IAS program HKUST - 10 Jan 2019

Fusing Vectors into Scalars at High Energy Lepton Colliders

with Dario Buttazzo, Diego Redigolo and Filippo Sala

[1807.04743/JHEP11(2018)144]

Andrea Tesi

INFN
Istituto Nazionale di Fisica Nucleare

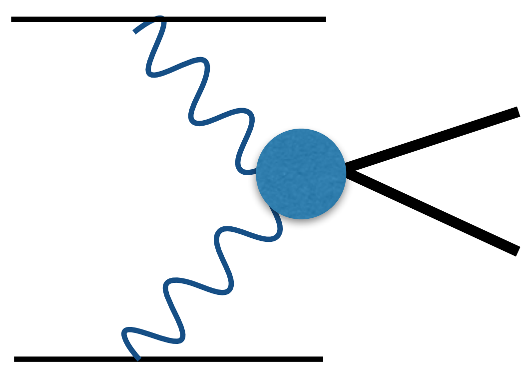
Boeing 747 maiden flight in 1969

initial debt of the project 2b$, it was worth the risk

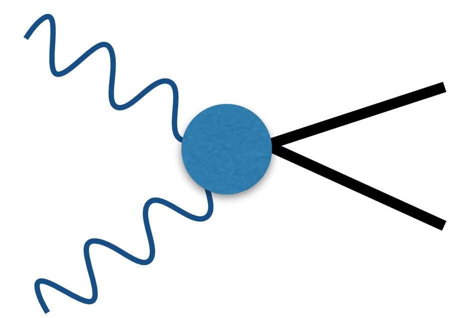
(CLIC is very ambitious, but first technical notes from the mid ‘80s…)

At high energy lepton colliders

we can collide (massless) W and Z's



$$\overset{\hat{s} \gg M_V^2}{=} \quad \mathscr{C}_{VV} \otimes$$



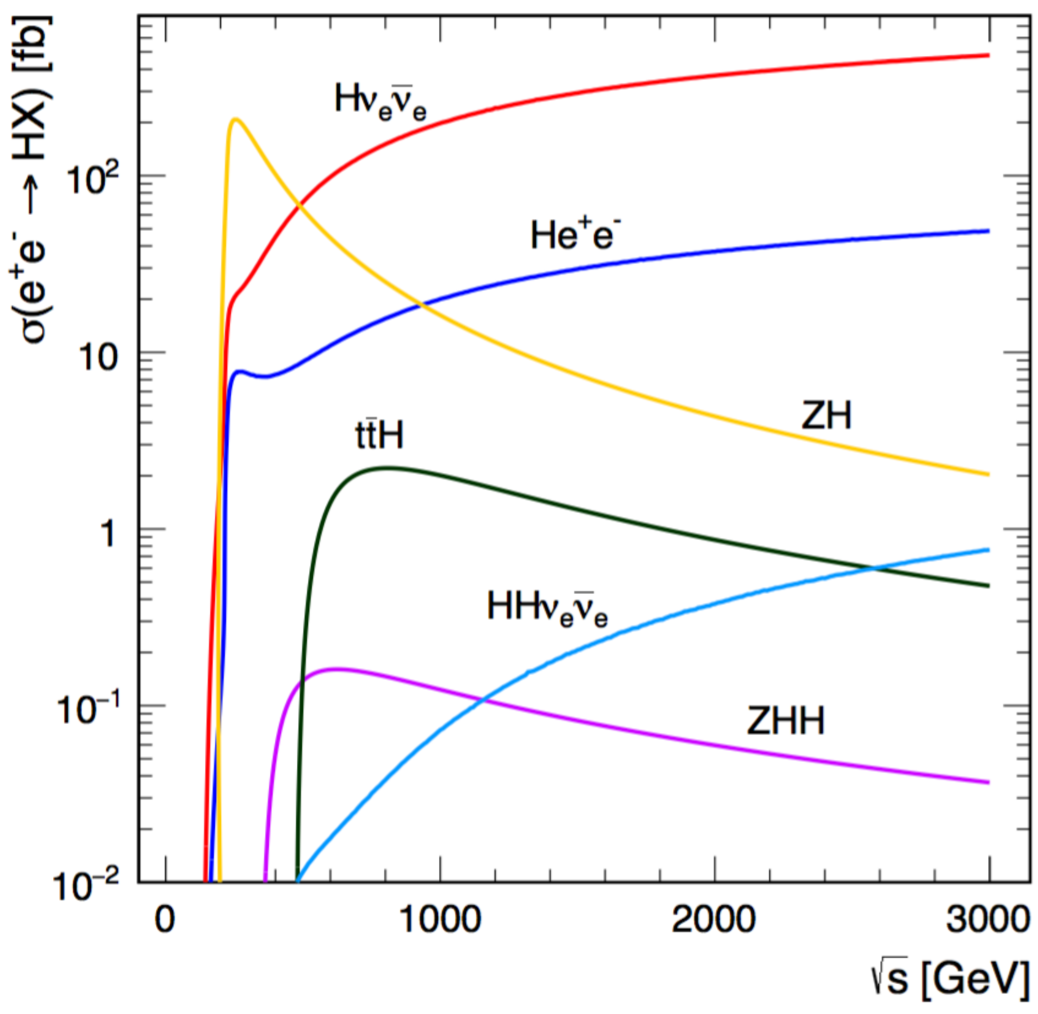
$$\mathscr{C}_{W_L W_L}(\hat{s}) = \frac{g^4}{4096\pi^4} \frac{s}{\hat{s}} \left[(1 + \frac{\hat{s}}{s}) \log \frac{s}{\hat{s}} + 2(\frac{\hat{s}}{s} - 1) \right]$$

[EWA, Dawson 1984]

potentially large cross-section for renormalizable interactions at high energies

At high energy lepton colliders

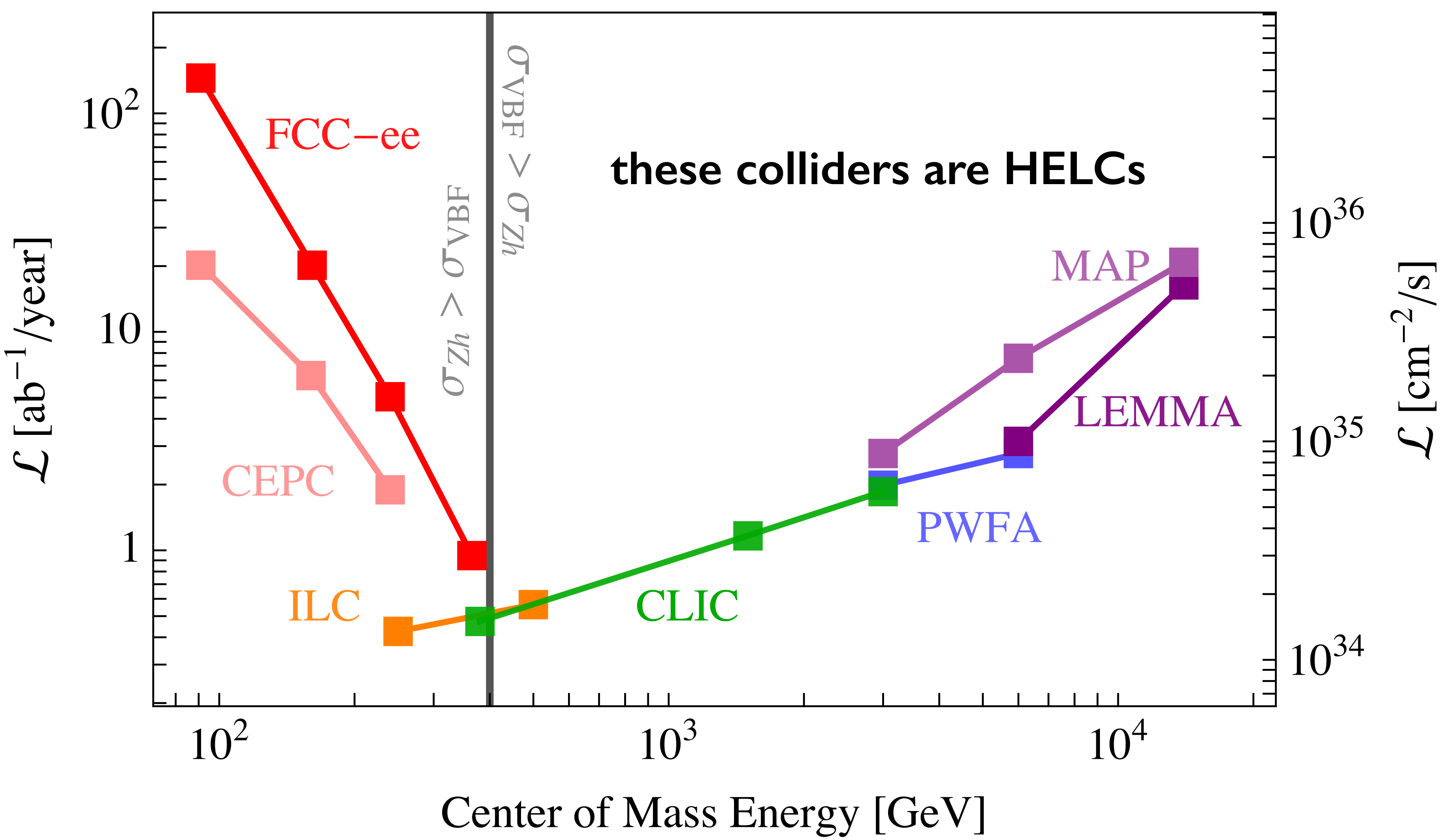
longitudinal W-fusion is the reason for the increase in the Higgs rate



$$\sigma_{e\bar{e}\to h+\nu\bar{\nu}} = \frac{g^4}{256\pi^3}\frac{1}{v^2}\left[\log\frac{s}{m_h^2} - 2 + \mathcal{O}\Big(\frac{m_h^2}{s}\Big)\right]$$

[SM, plots from 1608.07538]
[see also Kilian, Kramer, Zerwas 1995]

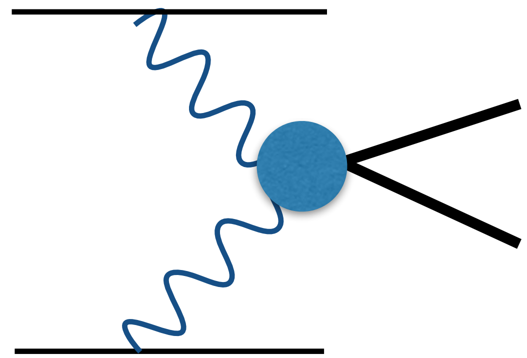
Not all the lepton colliders are the same



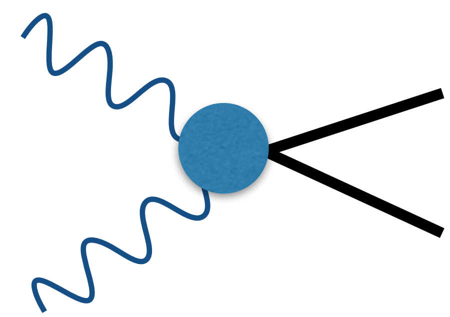
HELCs can have similar precision in single Higgs production:

high energy ≈ high statistics

HELCs sensitive also to on-shell NP



$$\stackrel{\hat{s} \gg M_V^2}{=} \quad \mathscr{C}_{VV} \otimes$$



largest effects from the following interactions

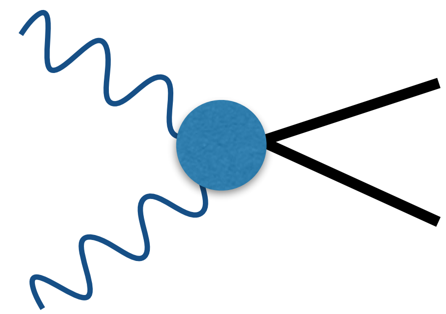
$$|D_\mu X|^2, \quad |H|^2 |X|^2$$

$V_T V_T$ ↙ only pair production

$V_L V_L$ ↘ also single production upon EWSB when X is SM singlet

$X|H|^2$

off shell new phyisics can be tested in similar way (WW scattering)
[Contino, Grojean, Pappadopulo, Rattazzi, Thamm]



$$X = S$$

real singlet

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - a_{HS} S|H|^2 - \frac{\lambda_{HS}}{2} S^2|H|^2 - \frac{a_S}{3}S^3 - \frac{\lambda_S}{4}S^4 + c\frac{\alpha}{4\pi}\frac{S}{f}F\tilde{F}$$

γ mixing angle

- Interplay between Higgs physics (single/double production) and direct searches
- Easy example to compare different machines (total singlet)
- An endless list of models with a low-lying scalar singlet (will not mention them, personal reasons)

Interplay with Higgs physics seen in the EFT

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{c_H}{\Lambda^2}\frac{1}{2}(\partial_\mu |H|^2)^2 - \frac{c_6 \lambda_H}{\Lambda^2}|H|^6 + \cdots$$

integrating out the singlet, we generate:

$$\frac{c_H}{\Lambda^2} = \frac{\sin^2\gamma}{v^2} + \frac{\lambda_{HS}^2}{192\pi^2 m_\phi^2}\,, \qquad \frac{c_6\,\lambda_H}{\Lambda^2} = \frac{\lambda_{HS}}{2v^2}\sin^2\gamma + \frac{\lambda_{HS}^3}{192\pi^2 m_\phi^2}$$

correlation between precision Higgs physics and direct searches

[see complete list by Jiang, Cragi, Li, Sutherland]

what are we testing?

the correlation between mixing and masses
is a hint of the underlying physics

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - a_{HS} S|H|^2 - \frac{\lambda_{HS}}{2}S^2|H|^2 - \frac{a_S}{3}S^3 - \frac{\lambda_S}{4}S^4$$

with the naive scaling

$$m_S^2 \approx M_*^2, \qquad \lambda_{HS} \approx g_*^2, \qquad \lambda_S \approx g_*^2 \qquad a_{HS} \approx g_* M_*, \qquad a_S \approx g_* M_*$$

the mixing angle has a slow decoupling $\quad \gamma \approx \dfrac{g_* v}{M_*}$

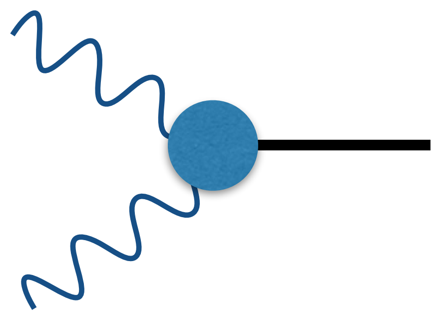
Parametrically small mixing

An extremely precise machine can face the difficulty of testing elusing new physics:

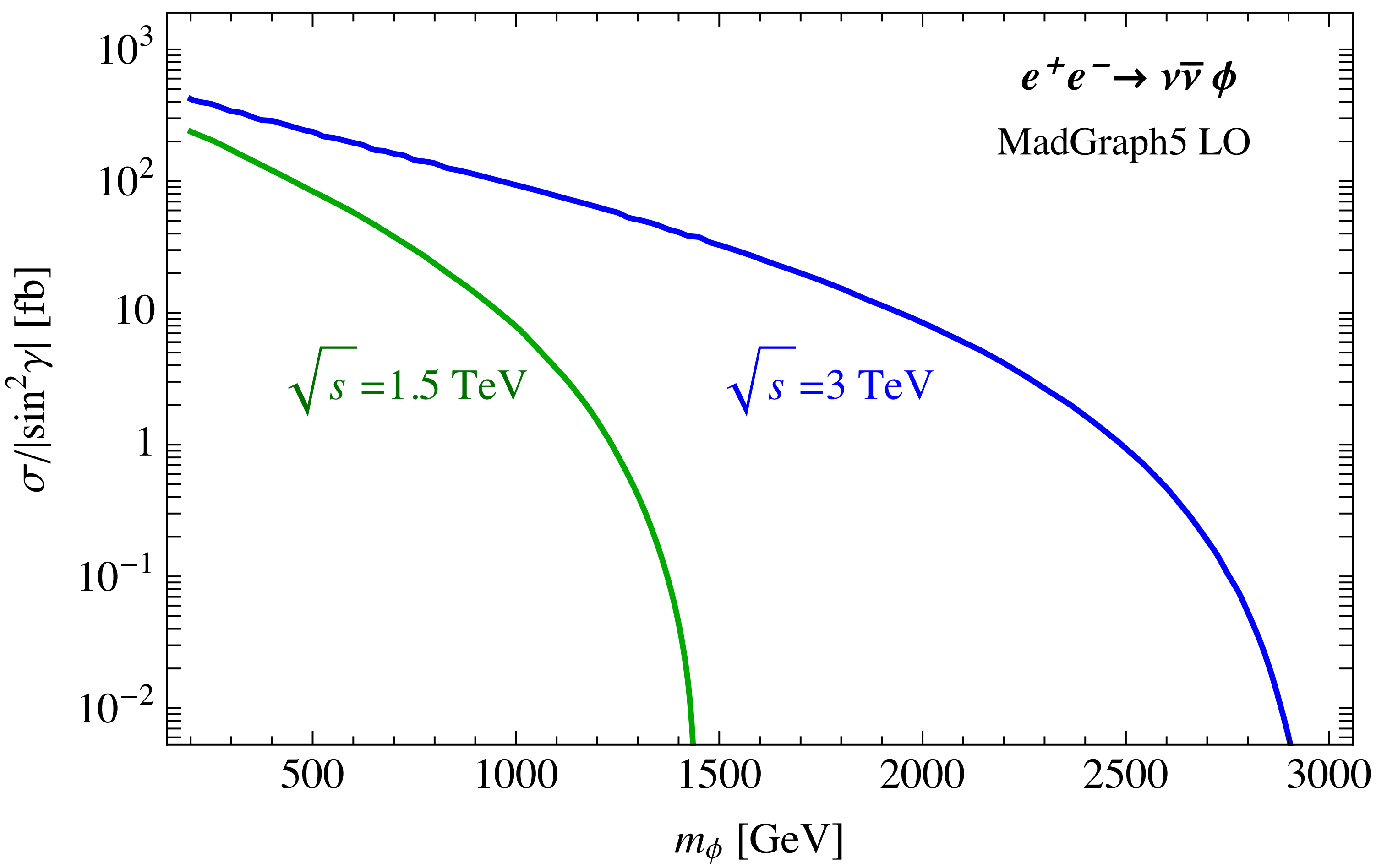
- Models where singlet gets a vev induced by EWSB
  [realized in scenarios of vector-like confinement]
- Models where $a_{HS} \sim g_* m$, maybe related to an approximate Z2, $S \to -S$
  [see later]

the mixing angle has a fast decoupling $$\gamma \approx (\frac{g_* v}{M_*})^2 \times \frac{m}{g_* v}$$

Single production



Total rate



$$\sigma_{e\bar{e}\to\nu\bar{\nu}S} = \sin^2\gamma\,\frac{g^4}{256\pi^3}\frac{1}{v^2}\left[2\Big(\frac{m_\phi^2}{s}-1\Big)+\Big(\frac{m_\phi^2}{s}+1\Big)\log\frac{s}{m_\phi^2}\right] \simeq \sin^2\gamma\,\frac{g^4}{256\pi^3}\,\frac{\log\frac{s}{m_\phi^2}-2}{v^2}$$

identical to the SM Higgs (times a rescaling)

which decay channels?

$$\phi \to ZZ$$

- Actively searched for at the LHC
- Extremely clean channel for CLIC

$$\phi \to hh(4b)$$

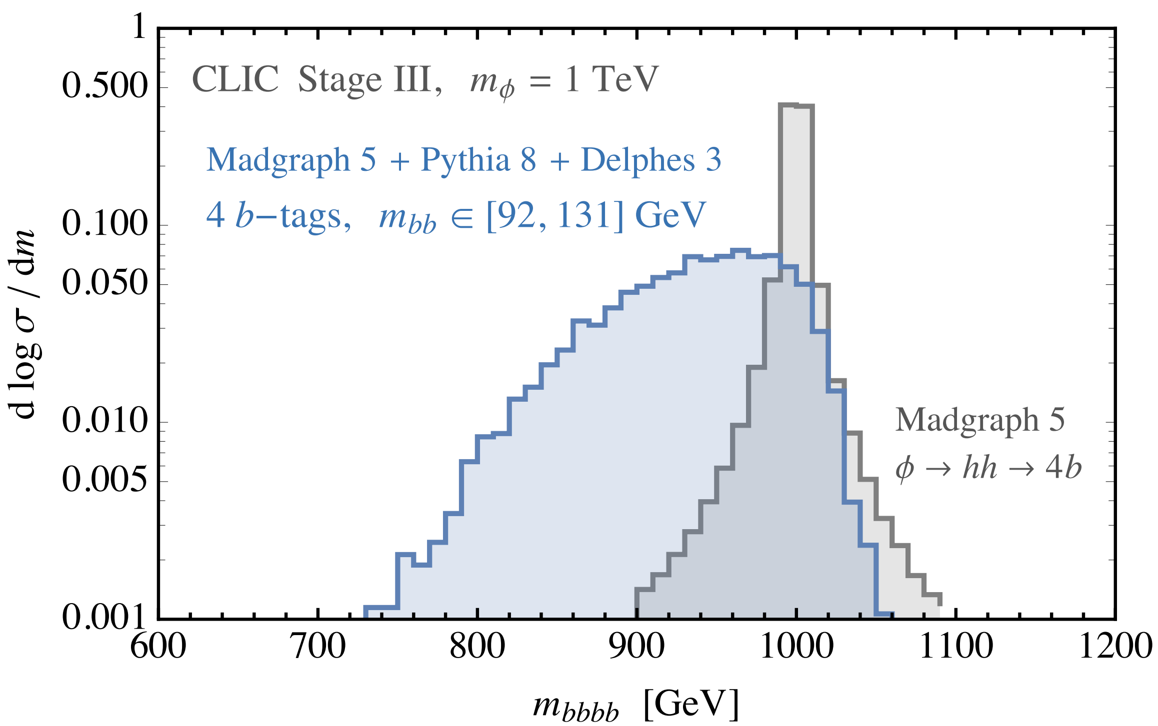
- Challengening for the LHC
- Clean channel for CLIC

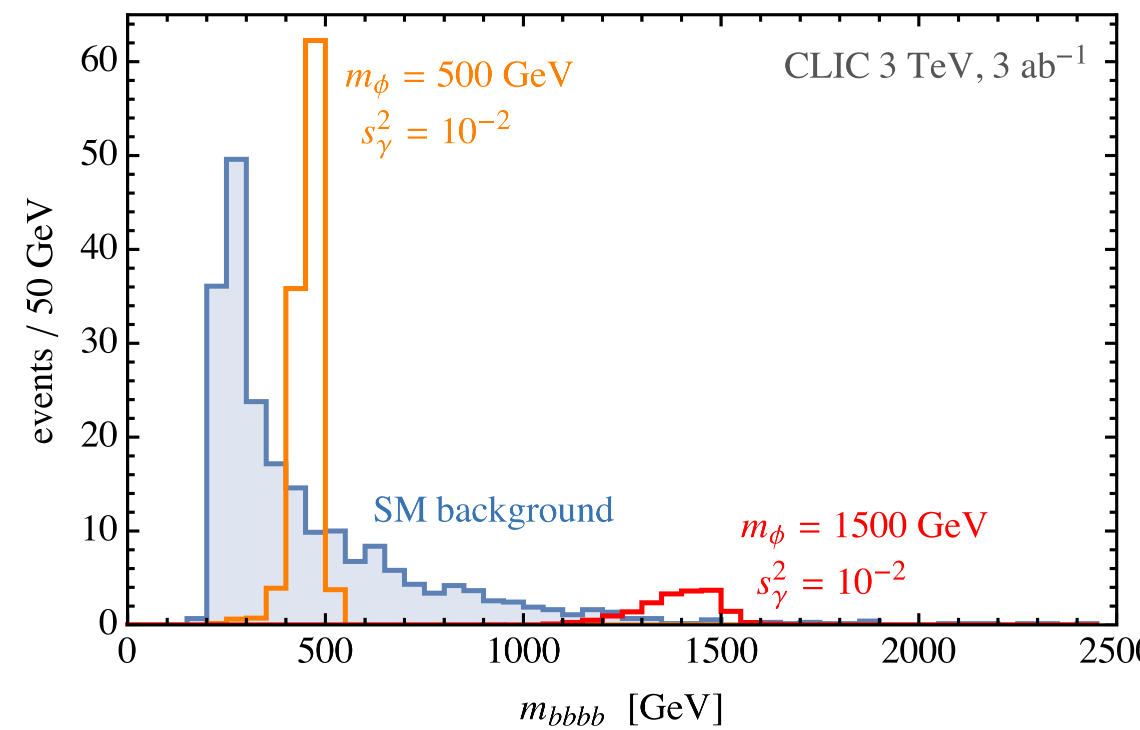
Aims:

- estimate the sensitivies of CLIC - 1.5/3TeV
- estimate the efficiencies on signals/bkg using CLIC card Delphes
- compare the two channels (and more)
- compare with the expected outcome of HL-LHC

Delphes with CLIC card

[Ulrike Schnoor]



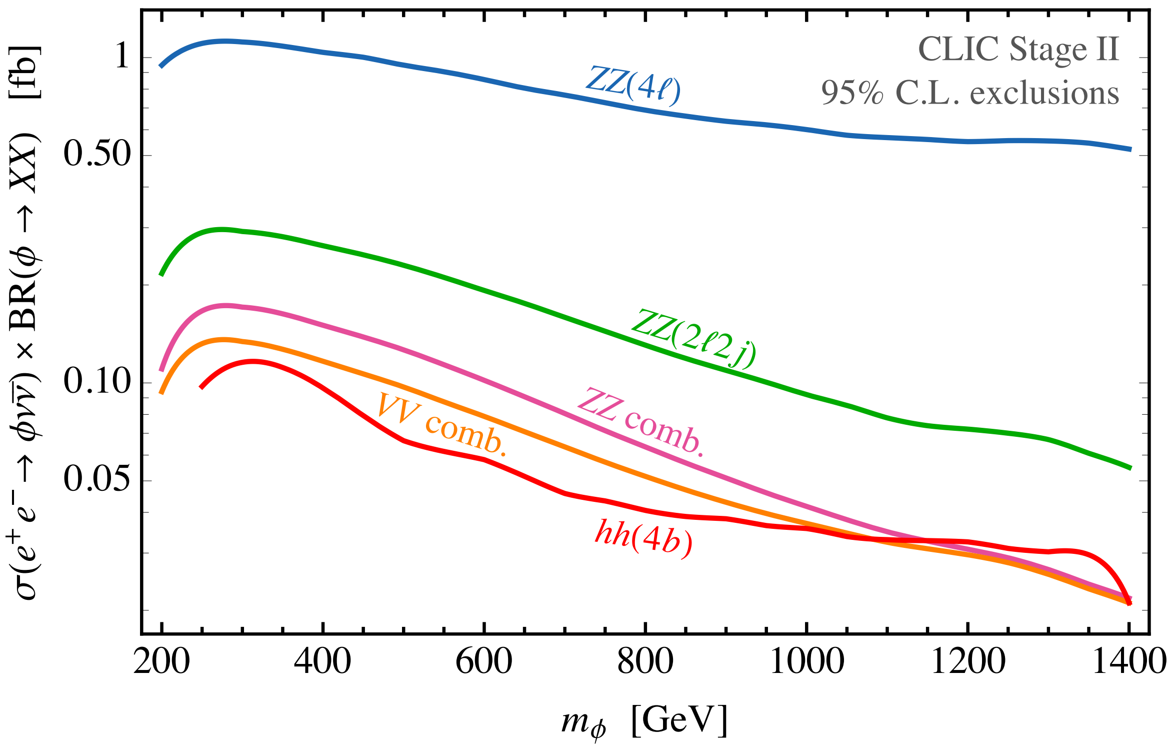


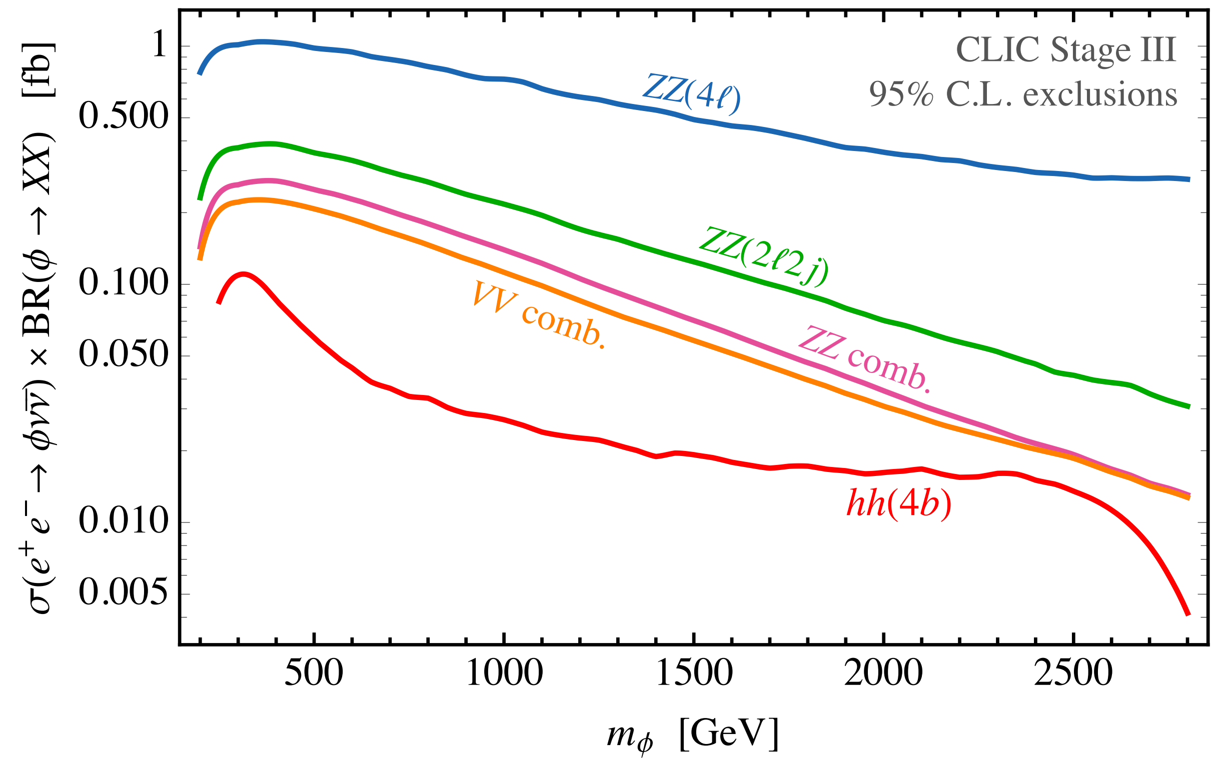
- Detector simulation with the CLIC card for stage III
- Largest background 4b2v, under control 4b

Cut	ϵ_{sig}	$\epsilon_{\text{bkg}}^{4b2\nu}$
$E_{\text{miss}} > 30$ GeV	94%	96%
4 b-tags	51%	33%
$m_{bb} \in [88, 137]$ GeV	60%	15%
$\lvert\cos\theta\rvert < 0.95$	97%	58%
$m_{4b} \in [1.5, 2.04]$ TeV	91%	0.7%
Total efficiency	26%	2×10^{-4}

(b) CLIC 3 TeV, $m_\phi = 2$ TeV

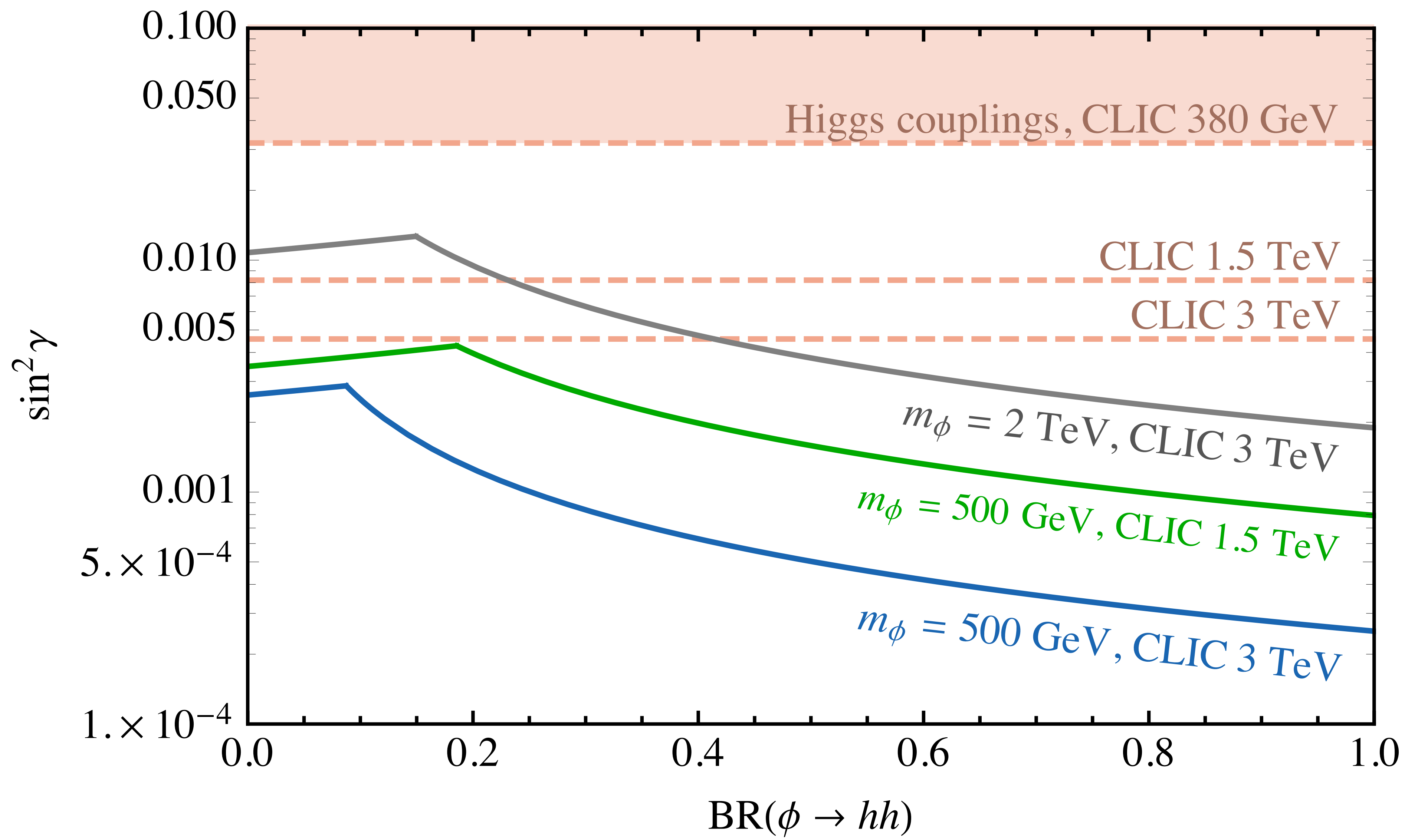
Results for the cross sections





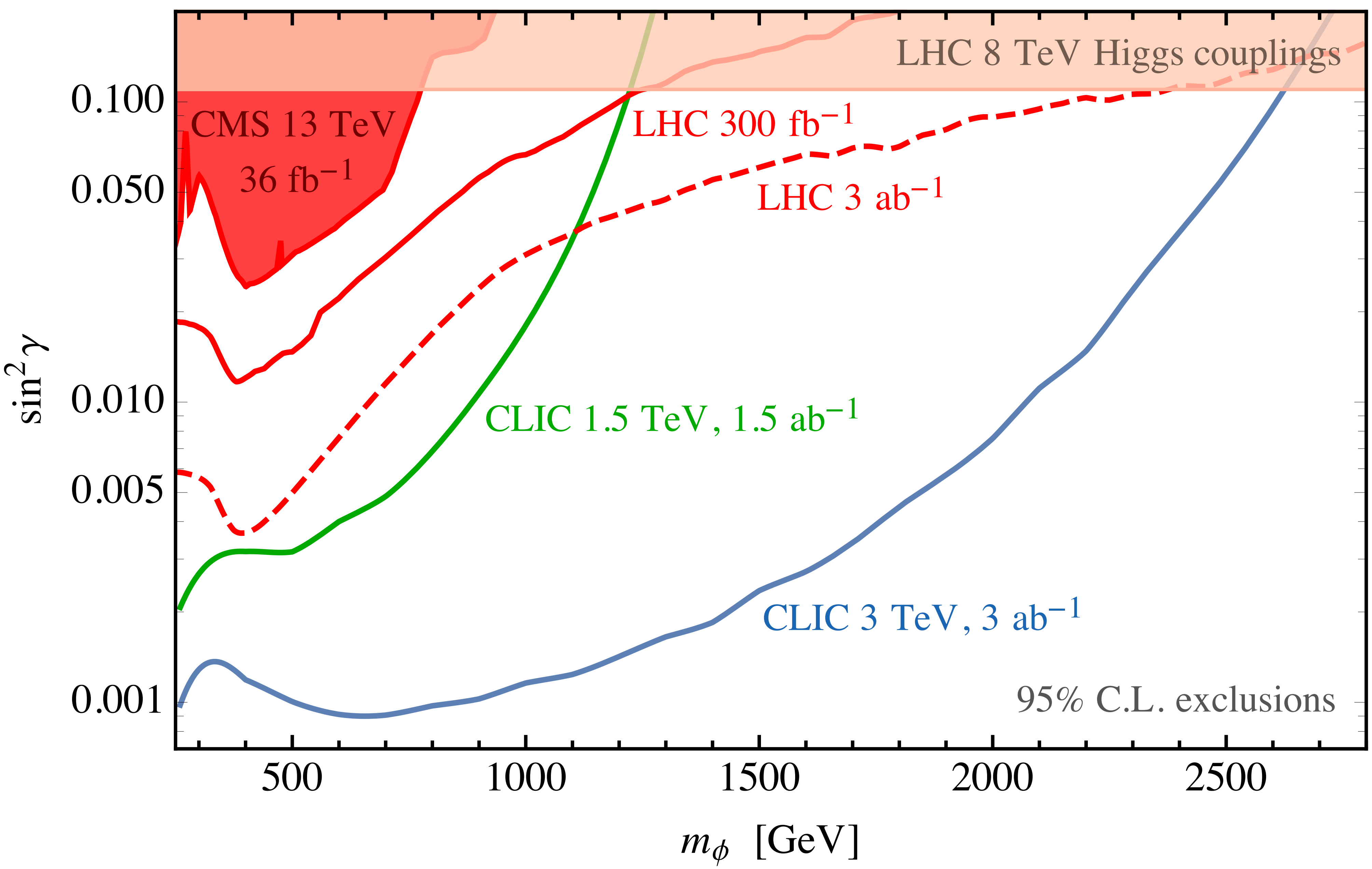
- hh(4b) always dominant as compared to WW/ZZ
- Mass windows for parton level analysis: $\Delta_{4\ell} = 5\%$, $\Delta_{2\ell 2j} = 10\%$, and $\Delta_{4j} = 15\%$

CLIC: single Higgs production and direct searches

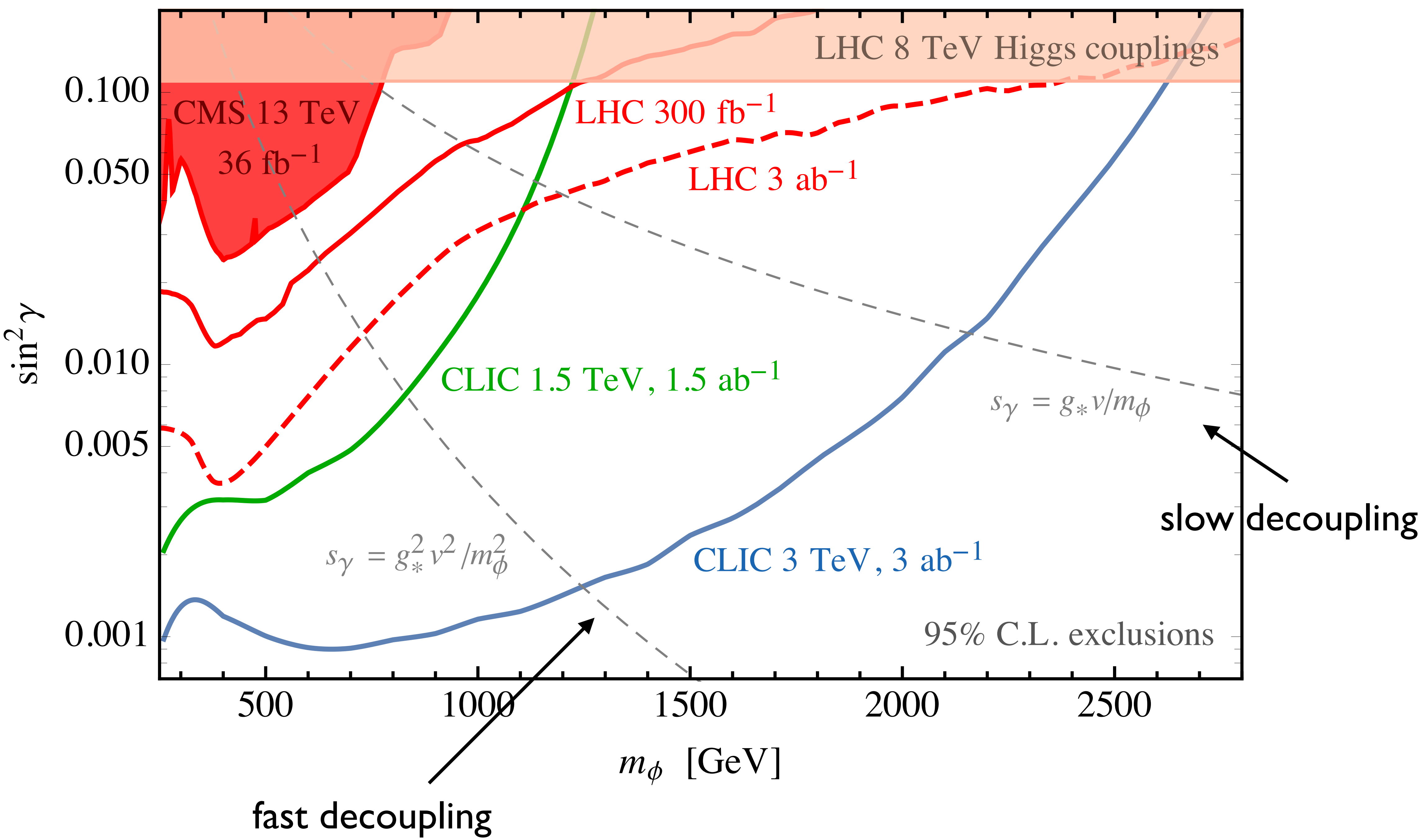


agreement with [JM No, M Spannowksy]

CLIC + LHC + HL-LHC



CLIC + LHC + HL-LHC

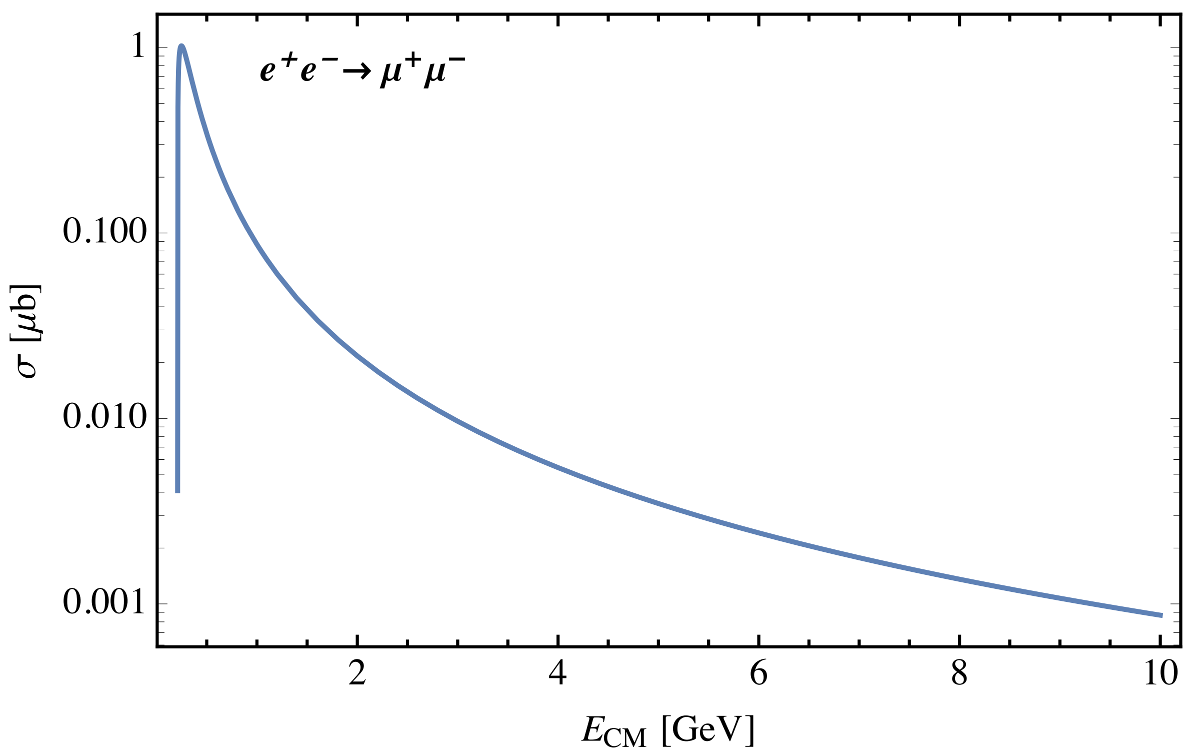


what if $e \rightarrow \mu$?

The LEMMA proposal

[Antonelli, Boscolo, Di Nardo,Raimondi]

positrons on electron target, instead of proton proton



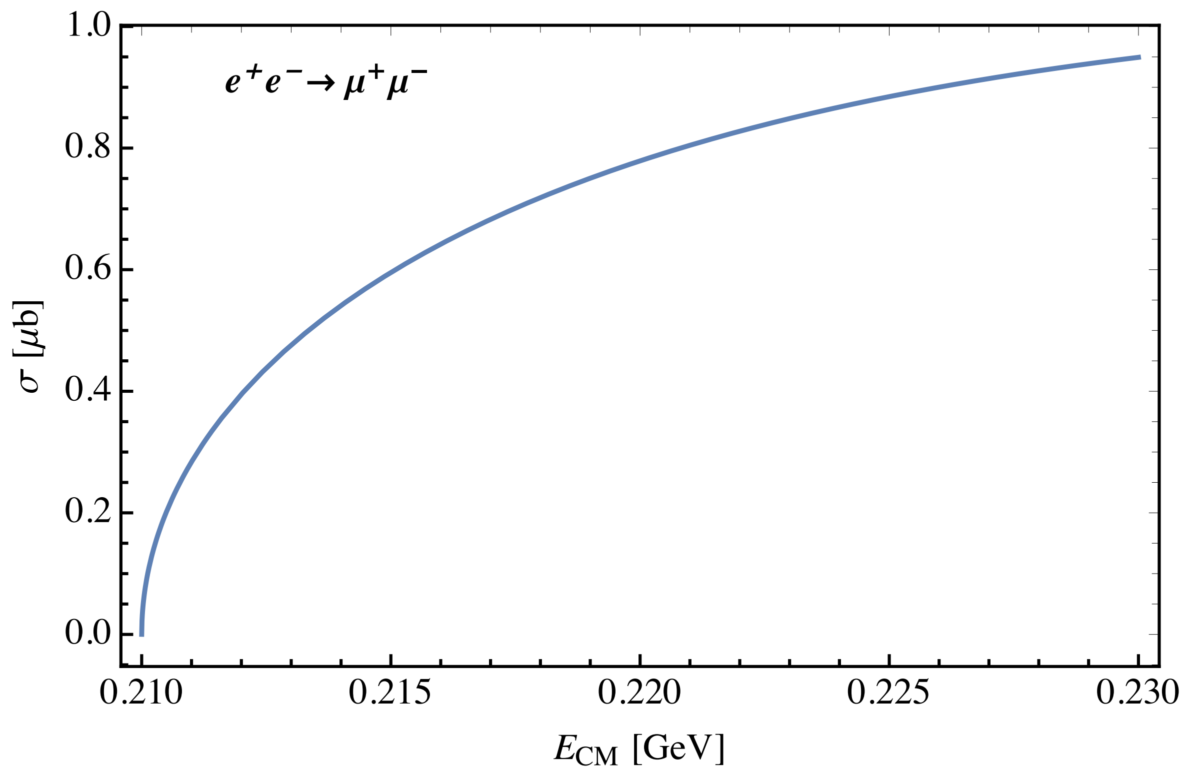
previously were considered pp collisions:

- muons with large emittance
- challenges of muon cooling

The LEMMA proposal

[Antonelli, Boscolo, Di Nardo,Raimondi]

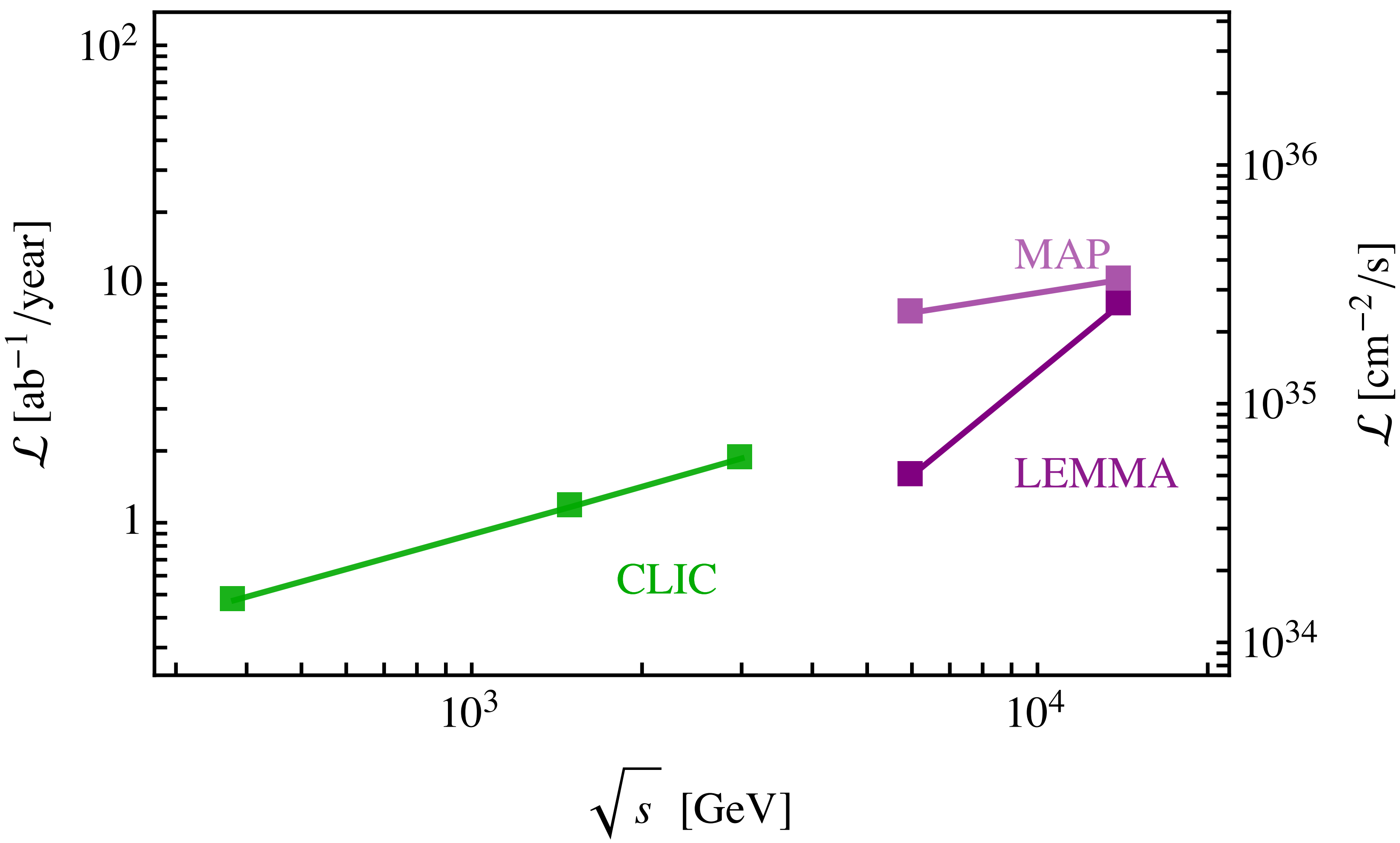
45 GeV positrons on electron target



- Avoid cooling problem with low emittance
- Main challenge: luminosity (any target)
- Many more challenges

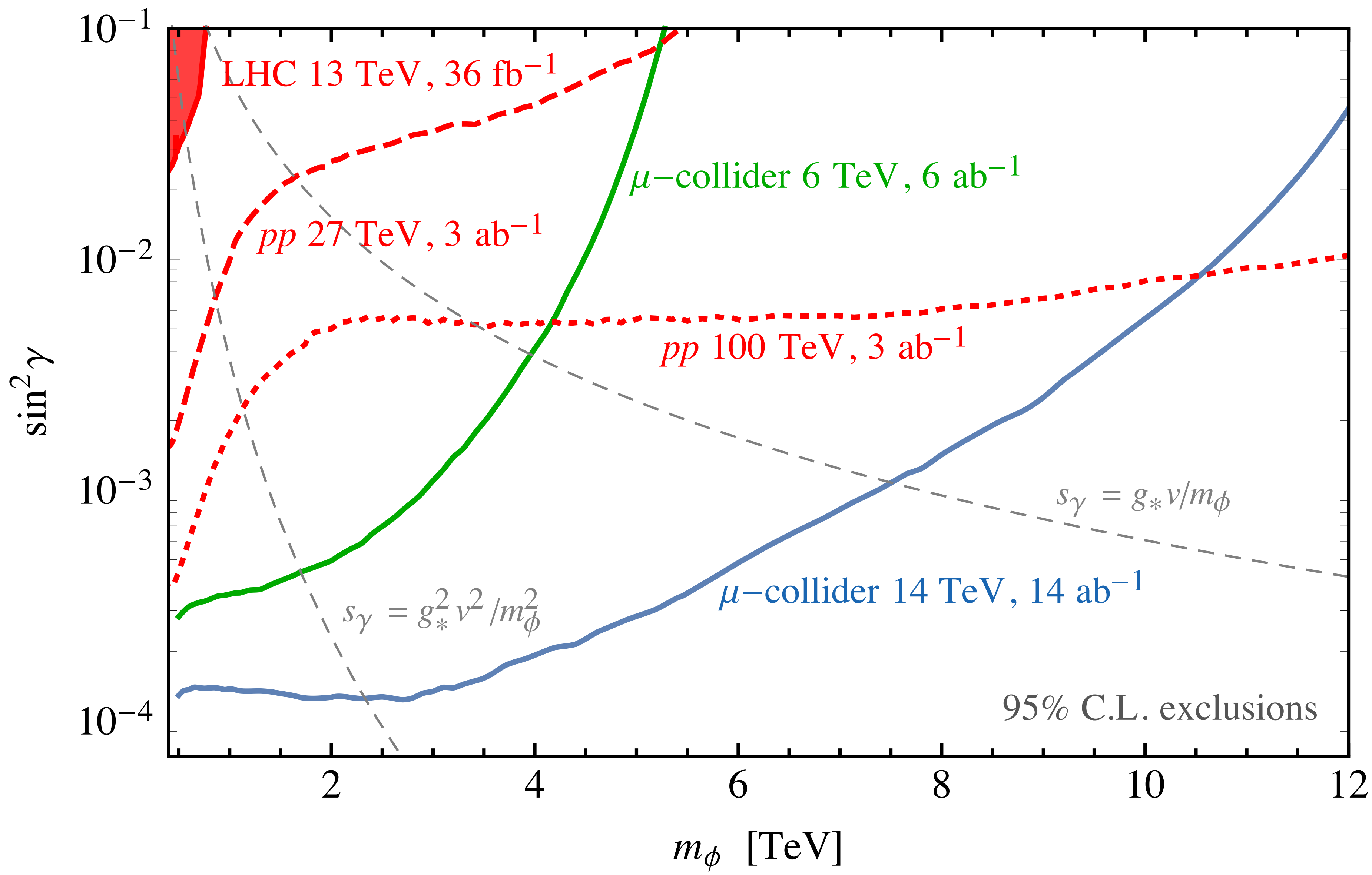
[see Zanetti's talk at GGI 2018]

As benchmark values



we perform a parton level analysis,
'validated' against the previous collider study
(backup slides)

A first muon-collider reach



- notice the competition with 100TeV
- several studies underway, for example EW multiplets [Di Luzio, Grober, Panico]

what if S is pseudoscalar?

$$c_1 \frac{\alpha_1}{4\pi} \frac{S}{f} B\tilde{B} + c_2 \frac{\alpha_2}{4\pi} \frac{S}{f} W\tilde{W}$$

in general a different analysis is needed

[Bauer, Neubert, Thamm]

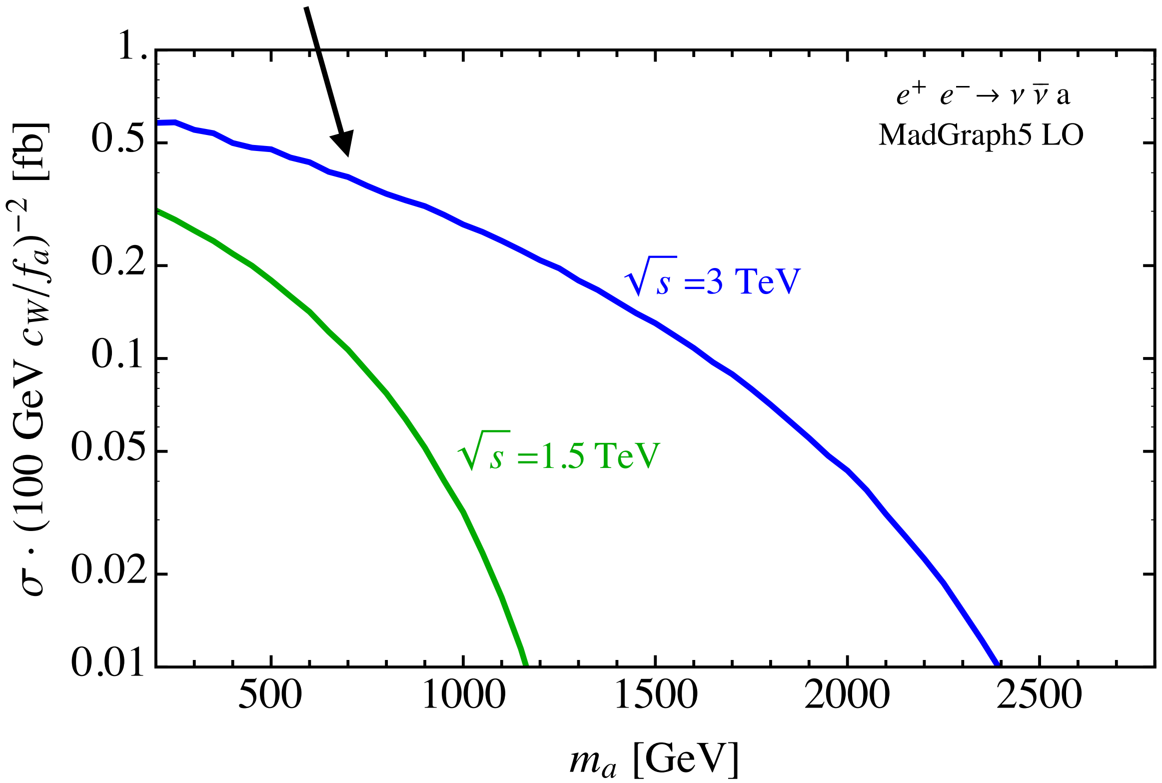
$$c_{WW} = c_2, \quad c_{ZZ} = c_2 + \tan\theta_W^4 \frac{5}{3} c_1, \quad c_{Z\gamma} = c_2 - \tan\theta_W^2 \frac{5}{3} c_1, \quad c_{\gamma\gamma} = c_2 + \frac{5}{3} c_1$$

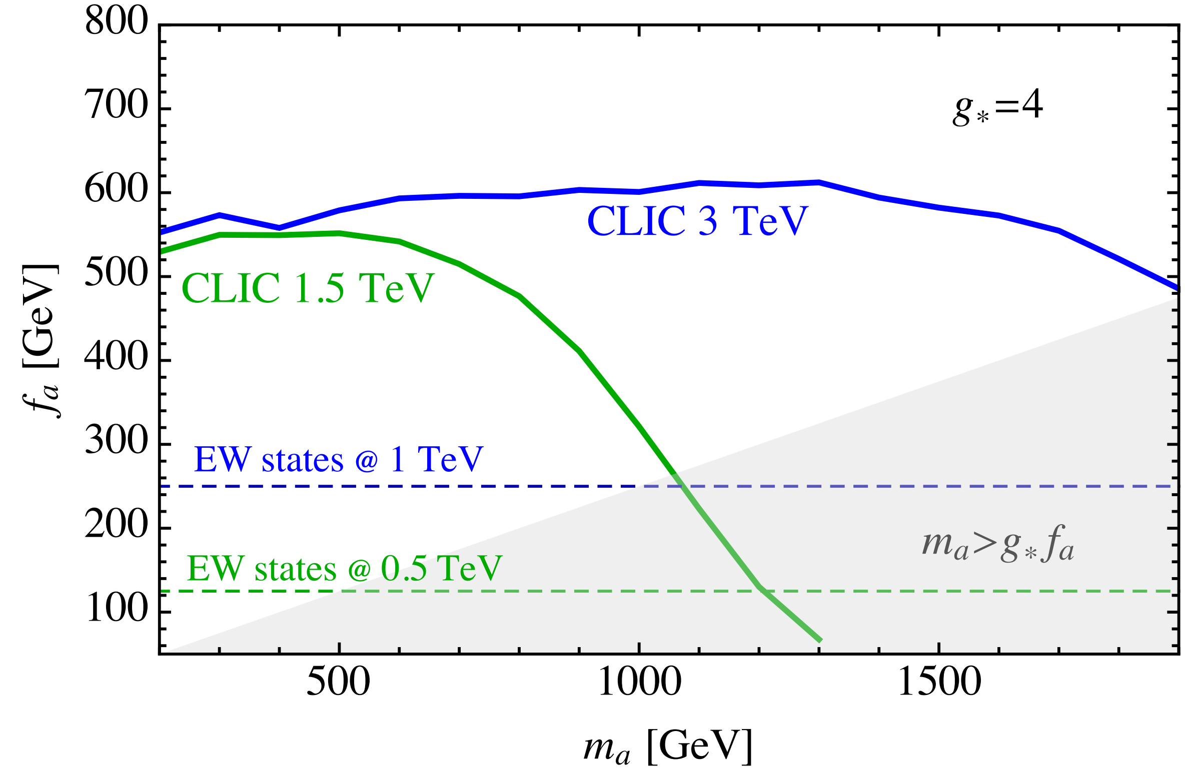
our results can be applied to 'photo-phobic' ALPs
where only one parameter enters the ALP decays to W/Z

[Craig, Hook, Kasko]

rates, limits and interpretations

production from $W_T W_T$

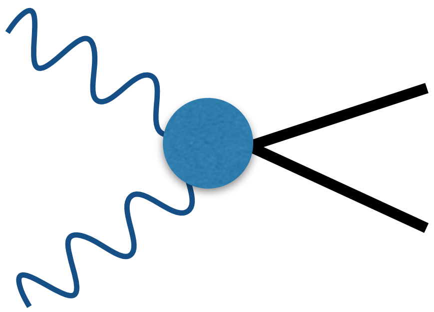




- Not all the regions have the same relevance
- Large couplings $c_{1,2}$ implies low cut-off
- Same rules for weakly and strongly coupled models

$$c_{1,2} \sim N, \quad g_* \sim 4\pi/\sqrt{N}$$

Double production

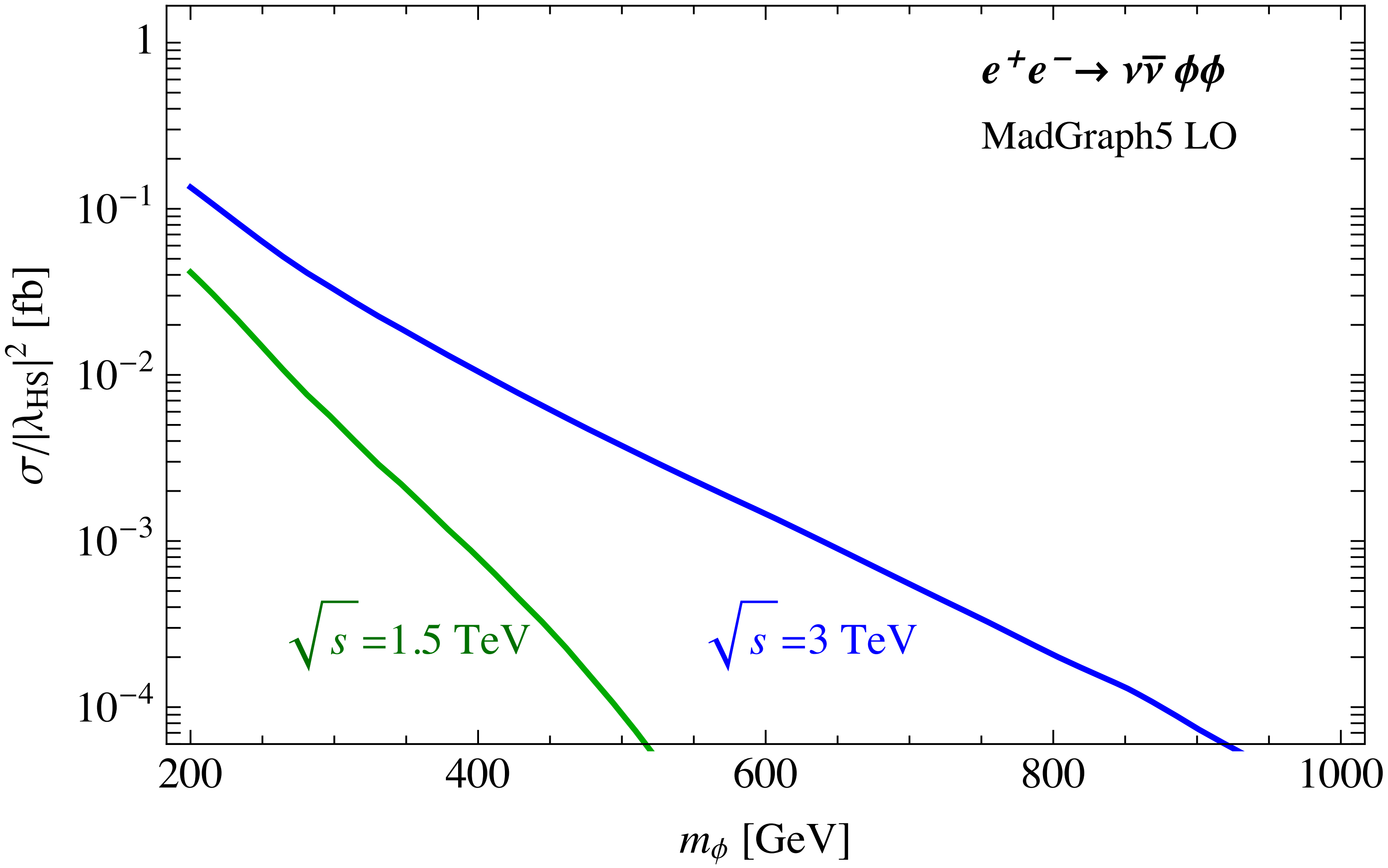


what are we testing?

for small mixing, just the portal coupling*

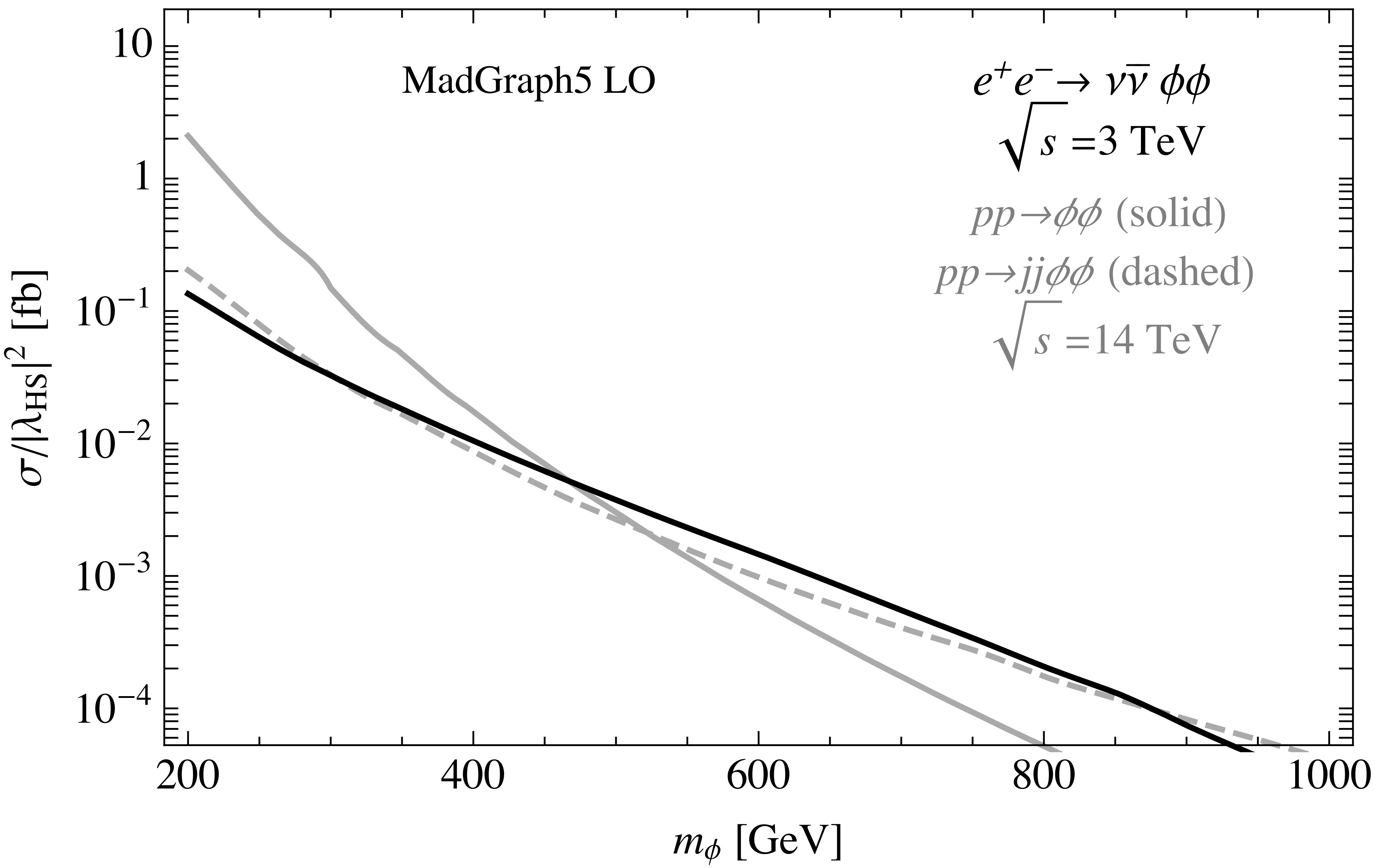
[* JM No, M Spannowsky]

$$\lambda_{HS} \sim g_*^2$$



$$\sigma_{e\bar{e}\to\nu\bar{\nu}SS} = \frac{g^4|\lambda_{HS}|^2}{49152\pi^5}\,\frac{1}{m_\phi^2}\left[\log\frac{s}{m_\phi^2} - \frac{14}{3} + \frac{m_\phi^2}{s}\left(3\log^2\frac{s}{m_\phi^2} + 18 - \pi^2\right) + \mathcal{O}\left(\frac{m_\phi^4}{s^2}\right)\right]$$

is it too small?



as small as at LHC, but in a much cleaner environment

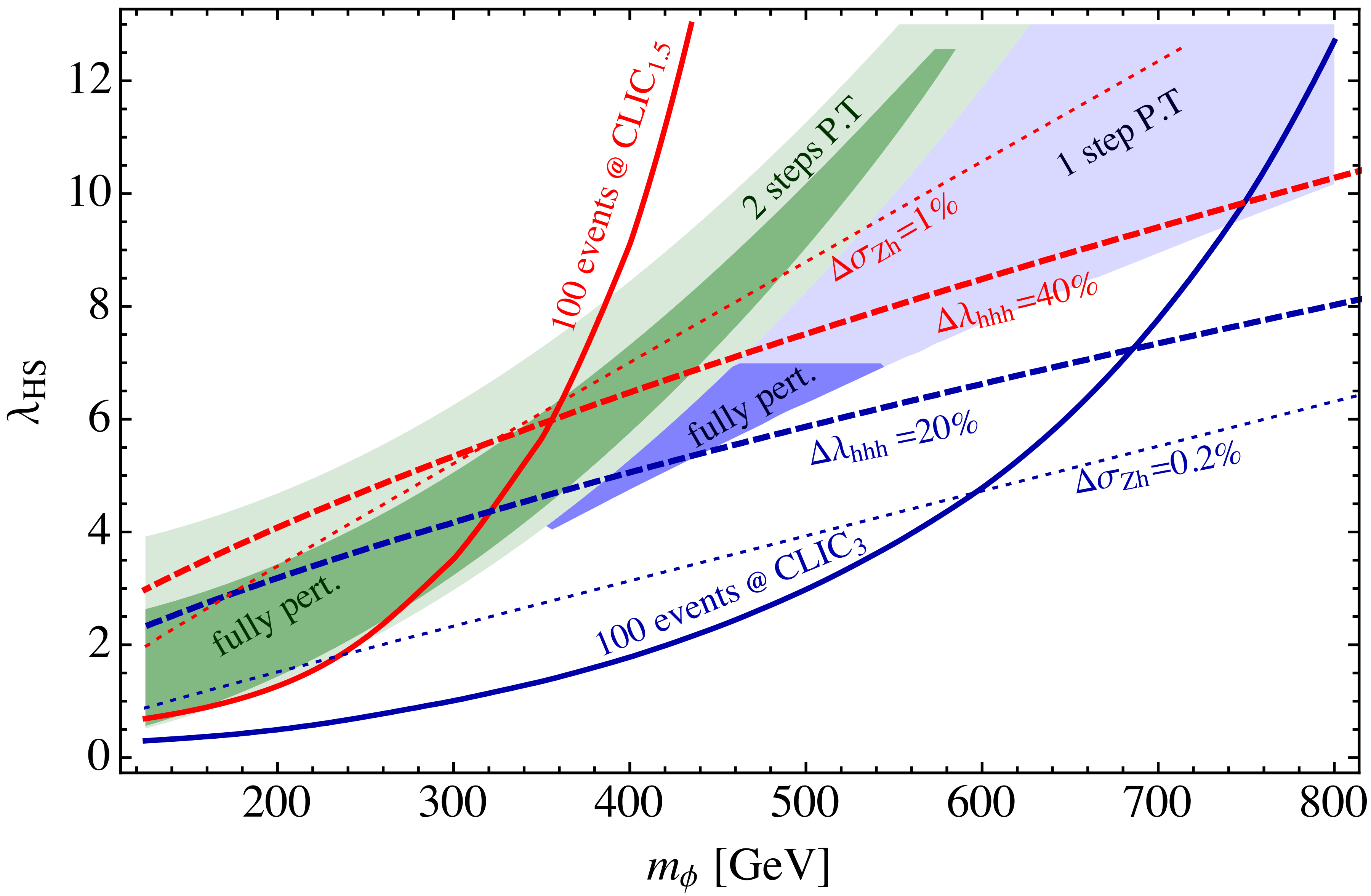
what is relevant for?

test of the electro-weak phase transition [...]

for my purposes summarized in "large coupling and light state"
or slighlty better as

- Two step phase transition $m_\phi^2 - \lambda_{HS} v^2/2 < 0\,, \quad \text{and} \quad \lambda_S v^2 \frac{m_h^2}{2} \geq |m_\phi^2 - \lambda_{HS} v^2/2|^2$
- Thermal effects from light state $\frac{v_c}{T_c} \approx \frac{\lambda_{HS}^{3/2}}{6\pi\lambda_h} \approx \frac{g_*^3}{6\pi\lambda_h}$
- $|H|^6$ term $\frac{c_6\,\lambda_H}{\Lambda^2} = \frac{\lambda_{HS}}{2v^2}\sin^2\gamma + \frac{\lambda_{HS}^3}{192\pi^2 m_\phi^2} \approx \frac{1}{\mathrm{TeV}^2}$

all in one plot



- Large number of events
- Phase diagram 'stolen' from [Curtin,Meade]
- Extremely small mixing still allow decay into detectors

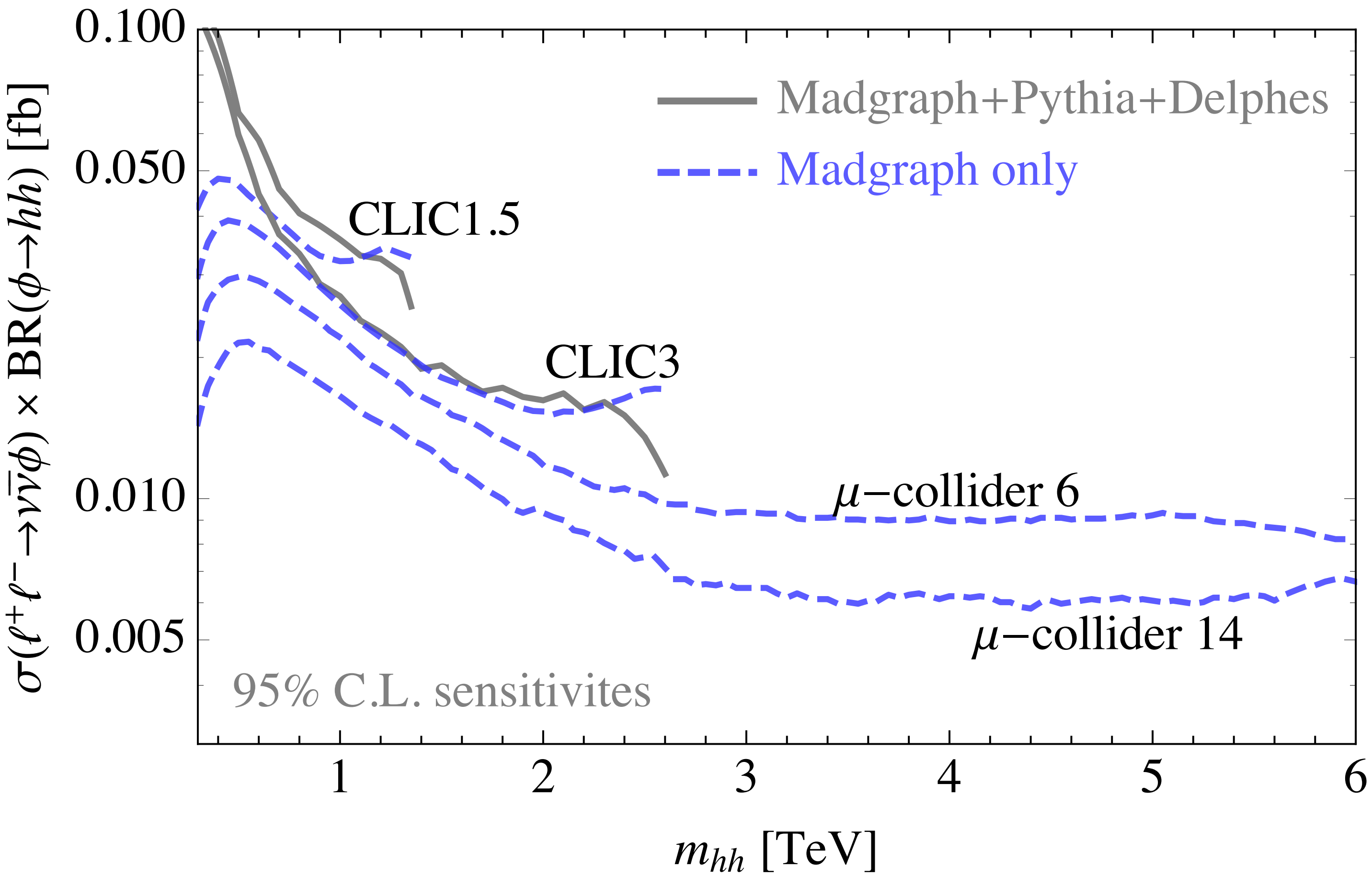
[need also to reconsider full invisible Z-fusion, beamstrahlung, MIM distribution….]

Conclusions

Thank you!

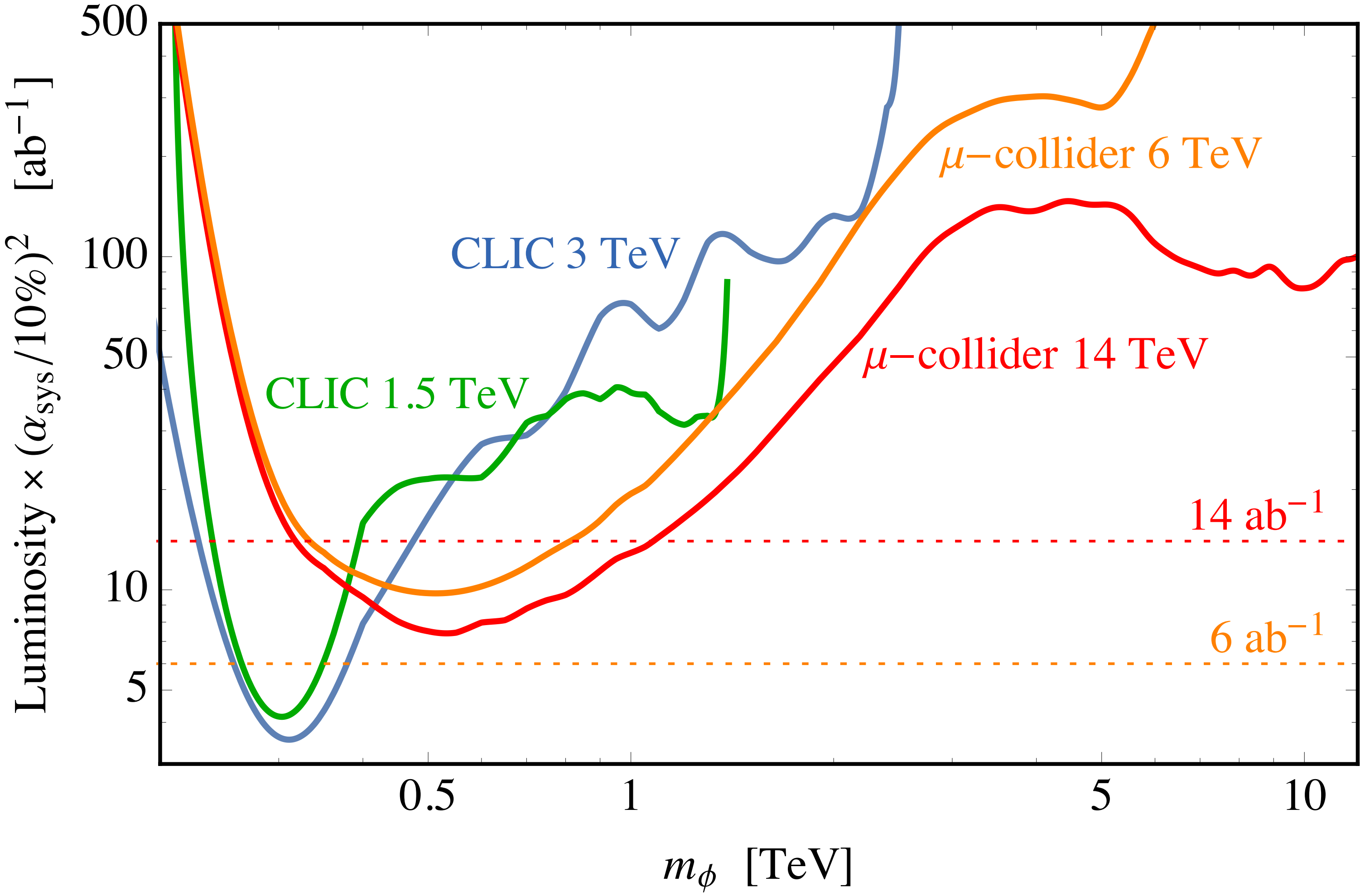
BACKUP

comparison between full and parton level analysis



BACKUP

systematics or statistics?



BACKUP

LHC and future pp machines