairing**
- do it dumber: use both pairings and that's it — **both pairings**

Identical particles

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left[1 + a^1_{LM} Y^M_L(\Omega_1) + a^2_{LM} Y^M_L(\Omega_2) + c_{L_1 M_1 L_2 M_2} Y^{M_1}_{L_1}(\Omega_1) Y^{M_2}_{L_2}(\Omega_2)\right]$$

mass pairing gives large values, but different in eeμμ and 4e / 4μ



mass pairing equivalent to BDT pairing where the bulk of events are

smaller values for large m_{Z1}, as previously discussed

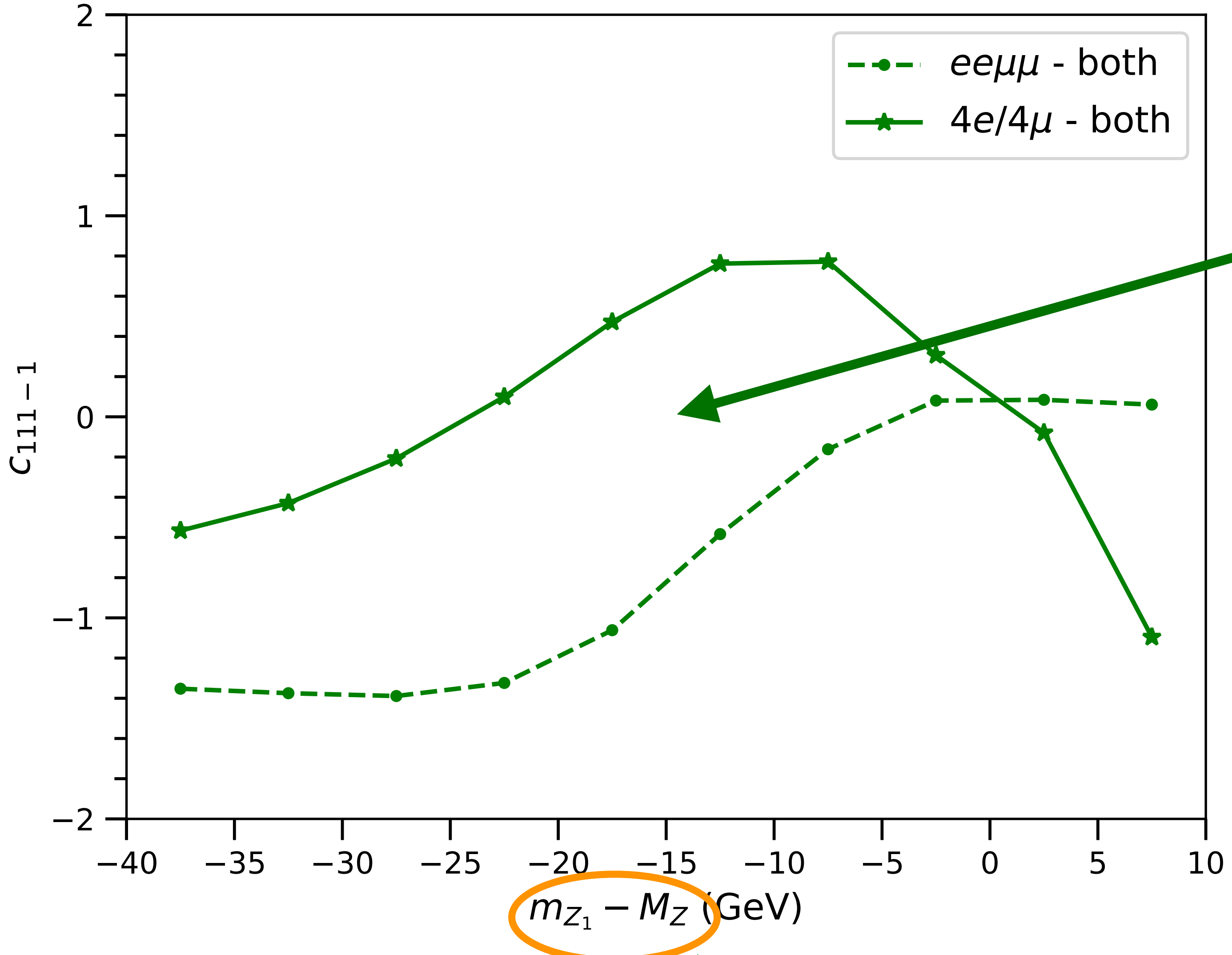
flavour pairing in eeμμ gives small value

as a funtion of m_{Z1}

Identical particles

… and with both pairings …

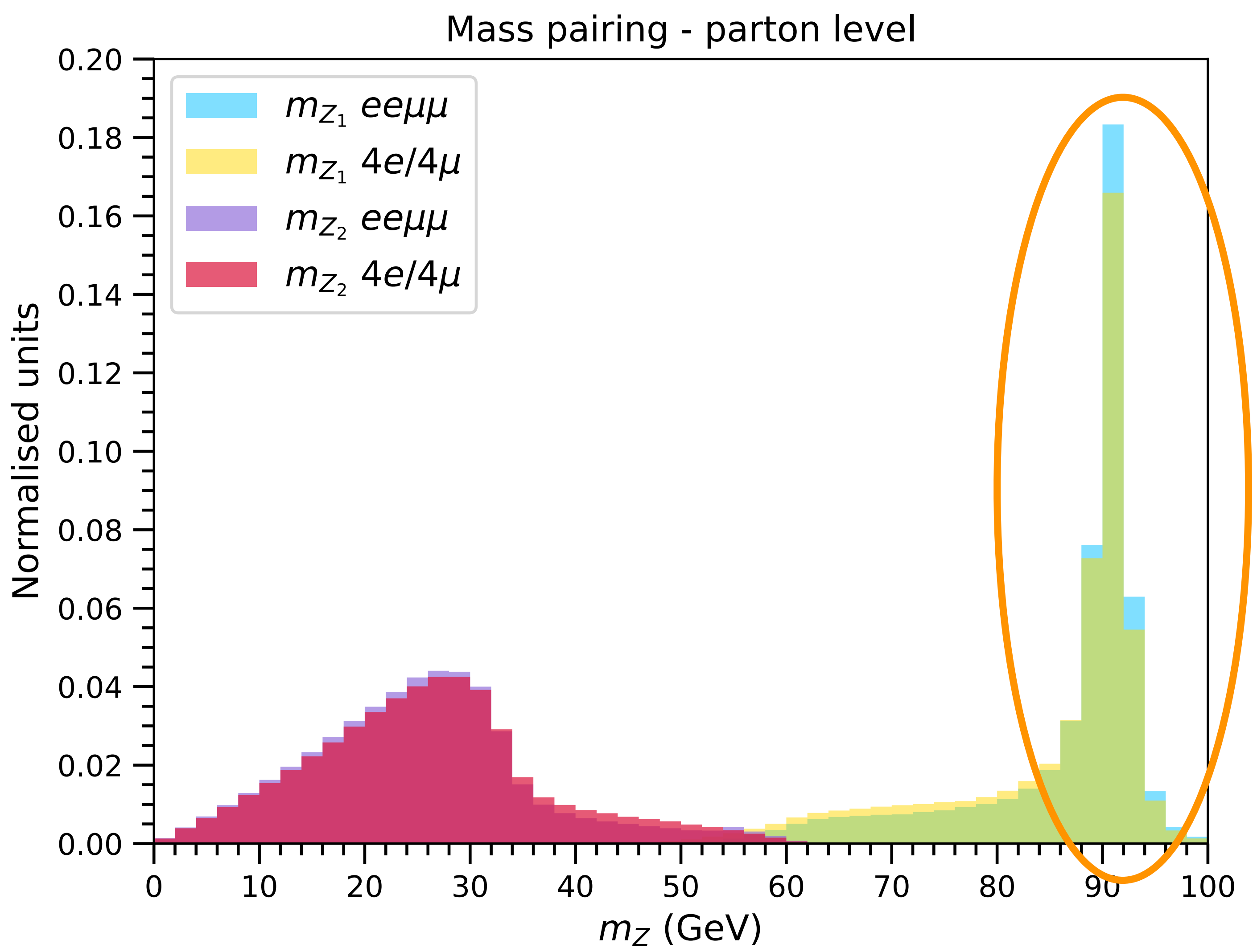
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\left[1 + a^1_{LM} Y^M_L(\Omega_1) + a^2_{LM} Y^M_L(\Omega_2) + c_{L_1 M_1 L_2 M_2} Y^{M_1}_{L_1}(\Omega_1) Y^{M_2}_{L_2}(\Omega_2)\right]$$



still different in eeμμ and 4e / 4μ

as a funtion of m_{Z1}

… and one can also use the distribution of m_{Z1} itself to test identical-particle effects!



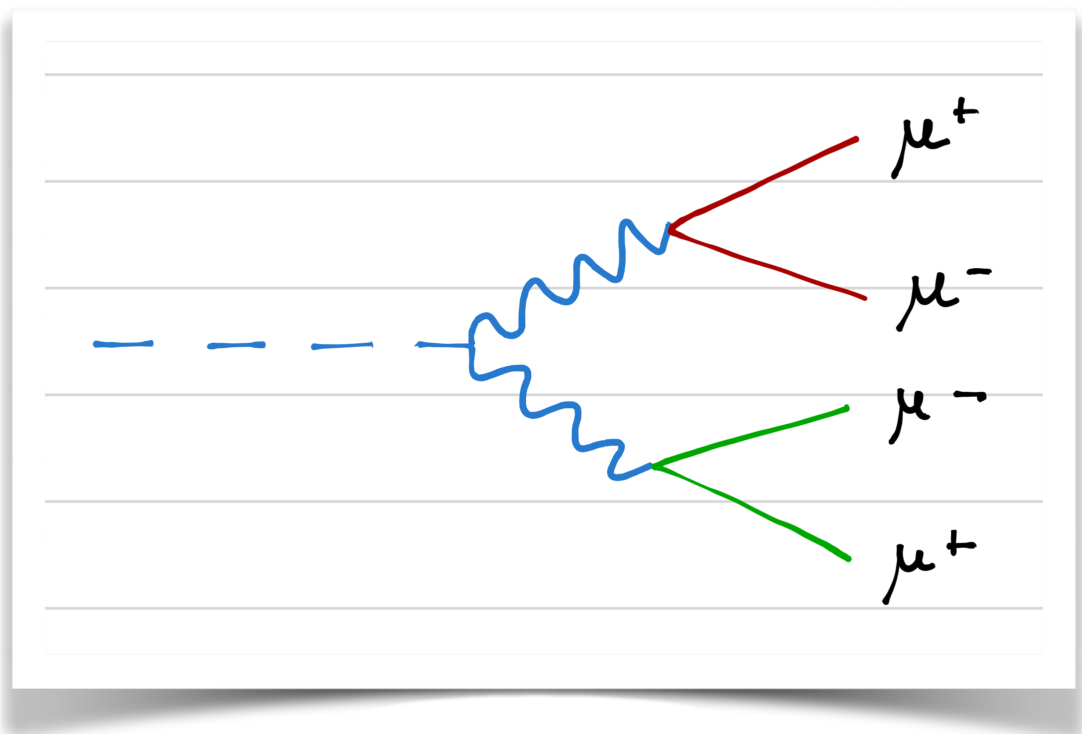
different in eeμμ and 4e / 4μ

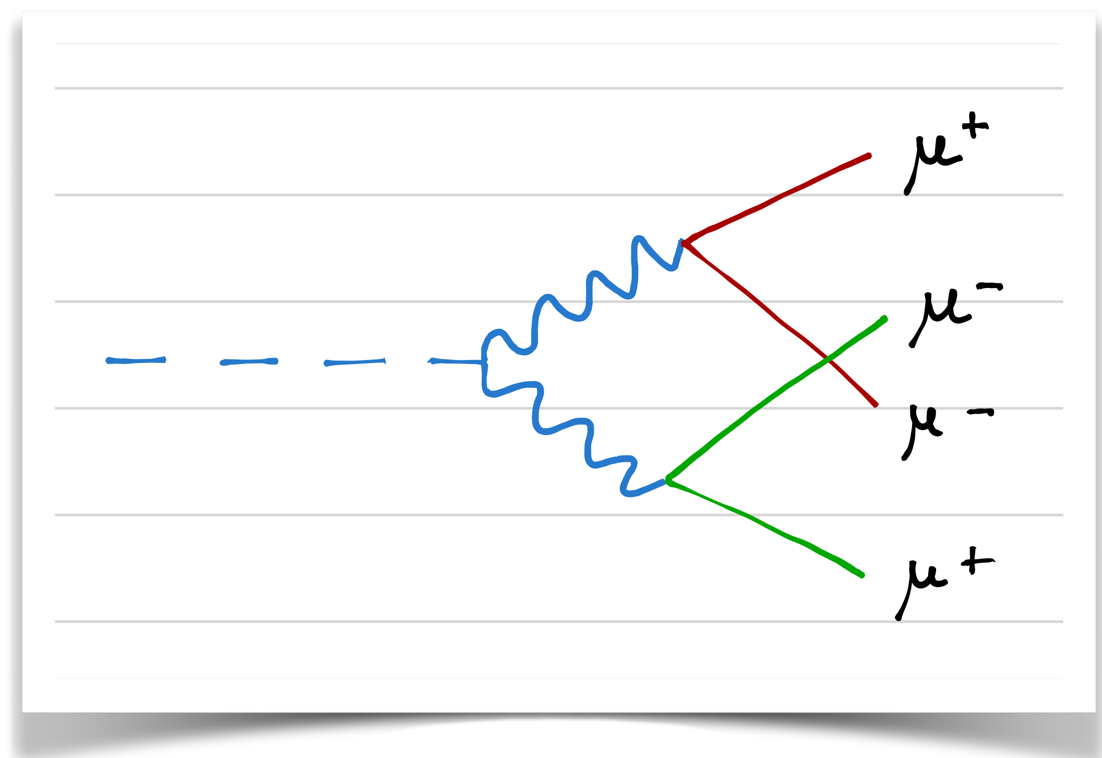
Interference!

Interference

JR´s remark in previous workshop: Feynman-diagram-based interference is not really quantum interference.

Do we have true quantum interference?

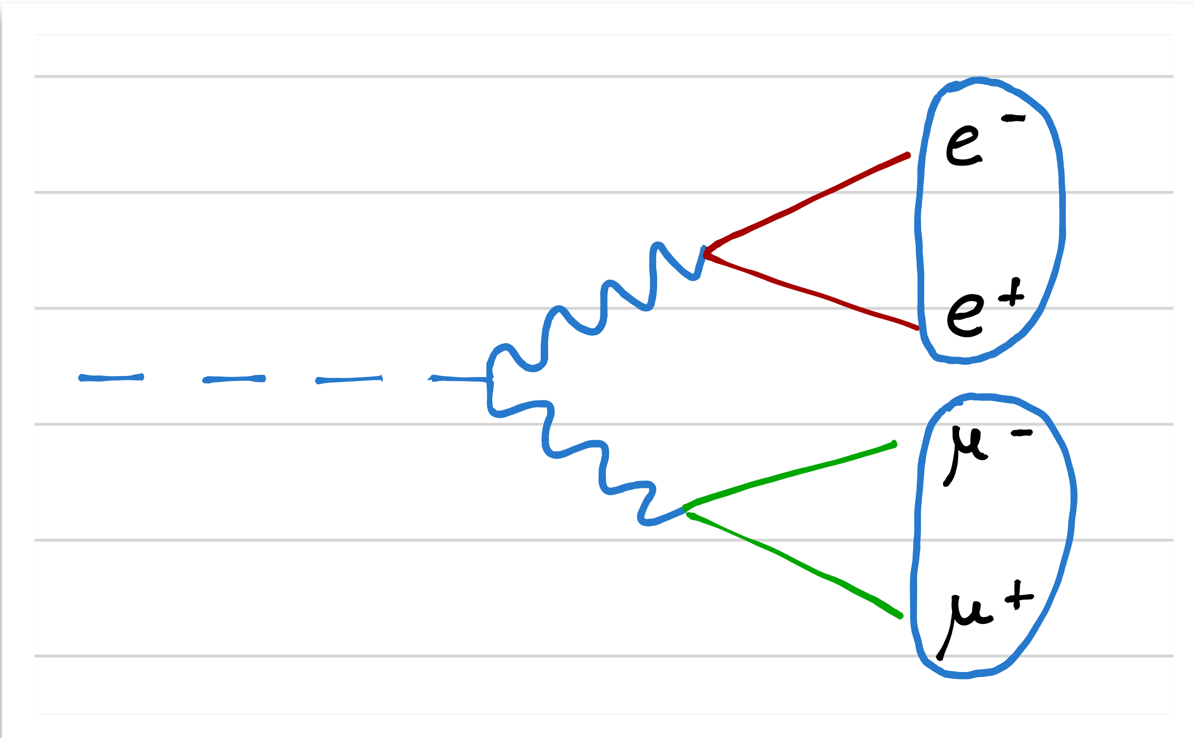




Need some definition that does not rely on diagrams → based on lepton pairing

Interference

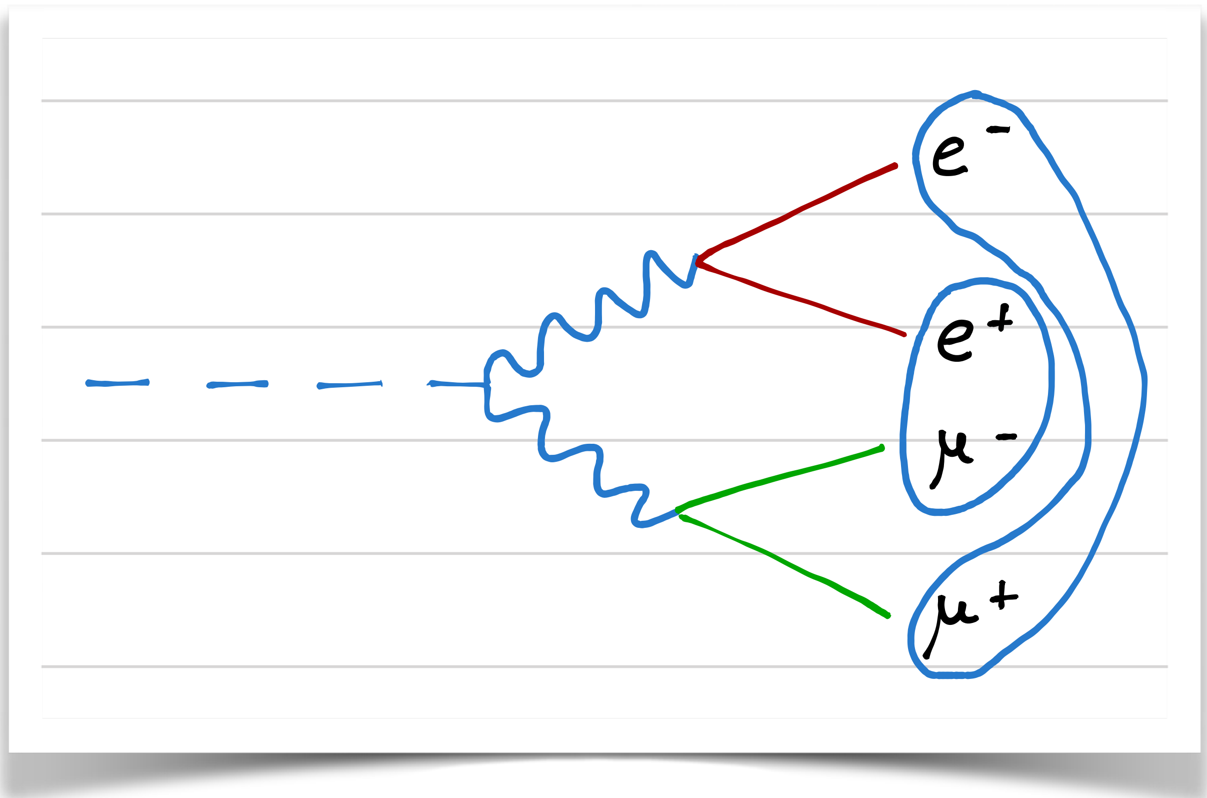
In the eeμμ final state we can



- pair leptons by flavour
- define $p_{Z1} = p_{e+} + p_{e-}$, $p_{Z2} = p_{\mu+} + p_{\mu-}$
  [which correspond to *Z* bosons]
- calculate angular coefficients in $\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2}$
- determine spin coefficients

Interference

but we can also

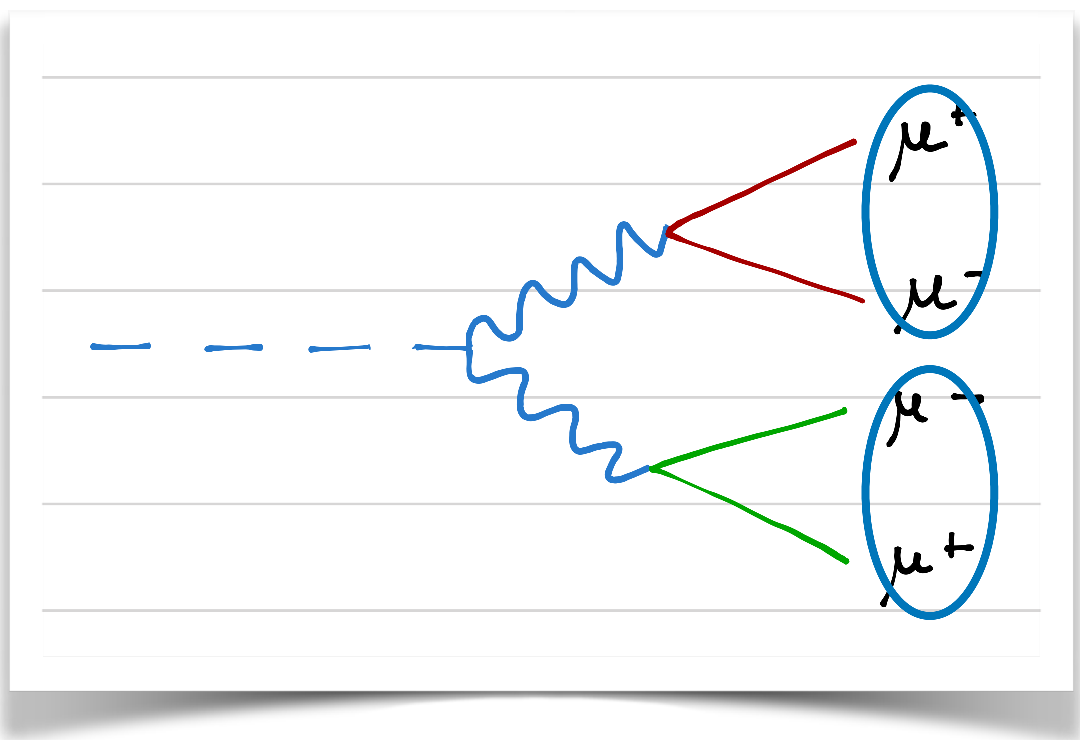


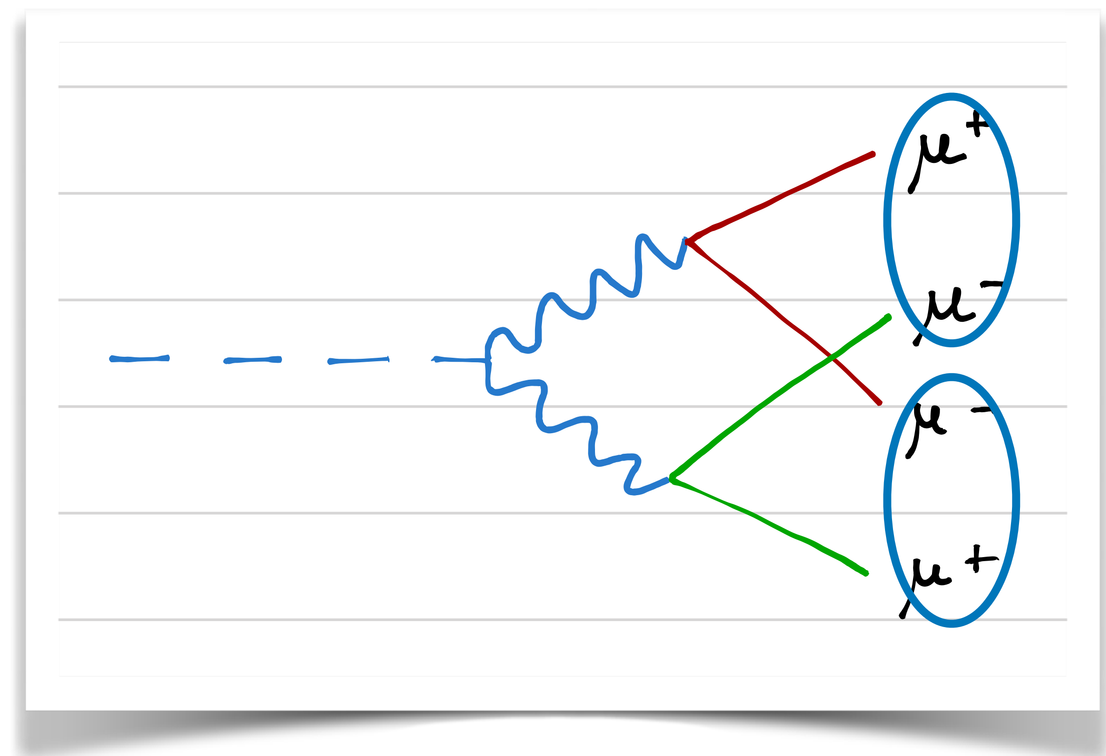
- pair leptons by wrong flavour
- define $p_{X1} = p_{e+} + p_{\mu-}$, $p_{X2} = p_{\mu+} + p_{e-}$ which do NOT correspond to Z bosons
- calculate angular coefficients in resulting $\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2}$

… but which is the purpose of that??? Precisely, to compare with 4e / 4μ

Interference

In the 4e / 4μ final state, when you select any lepton pairing, it is the *correct* pairing for one diagram but the *wrong* pairing for the other…





using *correct* and *wrong* pairings in eeμμ provides a diagram-independent method to compare with 4e / 4μ and investigate interference effects

Interference

In eeμμ:

- option A [correct] $c_{111\text{-}1} = 0.098$ $c_{1010} = -0.059$
- option B [wrong] $c_{111\text{-}1} = -1.210$ $c_{1010} = 14.244$

both pairings $c_{111\text{-}1} = -0.556$ $c_{1010} = 7.093$

average of A and B

In 4e / 4μ:

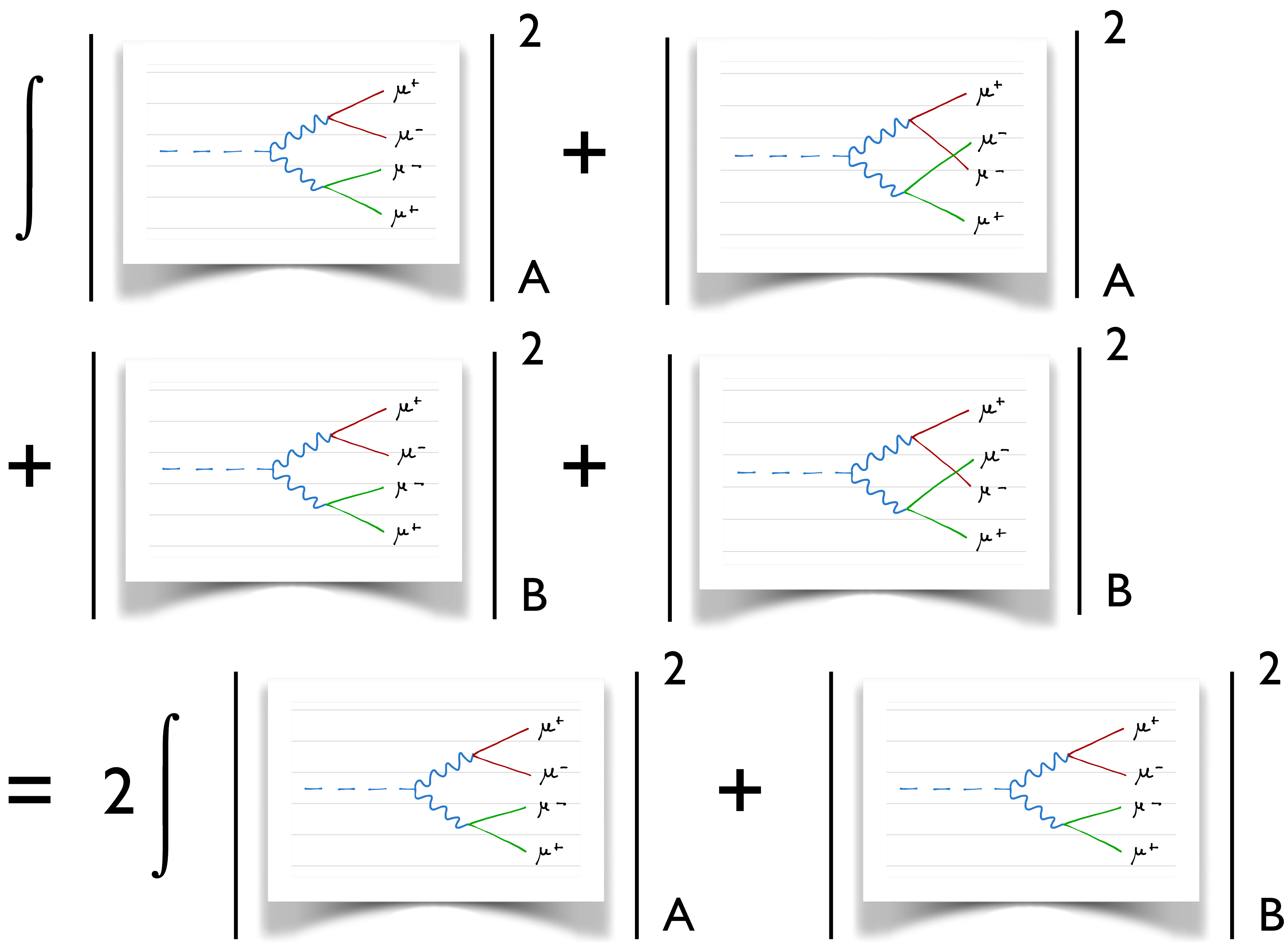
both pairings $c_{111\text{-}1} = -0.032$ $c_{1010} = 6.232$

not the average of A and B

This difference quite looks like an interference effect, is it actually?

Interference

If there were no interference *between Feynman diagrams* in 4e / 4μ,



$c_{111\text{-}1}$ and c_{1010} would be the average of A and B, as in eeμμ

Interference

In eeμμ:

- option A [correct] $c_{111\text{-}1} = 0.098$ $c_{1010} = -0.059$ slit A
- option B [wrong] $c_{111\text{-}1} = -1.210$ $c_{1010} = 14.244$ slit B

both pairings $c_{111\text{-}1} = -0.556$ $c_{1010} = 7.093$ incoherent sum

In 4e / 4μ:

both pairings $c_{111\text{-}1} = -0.032$ $c_{1010} = 6.232$ coherent sum

> $H \rightarrow ZZ \rightarrow$ 4e / 4μ is similar to a double-slit experiment, and we can measure in eeμμ the analogue to \`covering a slit´

Future prospects

Future prospects

Need statistics! We are comparing different lepton modes of $H \to ZZ$.

Simulation for HL-LHC, stat uncertainties assume 3 ab^{-1}.

cut $m_{Z1} \leq M_Z$ applied

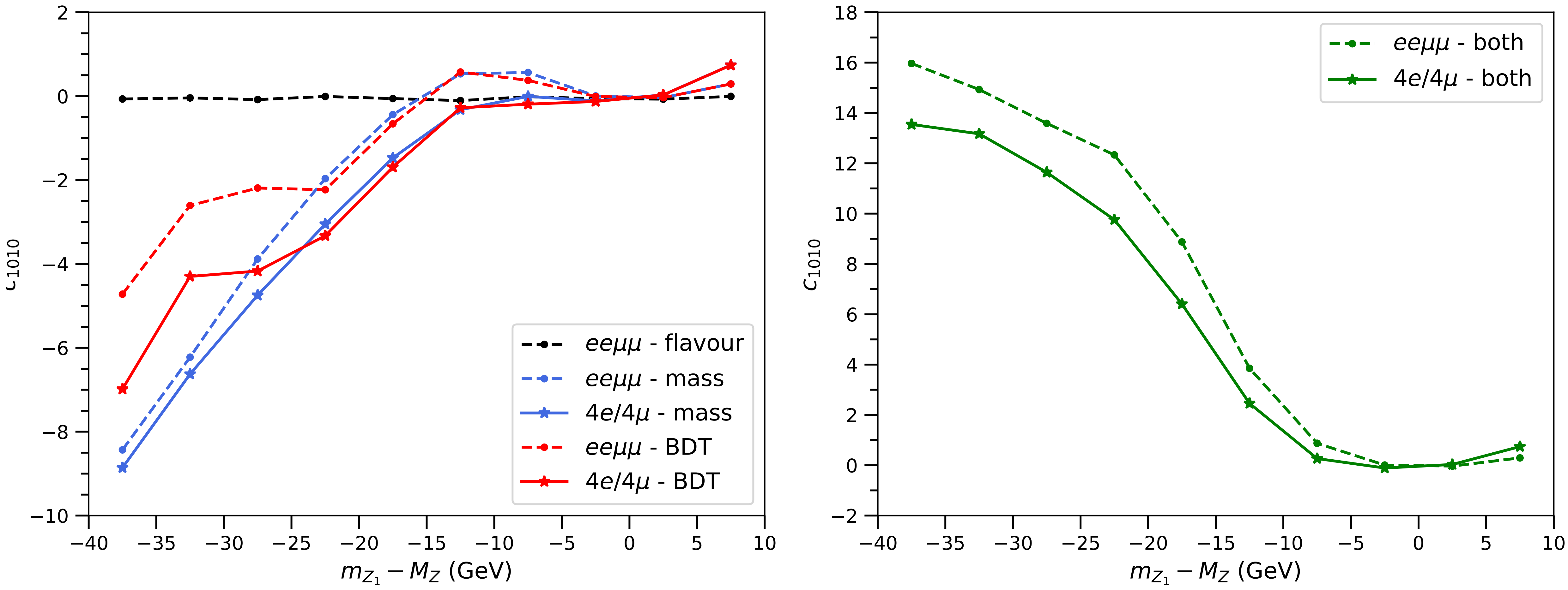
interference

identical particles

	angular coefficient	$e^+e^-\mu^+\mu^-$	4e / 4μ	4μ	interference	identical particles
both pairings	c_{111-1}	-0.88±0.22	-0.03±0.19	-0.06±0.21	2.9σ	2.7σ
	c_{1010}	7.68±0.27	6.45±0.23	6.47±0.27	3.5σ	3.2σ
	combination				4.9σ	4.5σ

and additional sensitivity from other angular coefficients, with differences at 1σ–2σ level end

c_{1010}



c_{1010}
$m_{Z_1} - M_Z$ (GeV)
$ee\mu\mu$ - flavour
$ee\mu\mu$ - mass
$4e/4\mu$ - mass
$ee\mu\mu$ - BDT
$4e/4\mu$ - BDT
c_{1010}
$m_{Z_1} - M_Z$ (GeV)
$ee\mu\mu$ - both
$4e/4\mu$ - both

Parton level vs simulation

mass pairing

angular coefficient	$e^+e^-\mu^+\mu^-$ parton level	$e^+e^-\mu^+\mu^-$ reconstructed	4e / 4μ parton level	4e / 4μ reconstructed
$c_{111\text{-}1}$	0.087	0.05	0.758	0.92
c_{1010}	-0.274	-0.30	-0.762	-0.86

both pairings

angular coefficient	$e^+e^-\mu^+\mu^-$ parton level	$e^+e^-\mu^+\mu^-$ reconstructed	4e / 4μ parton level	4e / 4μ reconstructed
$c_{111\text{-}1}$	-0.556	-0.76	-0.032	-0.03
c_{1010}	7.093	6.73	6.232	5.77

Signal vs background

mass pairing

angular coefficient	$e^+e^-\mu^+\mu^-$ signal	$e^+e^-\mu^+\mu^-$ background	4e / 4μ signal	4e / 4μ background
c_{111-1}	0.05	0.42	0.92	0.42
c_{1010}	-0.30	-0.53	-0.86	-0.69

both pairings

angular coefficient	$e^+e^-\mu^+\mu^-$ signal	$e^+e^-\mu^+\mu^-$ background	4e / 4μ signal	4e / 4μ background
c_{111-1}	-0.76	1.45	-0.03	1.42
c_{1010}	6.73	7.67	5.77	7.68

no interference!

now this is the
end