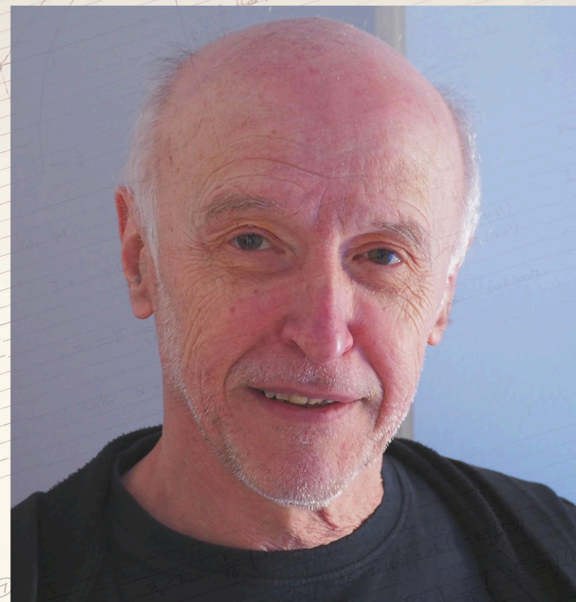


A Life in Phenomenology

A conference in honour of Paolo Nason

15-16 September 2022

U4 - 08 Aula Sironi
Milano-Bicocca University

Milan, Italy

https://indi.to/h4VDW

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN

Delighted and honored for the invitation

INFN Roma

Barbara Mele

some memories from junior times

* got to know Paolo in 1989 during my fellow at CERN

  great times => LEP just started

  in a few weeks running : $M_H^{(exp)}$ *> 4 GeV => 40 GeV*

* started to work with Paolo on b fragmentation functions

```
B.M. and P.Nason,
"Next-to-leading QCD calculation of the heavy quark fragmentation function",
Phys. Lett. B245, 635-639 (1990)

B.M. and P.Nason,
"The Fragmentation function for heavy quarks in QCD',
Nucl. Phys. B361, 626-644 (1991) [erratum: Nucl. Phys. B921, 841-842 (2017)]
```

* later on, worked (also with Giovanni) on QCD corrections to ZZ production at LHC

```
B.M., P.~Nason and G.~Ridolfi,
"QCD radiative corrections to ZZ production in hadronic collisions"
Nucl. Phys. B357, 409-438 (1991)
```

* of course, interacting with such a master, learned a lot on QCD...

improving in other disciplines during the weekends

with Mario Pernici and Nico Magnoli

one pupil versus many masters

everyone waiting for me (1)

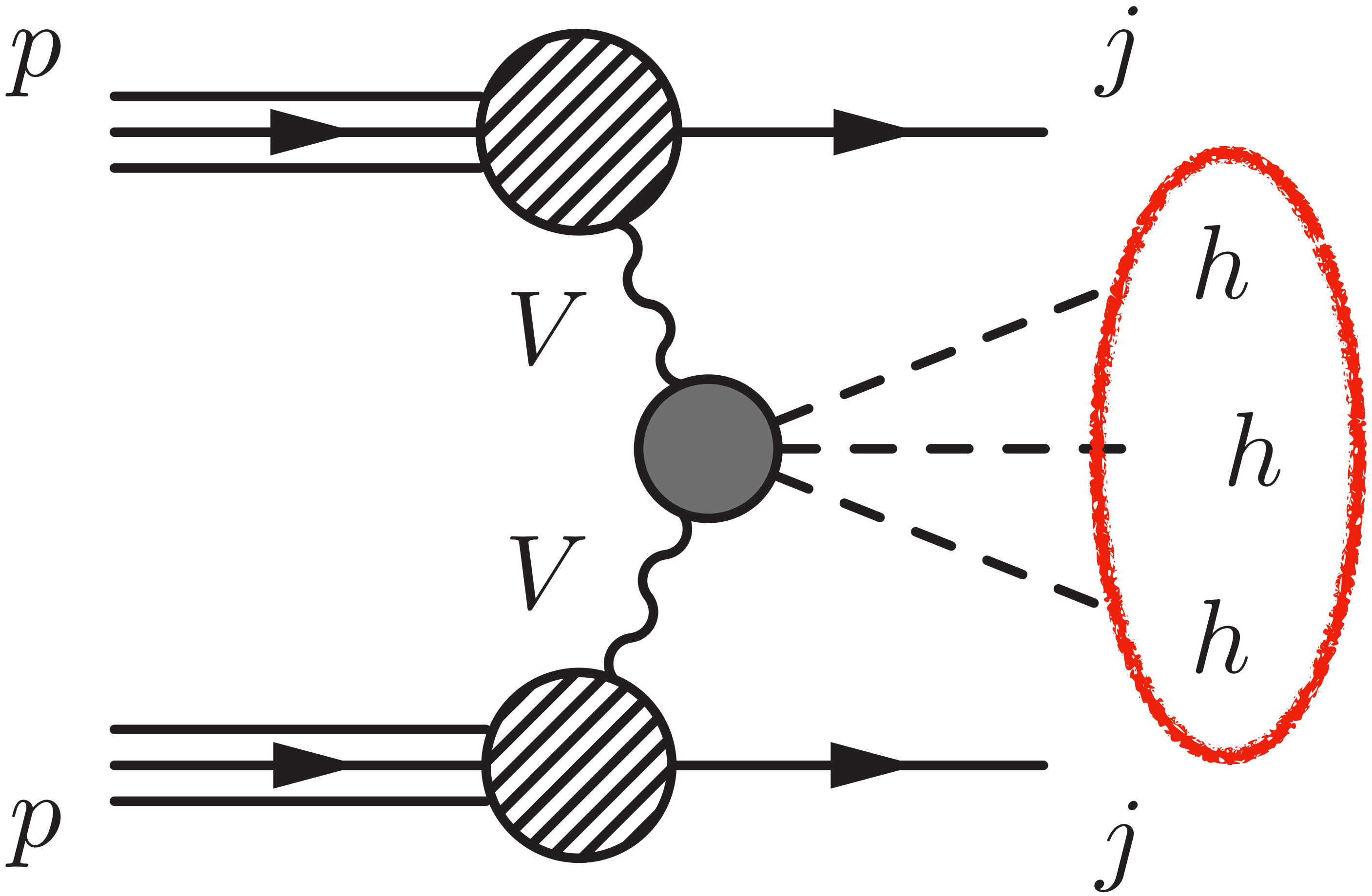
everyone waiting for me (2)

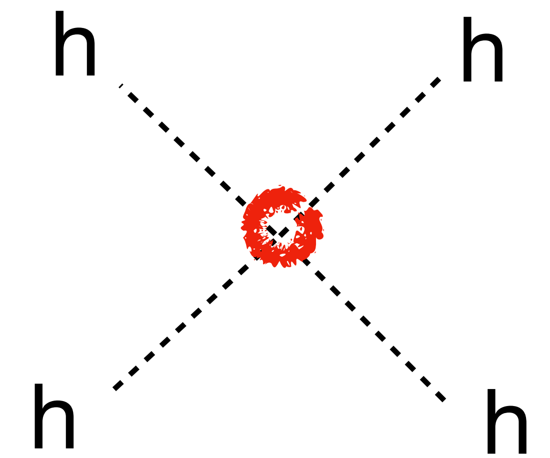
messing up while trying to pose for a photo

the whole team (including Fabio)

while LHC start-up approaching ...

- in 2006, organized with Paolo, Vittorio (Del Duca), Giacomo and Roberto (Tenchini) three Workshops on "Monte Carlo's, Physics and Simulations at the LHC" at LNF Frascati
- aimed at bringing together all Italian LHC physics communities (EXP, SM-TH, BSM-TH), to train them in complementary fields => speakers requested to use an introductory language for people with expertise in different fields
- a lot of great contributions (and fun !!!)
- Paolo's GREAT work in Proceedings production





Measuring Quartic Higgs boson self-coupling at future colliders

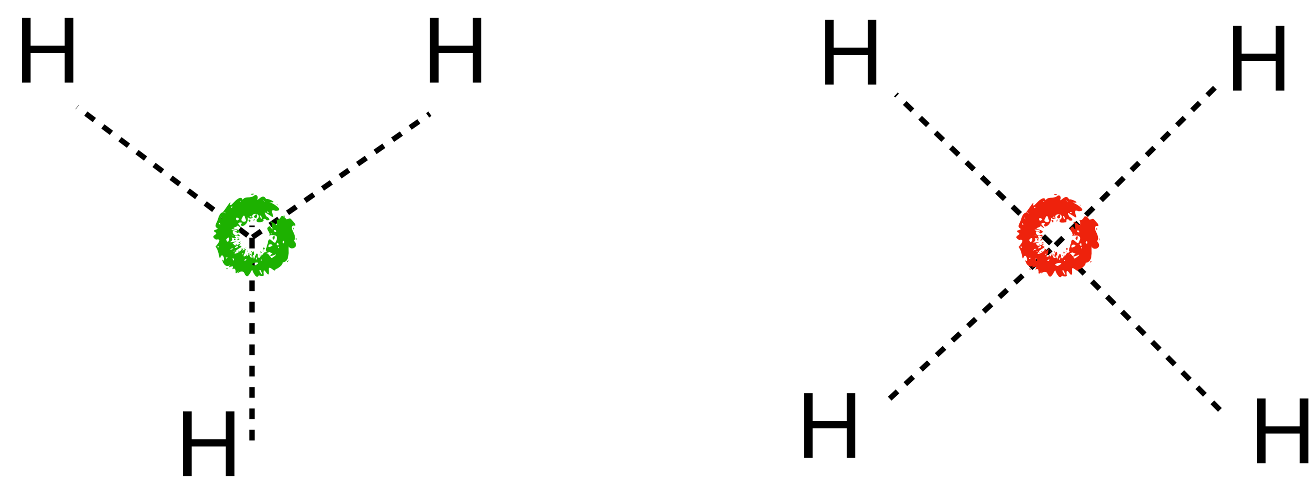
Higgs self-interaction couplings

* the "tough topic" even at "most-future" colliders
* most interesting to measure from theory side....

Higgs potential :

$$\mathcal{L} = -\frac{1}{2} m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

$$\lambda_3^{SM} = \lambda_4^{SM} = 1$$



multi-Higgs production needed for direct observation !!

HH / HHH production → tiny x-sections !

outline

* HHH sensitivity on λ_4 (λ_3) at 100TeV pp collider [$gg \to HHH$]

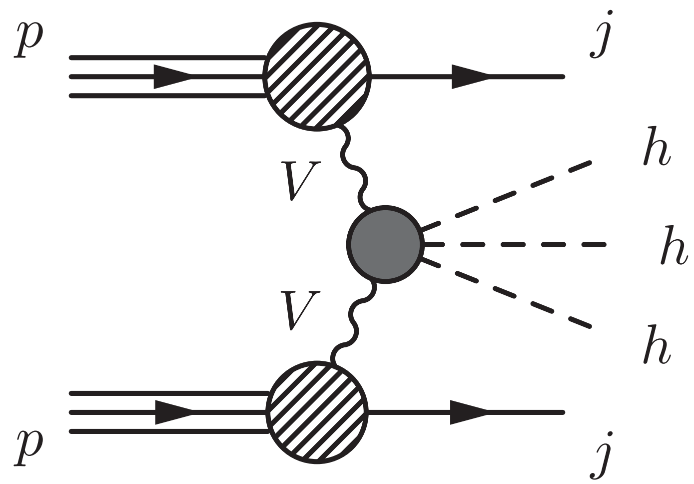
  * multi-TeV μμ colliders (revived after ESPP2020) → tentative parameters and timescales

* HHH sensitivity on λ_4 (λ_3) at multi-TeV μμ colliders [VBF → HHH] [for negligible bckgrs...]

Chiesa, Maltoni, Mantani, BM, Piccinini, JHEP 09 (2020) 098

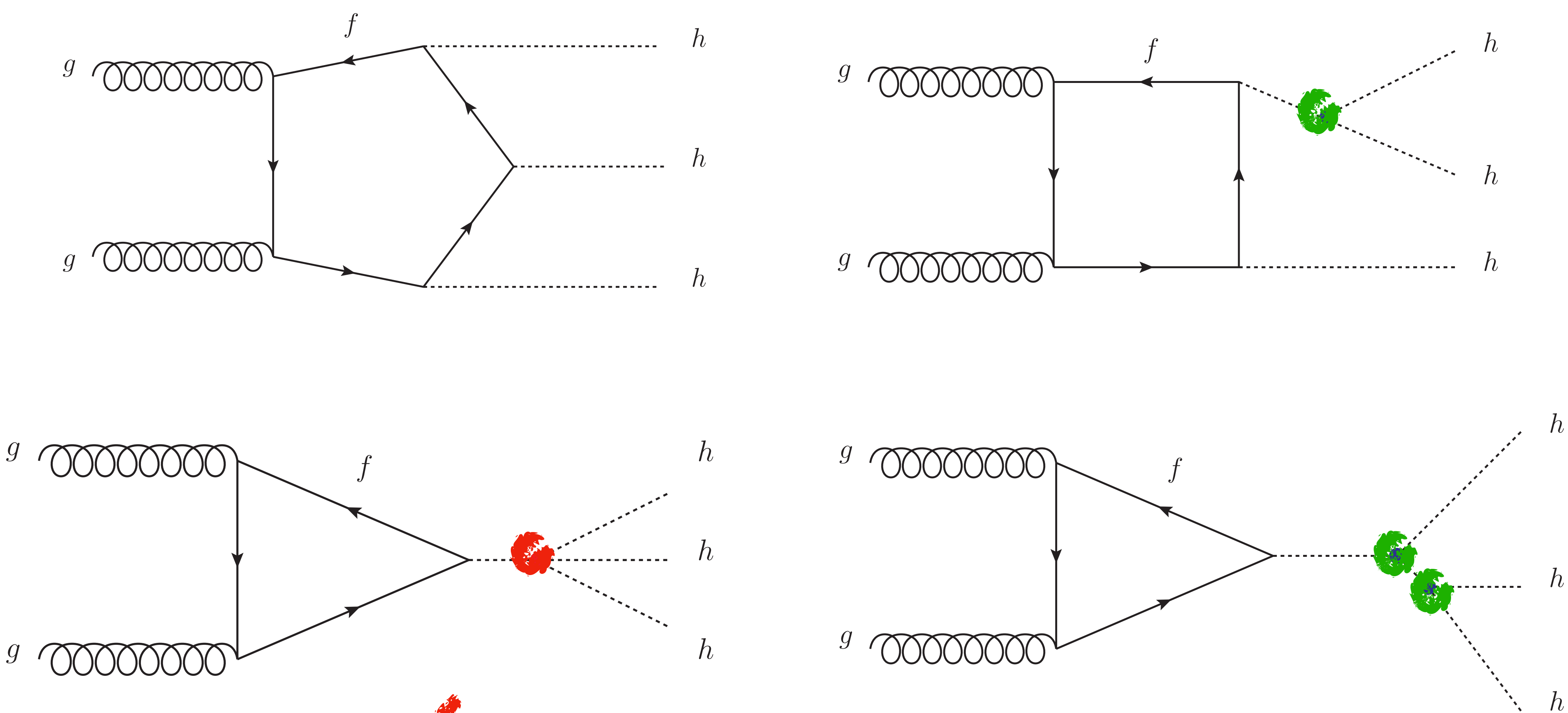
* impact of physics bckgrs (preliminary)

Chiesa, Maltoni, Mantani, BM, Moretti, Piccinini, Zhao



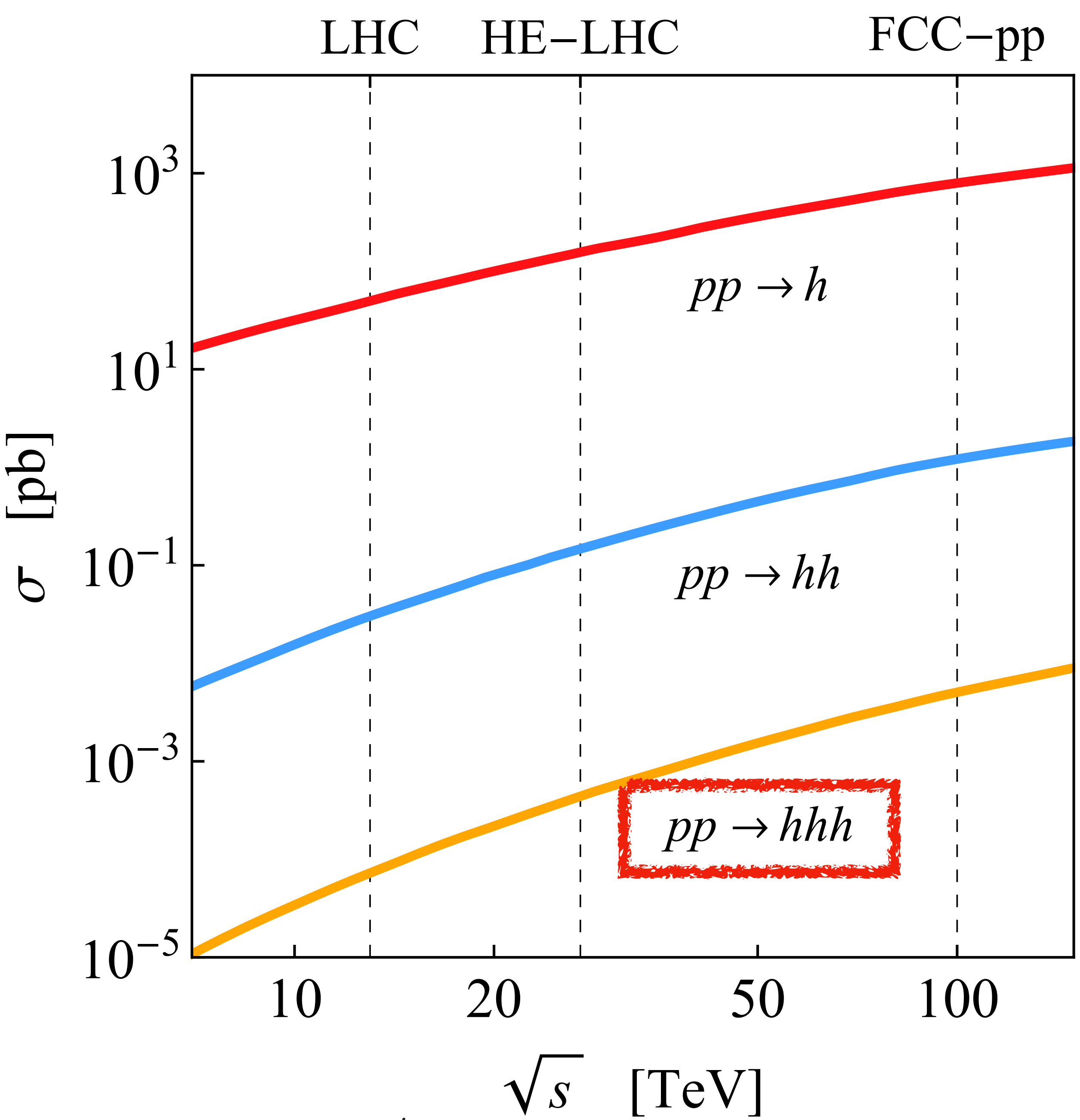
pp collisions

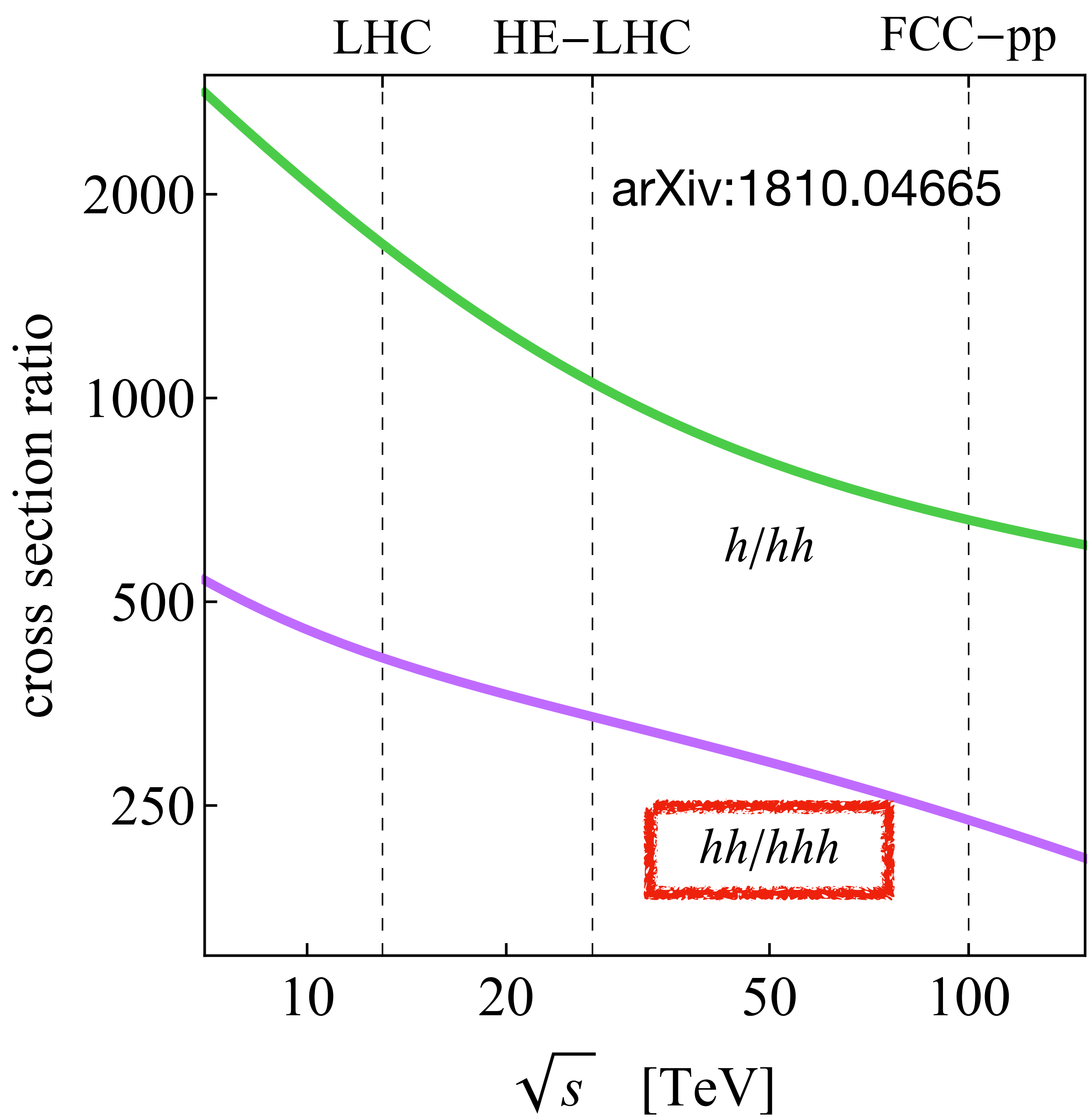
✱ gg → HHH

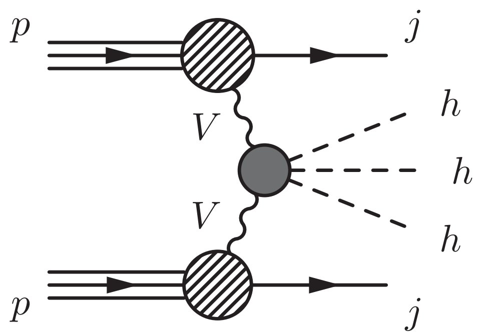


$$\sigma(\lambda_3, \lambda_4) = A\lambda_4^2 + \left(B\lambda_3^2 + C\lambda_3 + D\right)\lambda_4 + E\lambda_3^4 + F\lambda_3^3 + G\lambda_3^2 + H\lambda_3 + I$$

(SM) $\sigma_{(HHH)}$ vs $\sigma_{(HH,\,H)}$ [pp collisions]







$\sigma_{(HHH)} < \sigma_{(HH)}/100 < \sim$ fb

at $\sqrt{S} < 100$ TeV

arXiv:1508.06524

- $hhh \to (b\bar{b})(b\bar{b})(b\bar{b})$
- $hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$,
- $hhh \to (b\bar{b})(b\bar{b})(\tau^+\tau^-)$,
- $hhh \to (b\bar{b})(\tau^+\tau^-)(\tau^+\tau^-)$,
- $hhh \to (b\bar{b})\ (W^+W^+)(W^+W^-)$

$hhh \to$ final state	BR (%)	σ (ab)	$N_{30\mathrm{ab}^{-1}}$
$(b\bar{b})(b\bar{b})(b\bar{b})$	19.21	1110.338	33310
$(b\bar{b})(b\bar{b})(WW_{1\ell})$	7.204	416.41	12492
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	6.312	364.853	10945
$(b\bar{b})(\tau\bar{\tau})(WW_{1\ell})$	1.578	91.22	2736
$(b\bar{b})(b\bar{b})(WW_{2\ell})$	0.976	56.417	1692
$(b\bar{b})(WW_{1\ell})(WW_{1\ell})$	0.901	52.055	1561
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	0.691	39.963	1198
$(b\bar{b})(b\bar{b})(ZZ_{2\ell})$	0.331	19.131	573
$(b\bar{b})(WW_{2\ell})(WW_{1\ell})$	0.244	14.105	423
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	0.228	13.162	394
$(b\bar{b})(\tau\bar{\tau})(WW_{2\ell})$	0.214	12.359	370
$(\tau\bar{\tau})(WW_{1\ell})(WW_{1\ell})$	0.099	5.702	171
$(\tau\bar{\tau})(\tau\bar{\tau})(WW_{1\ell})$	0.086	4.996	149
$(b\bar{b})(ZZ_{2\ell})(WW_{1\ell})$	0.083	4.783	143
$(b\bar{b})(\tau\bar{\tau})(ZZ_{2\ell})$	0.073	4.191	125
$(b\bar{b})(\gamma\gamma)(WW_{1\ell})$	0.057	3.291	98
$(b\bar{b})(\tau\bar{\tau})(\gamma\gamma)$	0.05	2.883	86
$(WW_{1\ell})(WW_{1\ell})(WW_{1\ell})$	0.038	2.169	65
$(\tau\bar{\tau})(WW_{2\ell})(WW_{1\ell})$	0.027	1.545	46
$(\tau\bar{\tau})(\tau\bar{\tau})(\tau\bar{\tau})$	0.025	1.459	43
$(b\bar{b})(WW_{2\ell})(WW_{2\ell})$	0.017	0.956	28
$(WW_{2\ell})(WW_{1\ell})(WW_{1\ell})$	0.015	0.882	26
$(b\bar{b})(b\bar{b})(ZZ_{4\ell})$	0.012	0.69	20
$(\tau\bar{\tau})(\tau\bar{\tau})(WW_{2\ell})$	0.012	0.677	20
$(b\bar{b})(ZZ_{2\ell})(WW_{2\ell})$	0.011	0.648	19
$(\tau\bar{\tau})(ZZ_{2\ell})(WW_{1\ell})$	0.009	0.524	15
$(b\bar{b})(\gamma\gamma)(WW_{2\ell})$	0.008	0.446	13
$(\tau\bar{\tau})(\gamma\gamma)(WW_{1\ell})$	0.006	0.36	10

many many different HHH final states with $N_{ev} > 10$ at 100 TeV (30 ab^{-1})

quite a few studies of gg → HHH at pp colliders :

hep-ph/0507321, arXiv:1508.06524
arXiv:1510.04013, arXiv:1602.05849
arXiv:1606.09408, arXiv:1702.03554
arXiv:1704.04298, arXiv:1708.03580
arXiv:1810.04665, arXiv:1811.12366
arXiv:1909.09166 ...

anomalous Higgs self-coupling parametrization

$$\lambda_{hhh}^{SM} = \lambda_{hhhh}^{SM} = \frac{m_h^2}{2v^2}$$

$$V_h = \frac{m_h^2}{2} h^2 + (1+\delta_3)\lambda_{hhh}^{SM} v h^3 + \frac{1}{4}(1+\delta_4)\lambda_{hhhh}^{SM} h^4$$

typical of well-behaved EFTs → → $\delta_3 = \bar{c}_6$ $\delta_4 = 6\,\bar{c}_6 + \bar{c}_8$

$$V^{NP}(\Phi) \equiv \sum_{n=3}^{\infty} \frac{c_{2n}}{\Lambda^{2n-4}} \left(\Phi^\dagger \Phi - \frac{1}{2}v^2\right)^n$$

$$\bar{c}_6 \equiv \frac{c_6 v^2}{\lambda^{SM}\Lambda^2} = \delta_3$$

$$\bar{c}_8 \equiv \frac{4 c_8 v^4}{\lambda^{SM}\Lambda^4} = \delta_4 - 6\delta_3$$

$$\lambda_3 = \lambda_{SM}(1+\delta_3)$$

$$\lambda_4 = \lambda_{SM}(1+\delta_4)$$

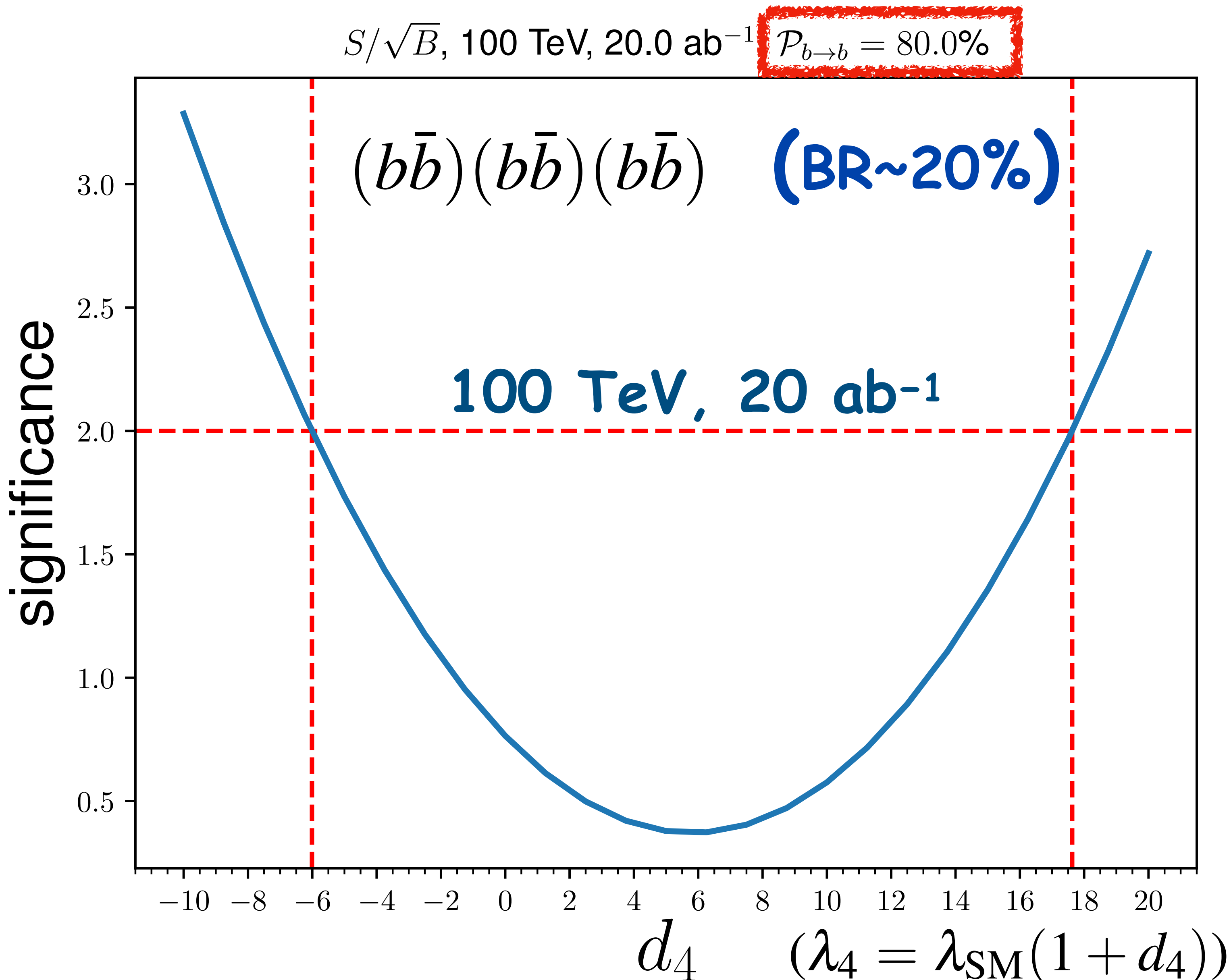
3 interesting benchmarks :

- $\delta_3 = 0\,;$ *free* δ_4
- $\delta_4 = 6\,\delta_3$ *(well-behaved SMEFT)*
- *free* (δ_3, δ_4)

be agnostic about how UV dynamics modifies Higgs self-interactions

→ no assumption about the actual size of (δ_3, δ_4)

σ(HHH → bbbbbb) [pp , 100 TeV]



arXiv:1909.09166

$$\lambda_3 = \lambda_{SM}(1+\delta_3)$$
$$\lambda_4 = \lambda_{SM}(1+\delta_4)$$

[δ_3=0] $-6 < \delta_4 < 18$ (95%CL)

"typical" constraining power of HHH in pp

$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$ pp, 100 TeV, 30 ab-1

(BR~0.2%) $S/B \sim 0.5$ $S/\sqrt{B} \sim 2.1$

process	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO} \times {\rm BR} \times \mathcal{P}_{\rm tag}$ (ab)	$\epsilon_{\rm analysis}$	$N^{\rm cuts}_{30\ {\rm ab}^{-1}}$
$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$, SM	2.89	5.4	0.06	9.7
$b\bar{b}b\bar{b}\gamma\gamma$	1.28	1050	2.6×10^{-4}	8.2
hZZ, (NLO) $(ZZ \to (b\bar{b})(b\bar{b}))$	0.817	0.8	0.002	$\ll 1$
hhZ, (NLO)$(Z \to (b\bar{b}))$	0.754	0.8	0.007	$\ll 1$
hZ, (NLO) $(Z \to (b\bar{b}))$	8.02×10^3	1130	$\mathcal{O}(10^{-5})$	$\ll 1$
$b\bar{b}b\bar{b}\gamma$ + jets	2.95×10^3	2420	$\mathcal{O}(10^{-5})$	$\mathcal{O}(1)$
$b\bar{b}b\bar{b}$ + jets	5.45×10^3	4460	$\mathcal{O}(10^{-6})$	$\ll 1$
$b\bar{b}\gamma\gamma$ + jets	98.7	4.0	$\mathcal{O}(10^{-5})$	$\ll 1$
hh + jets, SM	275	593	7×10^{-4}	12.4

[$\delta_3=0$] $-5 < \delta_4 < 15$ (95%CL)

in "optimistic" scenario !!!

arXiv:1508.06524
arXiv:1606.09408

for indirect λ_4 bounds from H and HH production: 1810.04665,1811.12366

multi-TeV muon colliders

renewed interest after ESPP2020

μ^+ → ← μ^-

$\sqrt{S_{\mu\mu}} \sim 3,\ 6,\ 10,\ 14,\ 30$ TeV

$$\mathcal{L} = (E_{\rm CM}/10\ \ {\rm TeV})^2 \times 10\,{\rm ab}^{-1}$$

$$\sim 1fb\,(\frac{10\,TeV}{\sqrt{S}})^2$$

$\sigma_{point} \times \int L \sim 10^4$ evts

$\delta_{stat} \sim 1\%$

allows precision on whatever is pair-produced in s-channel !

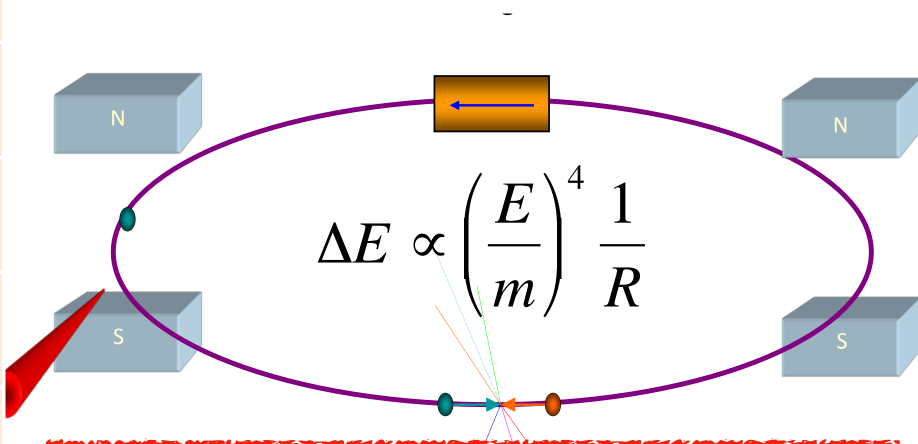
not yet systematic Physics studies, a few preliminary projections !

Tentative Target Parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Schulte, July 2020

Based on extrapolation of MAP parameters



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

cf. CLIC_3TeV requiring a 50 Km tunnel !
(and P_{beam}~ 28 MW !!)

$$L \sim 10^{35} cm^{-2} s^{-1} \sim 1\, ab^{-1}/y$$

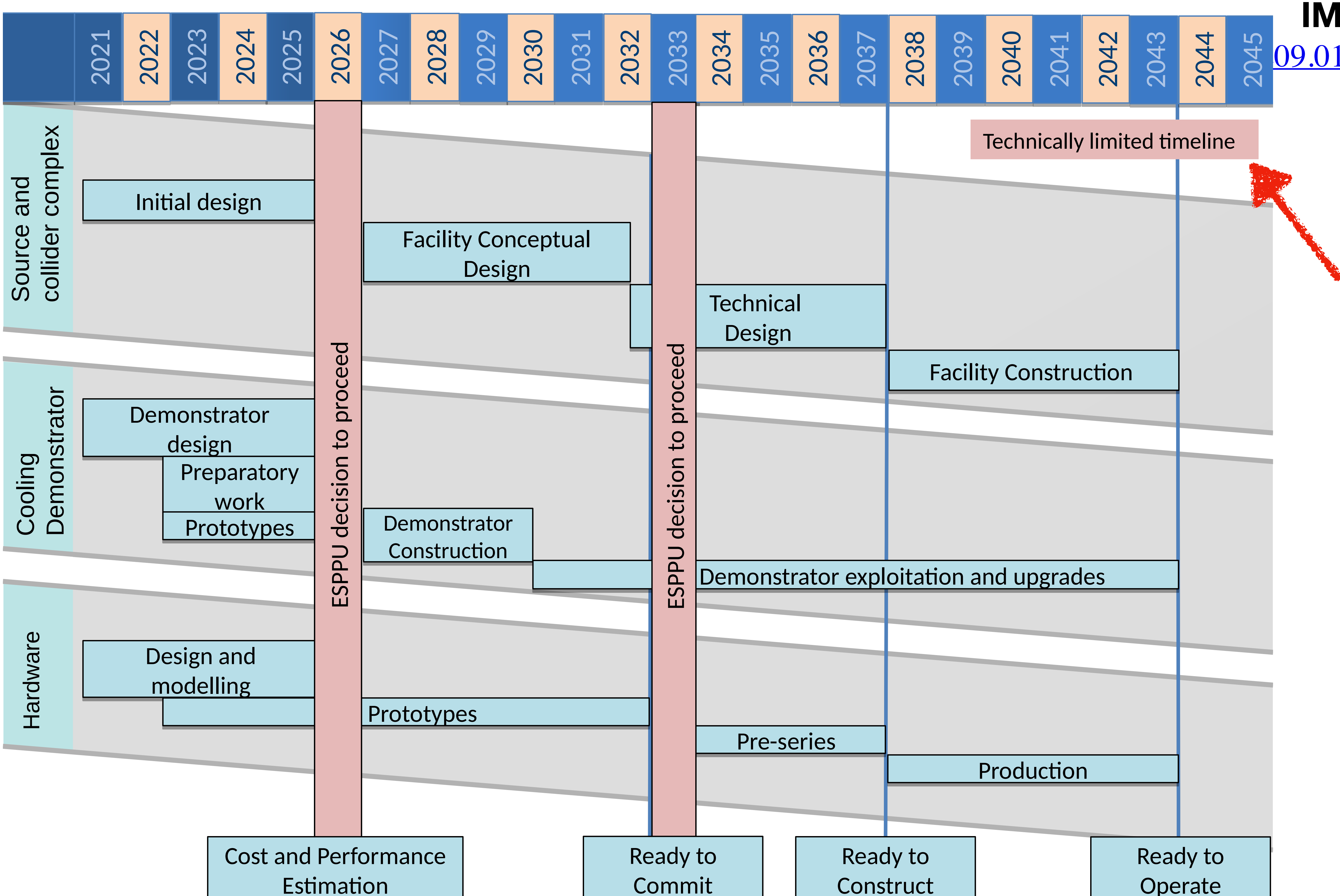
integrated lumi for 5 years (10^7 s) run

$$\mathcal{L} = (E_{\rm CM}/10\ \text{TeV})^2 \times 10\,\text{ab}^{-1}$$

Muon-Collider (3 TeV) "technical" timescale

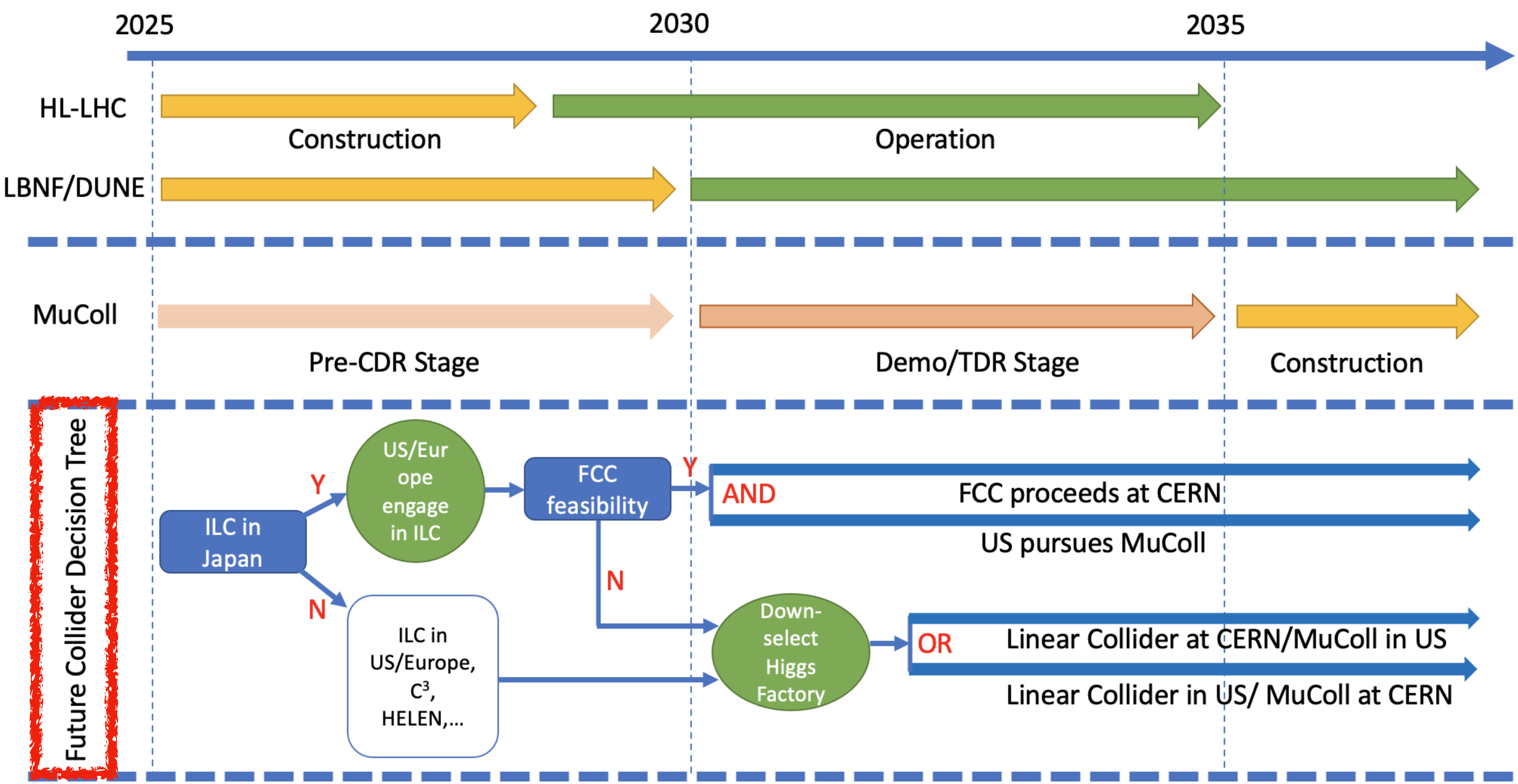
IMCC

09.01318



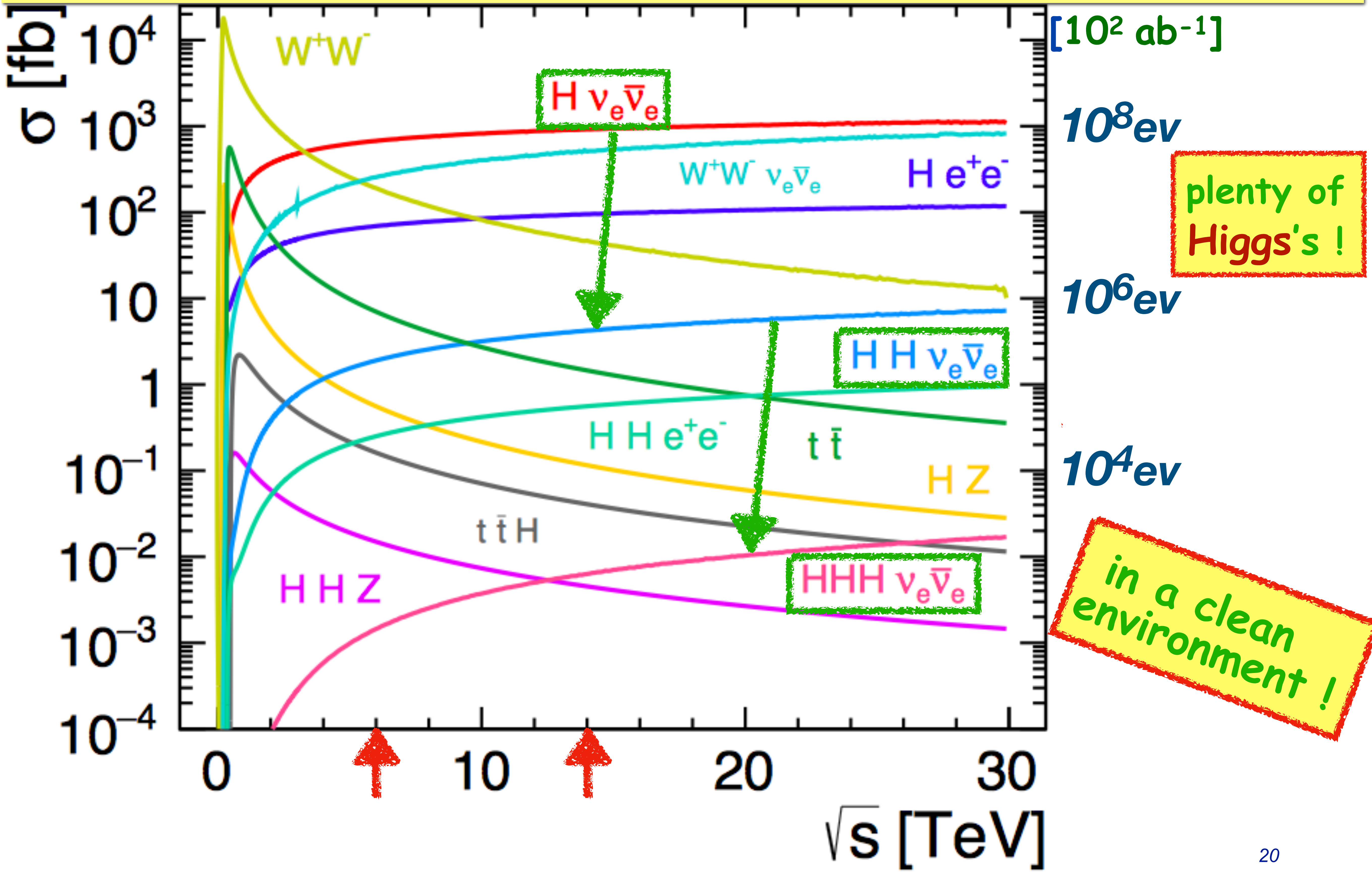
Muon-Collider comparative timescale

Snowmass MC Forum 2209.01318



a muon collider might be a NEXT-GENERATION machine !!

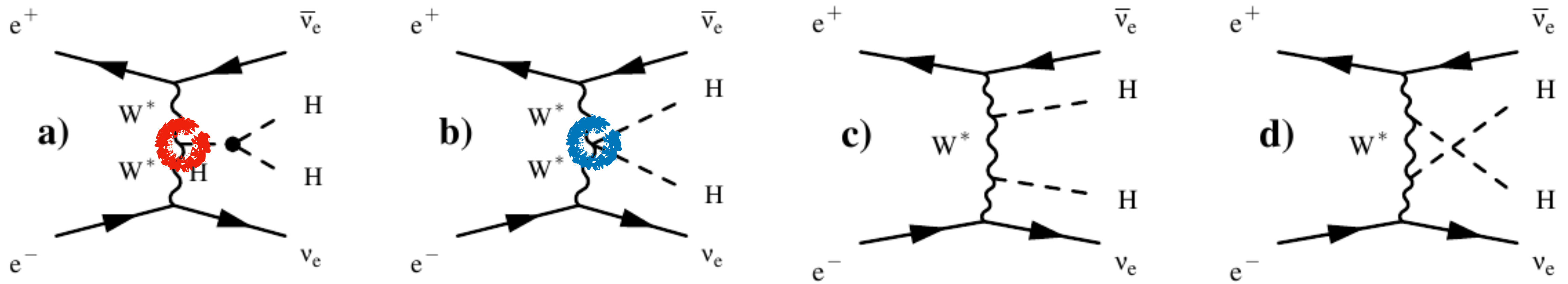
at [$\sqrt{S_{\mu\mu}}$ > a few TeV's], point $\sigma_{\mu\mu\to X}$ (~1/s) superseeded by $\sigma_{WW\to X}$ (~$\log^n s$) !



trilinear Higgs coupling at Muon Colliders

$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

✱ 40.000 HH pairs at 14 TeV !



$HH \to 4b$

$p_T(b) > 30$ GeV, $10^\circ < \theta_b < 170^\circ$, $\Delta R_{bb} > 0.4$. $|m_{jj} - m_H| < 15$ GeV

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
HHWW $(\Delta\kappa_{W_2})_{in}$	5.3%	1.3%	0.62%	0.41%	0.20%
HHH $(\Delta\kappa_3)_{in}$	25%	10%	5.6%	3.9%	2.0%

(other projects)

5% CLIC

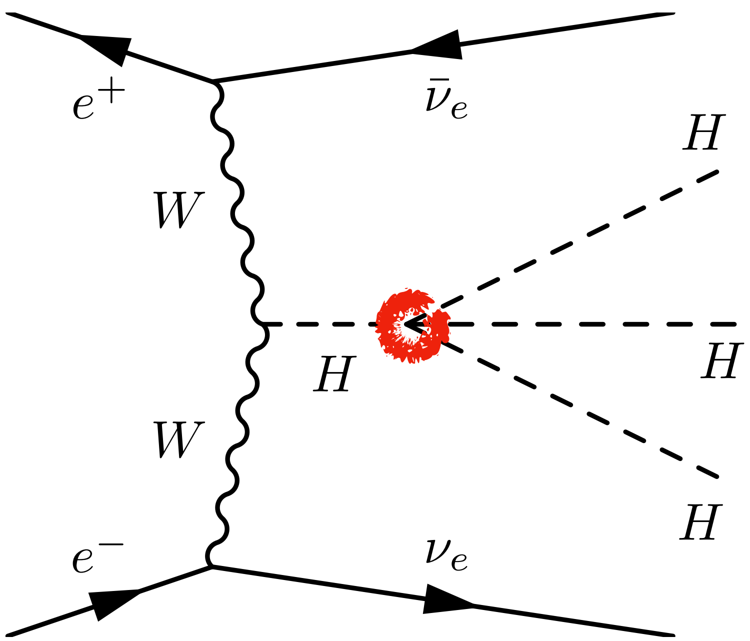
5% FCC-hh 68%CL

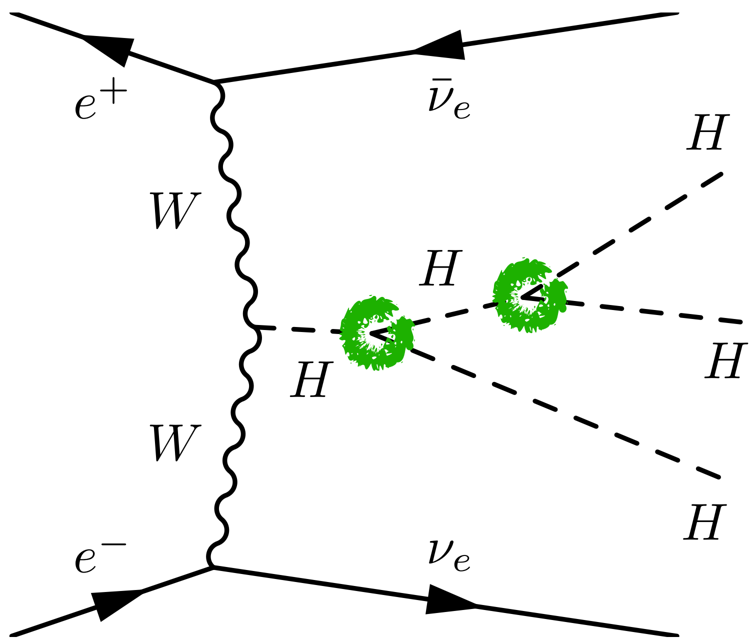
(95% CL, single-parameter fit)

T. Han et al. arXiv:2008.12204

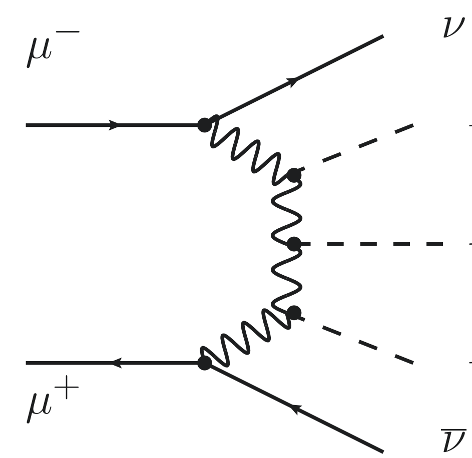
$\mu^+\mu^- \to HHH\nu\bar{\nu},\ (\nu = \nu_e, \nu_\mu, \nu_\tau)$

$$V_{\rm h} = \frac{m_h^2}{2}h^2 + (1+\delta_3)\lambda_{hhh}^{\rm SM} v h^3 + \frac{1}{4}(1+\delta_4)\lambda_{hhhh}^{\rm SM} h^4$$



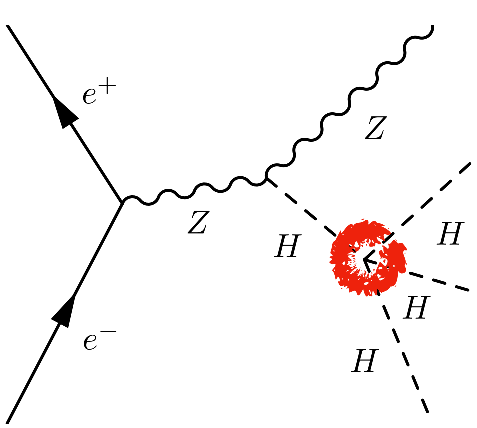


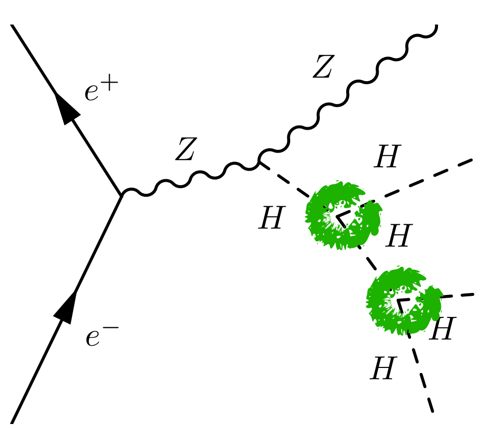
$$\mu^+\mu^- \to W^*W^*\nu_\mu\bar{\nu}_\mu$$
$$\to HHH\nu_\mu\bar{\nu}_\mu$$



+ . . .

$$\sigma = c_1 + c_2\delta_3 + c_3\delta_4 + c_4\delta_3\delta_4 + c_5\delta_3^2 + c_6\delta_4^2 + c_7\delta_3^3 + c_8\delta_3^2\delta_4 + c_9\delta_3^4$$





HHHZ subdominant !

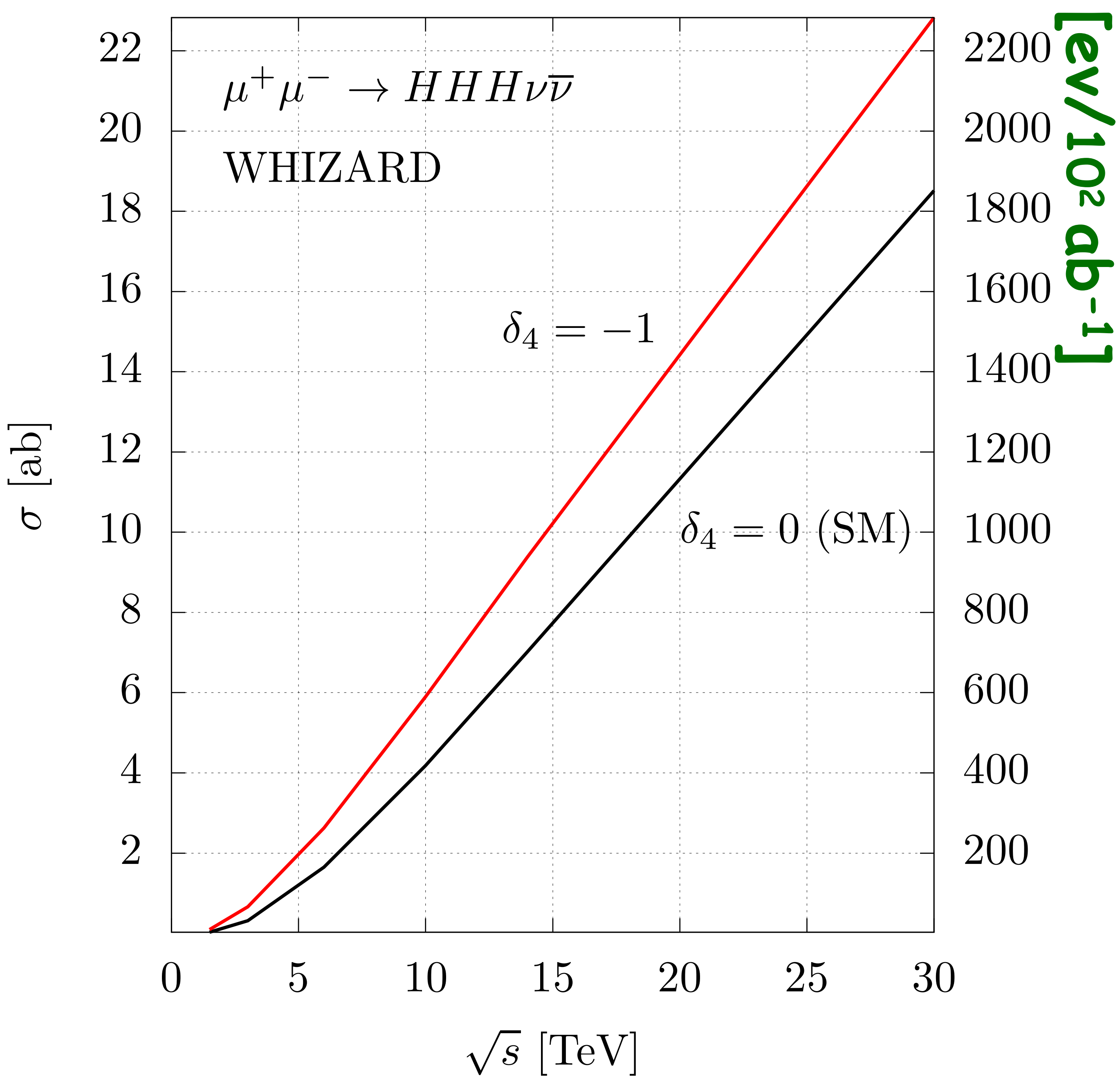
σ_{HHHZ} ~ 1/2 $\sigma_{HHH\nu\nu}$ @ 3TeV

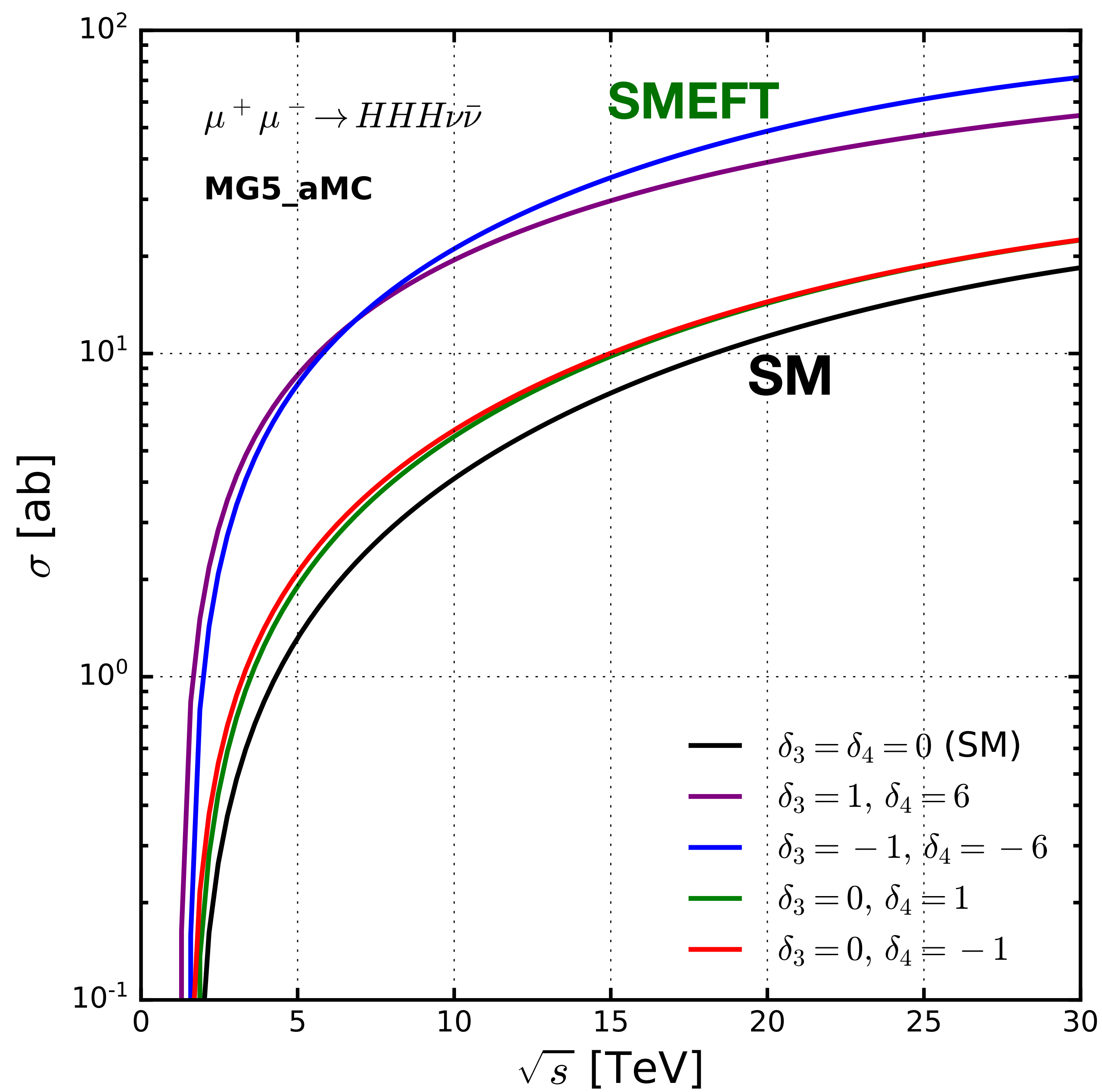
~ 1/50 $\sigma_{HHH\nu\nu}$ @ 30TeV

$\sigma_{HHH\nu\nu}$ $(\delta_3\ ,\ \delta_4)$ [μμ collisions]

Chiesa, Maltoni, Mantani, BM, Piccinini, Zhao,
arXiv:2003.13628, JHEP 09 (2020) 098

$$\lambda_3 = \lambda_{SM}(1+\delta_3)$$
$$\lambda_4 = \lambda_{SM}(1+\delta_4)$$

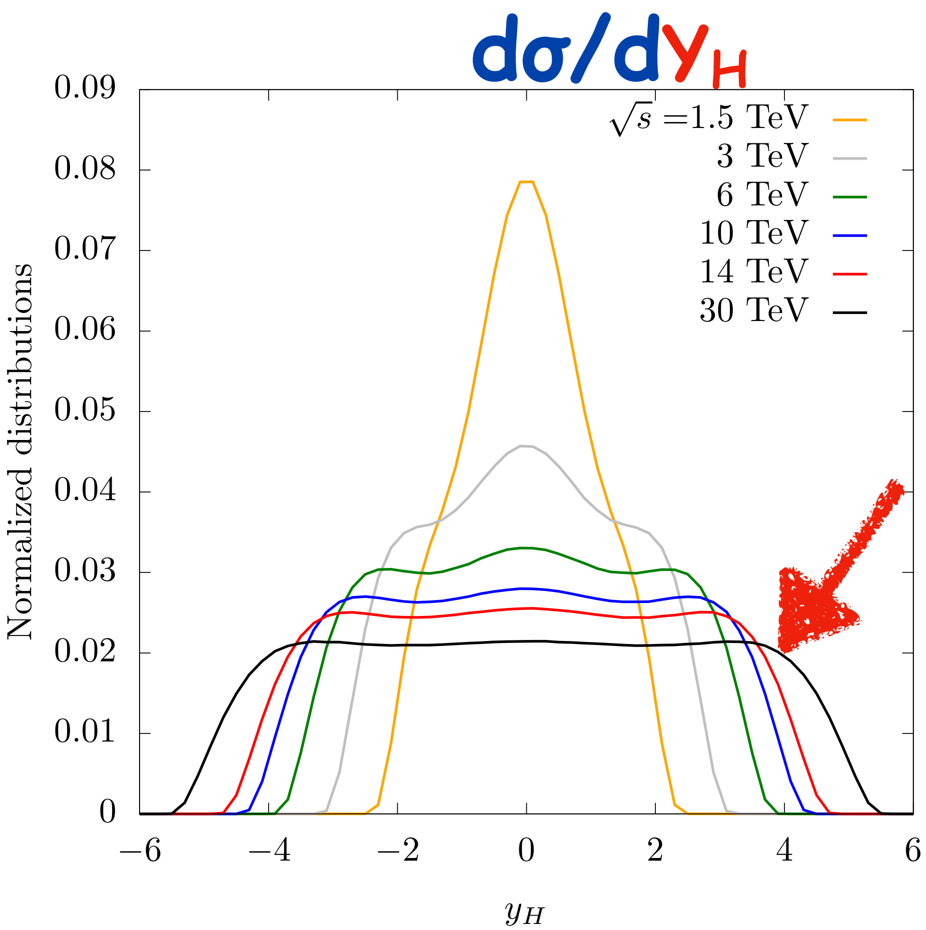


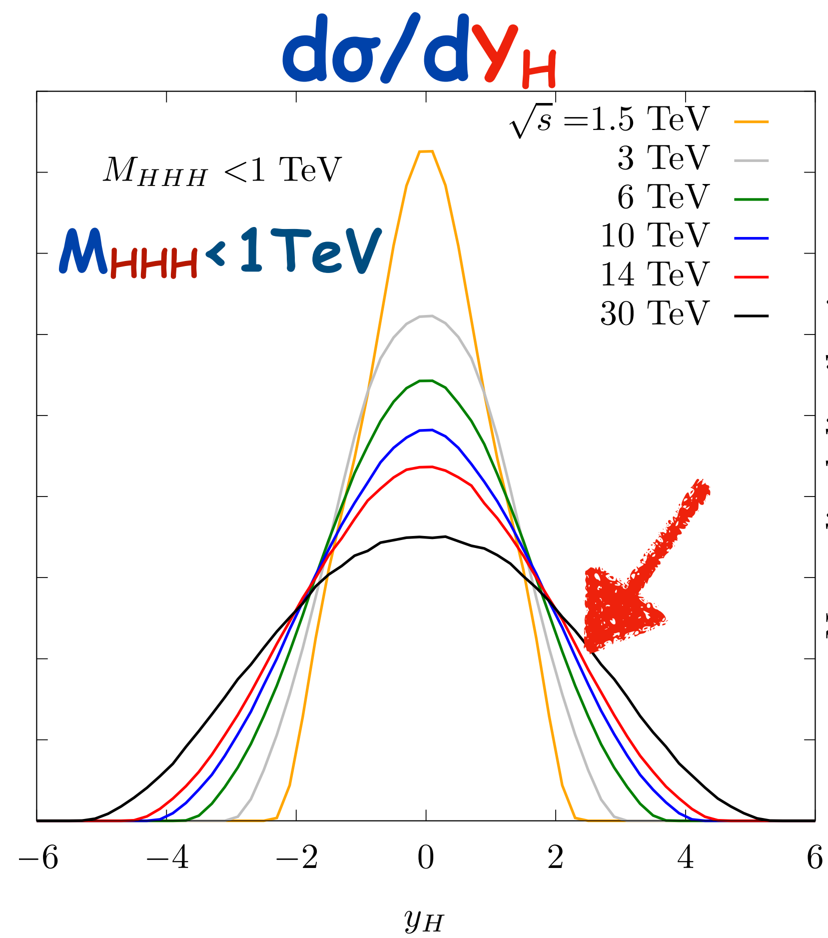


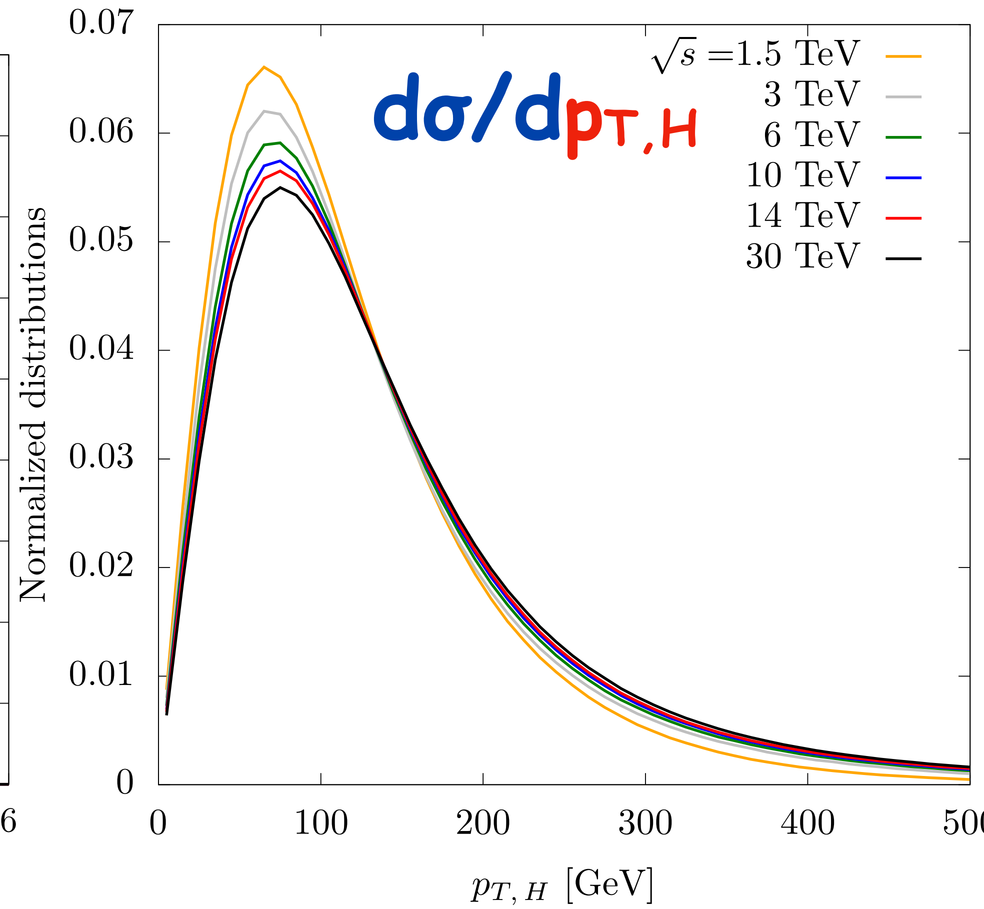
$\sigma_{HHH\nu\nu}$ (SM) [μμ collisions]

$\sqrt{s}$ (TeV) / L (ab^{-1})	10 / 20	14 / 33	30 / 100
σ_{SM} (ab) $[N_{ev}]$			
σ^{tot}	4.18 [84]	7.02 [232]	18.51 [1851]
$\sigma(M_{HHH} < 3\text{TeV})$	2.89 [58]	3.98 [131]	6.69 [669]
$\sigma(M_{HHH} < 1\text{TeV})$	0.37 [7]	0.45 [15]	0.64 [64]

$M_{\bar{\nu}\nu} \gtrsim 150\text{GeV}$ *applied everywhere (selects VBF contribution)*

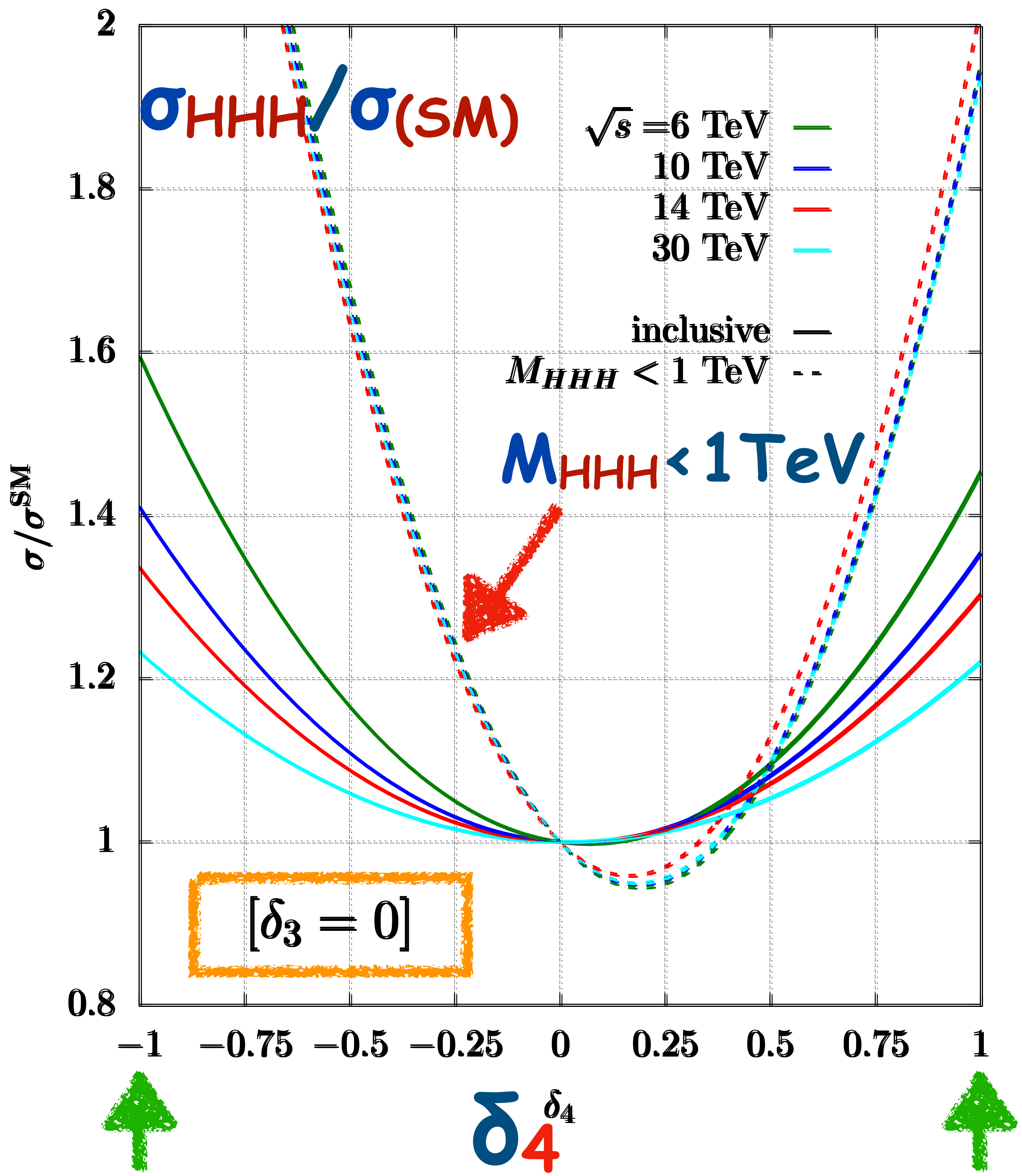




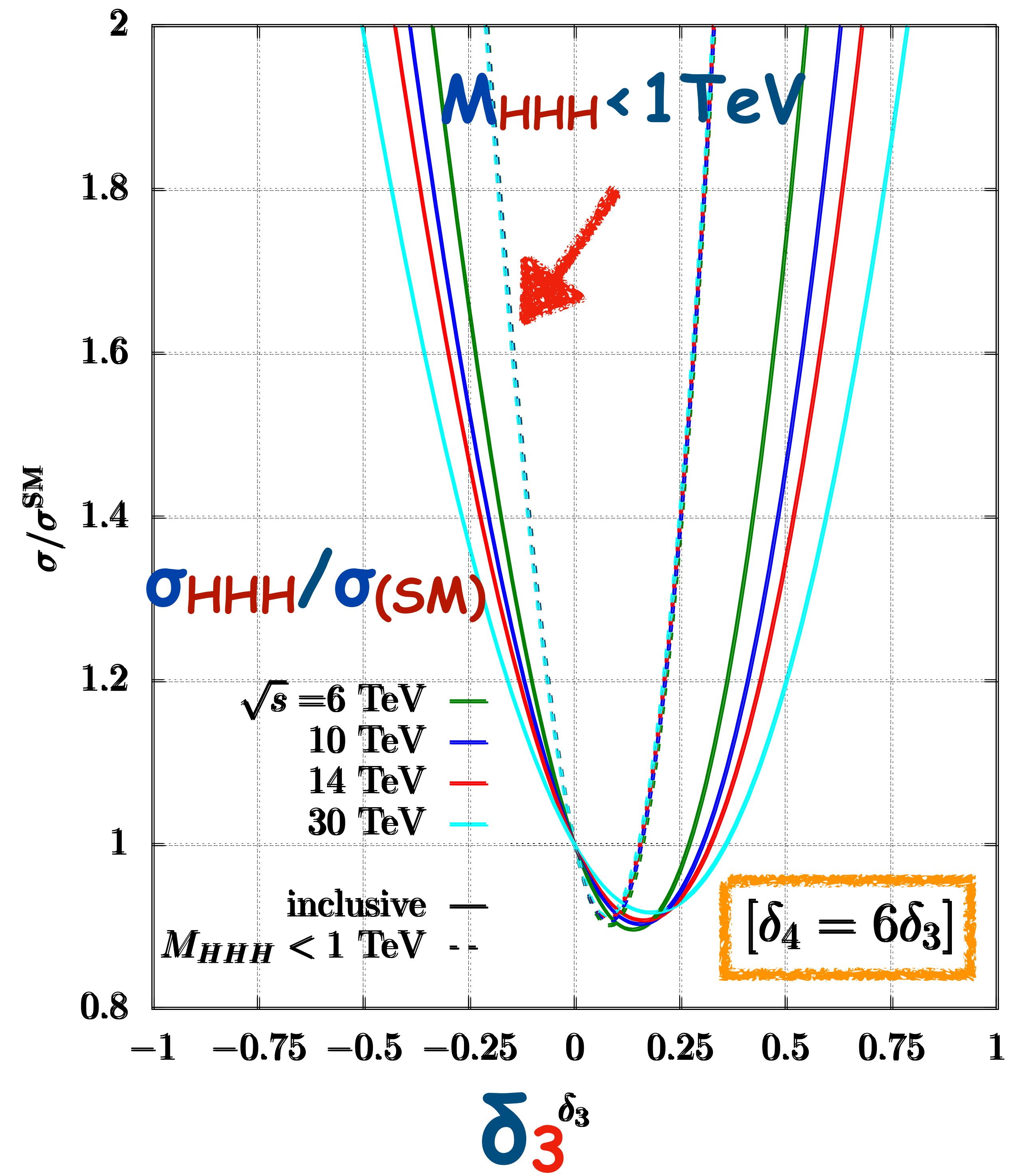


arXiv:2003.13628

$\sigma_{HHH} / \sigma_{(SM)}$ versus (δ_3 , δ_4)



arXiv:2003.13628



$$\lambda_3 = \lambda_{SM}(1 + \delta_3)$$

$$\lambda_4 = \lambda_{SM}(1 + \delta_4)$$

maximal λ_4 (λ_3) sensitivity for M_{HHH} close to threshold [independently of $\sqrt{S_{\mu\mu}}$]

bckgds to VBF → HH at CLIC_3TeV

S/B ~ 1

$\sqrt{s}$ =3 TeV $\mathcal{L} = 5\,\mathrm{ab}^{-1}$

Process	σ/fb	$\epsilon_{\mathrm{tightBDT}}$	N_{tightBDT}
$e^+e^- \to HH\nu\bar{\nu}$	0.59	8.43 %	367
only HH→ $b\bar{b}b\bar{b}$	0.19	26.3 %	361 ←
only HH→ other	0.40	0.2 %	6
$e^+e^- \to q\bar{q}q\bar{q}$	547	0.00033 %	13
$e^+e^- \to q\bar{q}q\bar{q}\nu\bar{\nu}$	72	0.017 %	90
$e^+e^- \to q\bar{q}q\bar{q}l\bar{\nu}$	107	0.0029 %	23
$e^+e^- \to q\bar{q}H\nu\bar{\nu}$	4.7	0.56 %	174 ←
$e^{\pm}\gamma \to \nu q\bar{q}q\bar{q}$	523	0.0014 %	52
$e^{\pm}\gamma \to q\bar{q}H\nu$	116	0.0026 %	21

Roloff at al, arXiv:1901.05897

→ let's assume no bckgr for VBF→HHH

$(N-N_{SM})/\sqrt{N_{SM}} \sim 1$ vs (δ_3, δ_4)

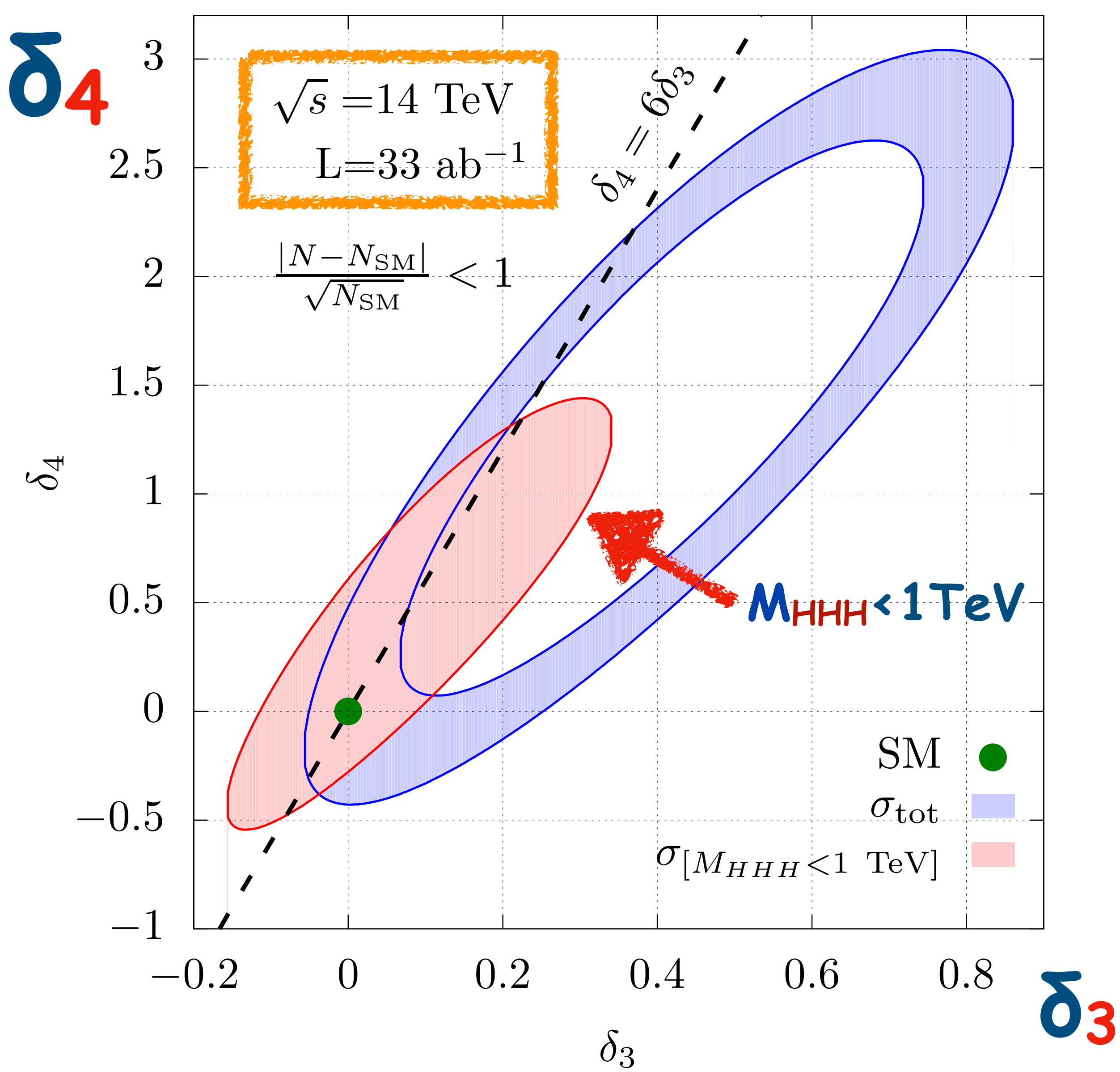
VBF→HHH

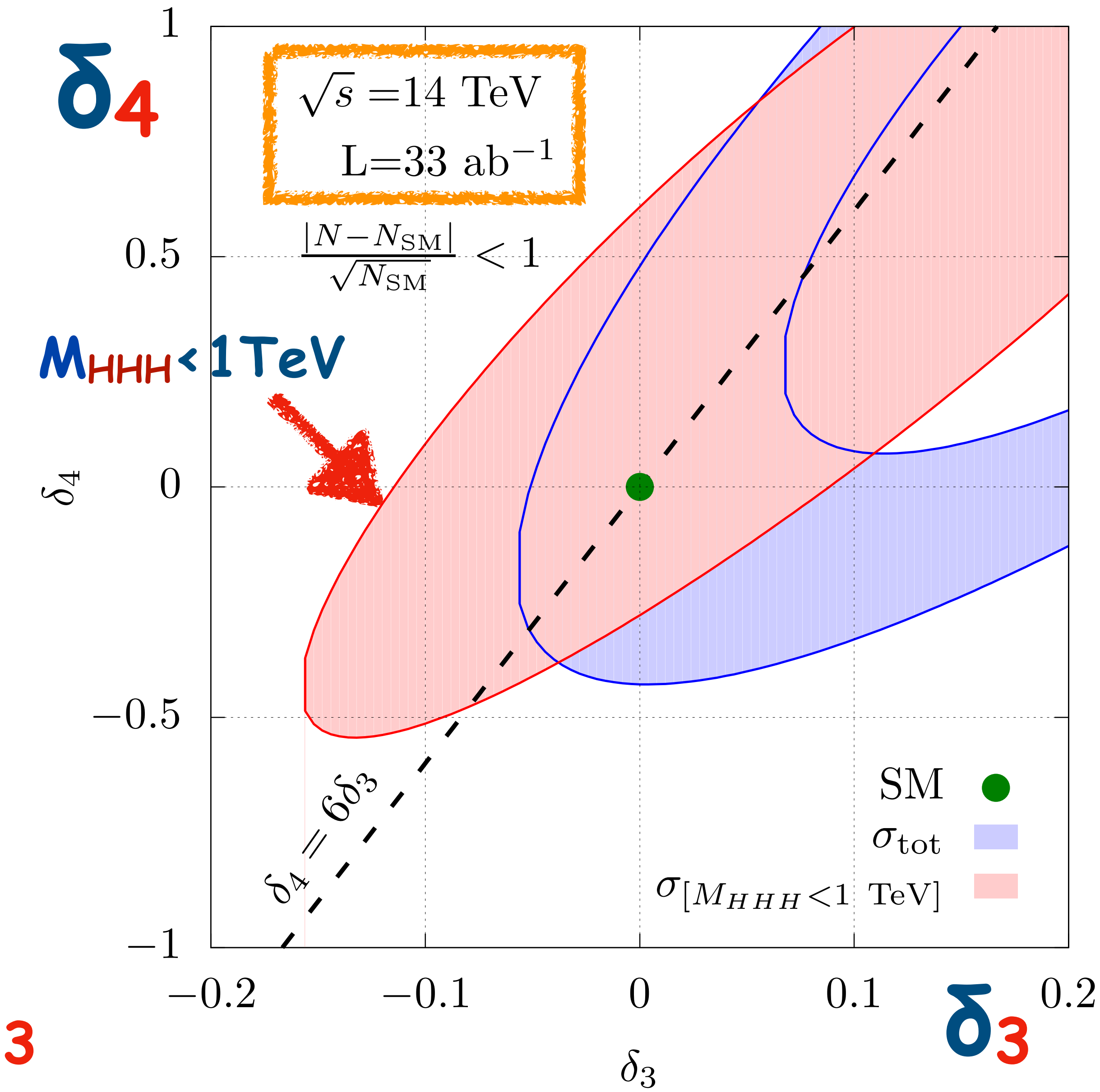
arXiv:2003.13628

$$\lambda_3 = \lambda_{SM}(1+\delta_3)$$

$$\lambda_4 = \lambda_{SM}(1+\delta_4)$$

$\sqrt{S_{\mu\mu}}$ = 14 TeV



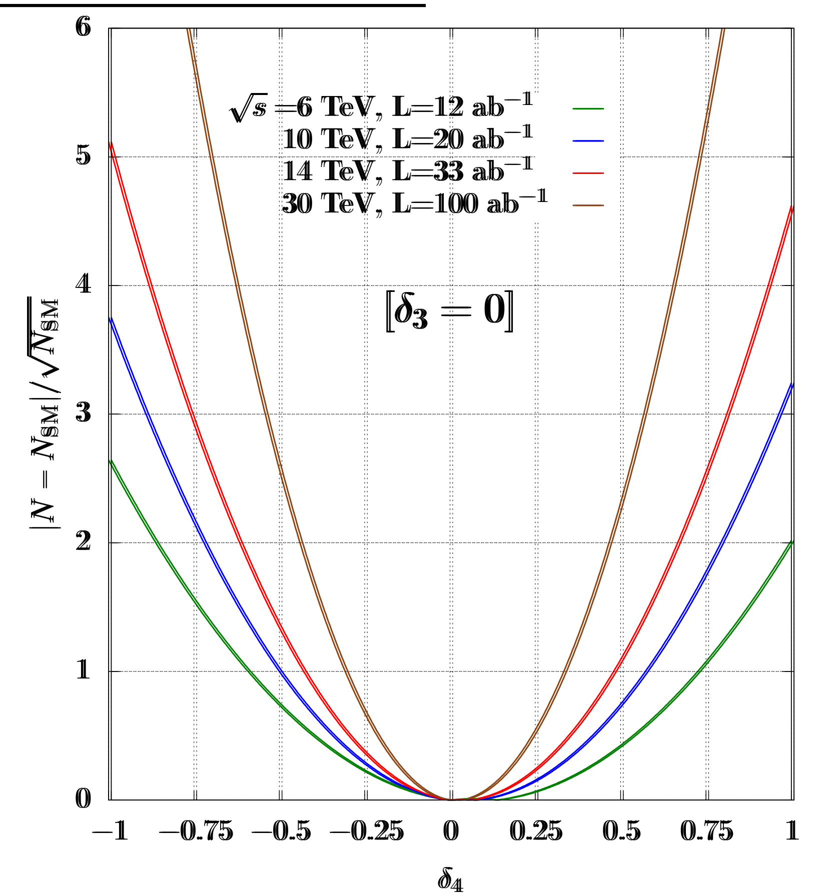


[δ_3=0] -0.3 < δ_4 <0.5 (68%CL) !!!

δ_4 bounds from $\sigma_{HHH(tot)}$ [δ_3=0] vs $\sqrt{S_{\mu\mu}}$

$\sqrt{s}$ (TeV)	Lumi (ab^{-1})	x-sec only 1 σ	x-sec only 2 σ
6	12	$[-0.60, 0.75]$	$[-0.90, 1.00]$
10	20	$[-0.50, 0.55]$	$[-0.70, 0.80]$
14	33	$[-0.45, 0.50]$	$[-0.60, 0.65]$
30	100	$[-0.30, 0.35]$	$[-0.45, 0.45]$
3	100	$[-0.35, 0.60]$	$[-0.50, 0.80]$

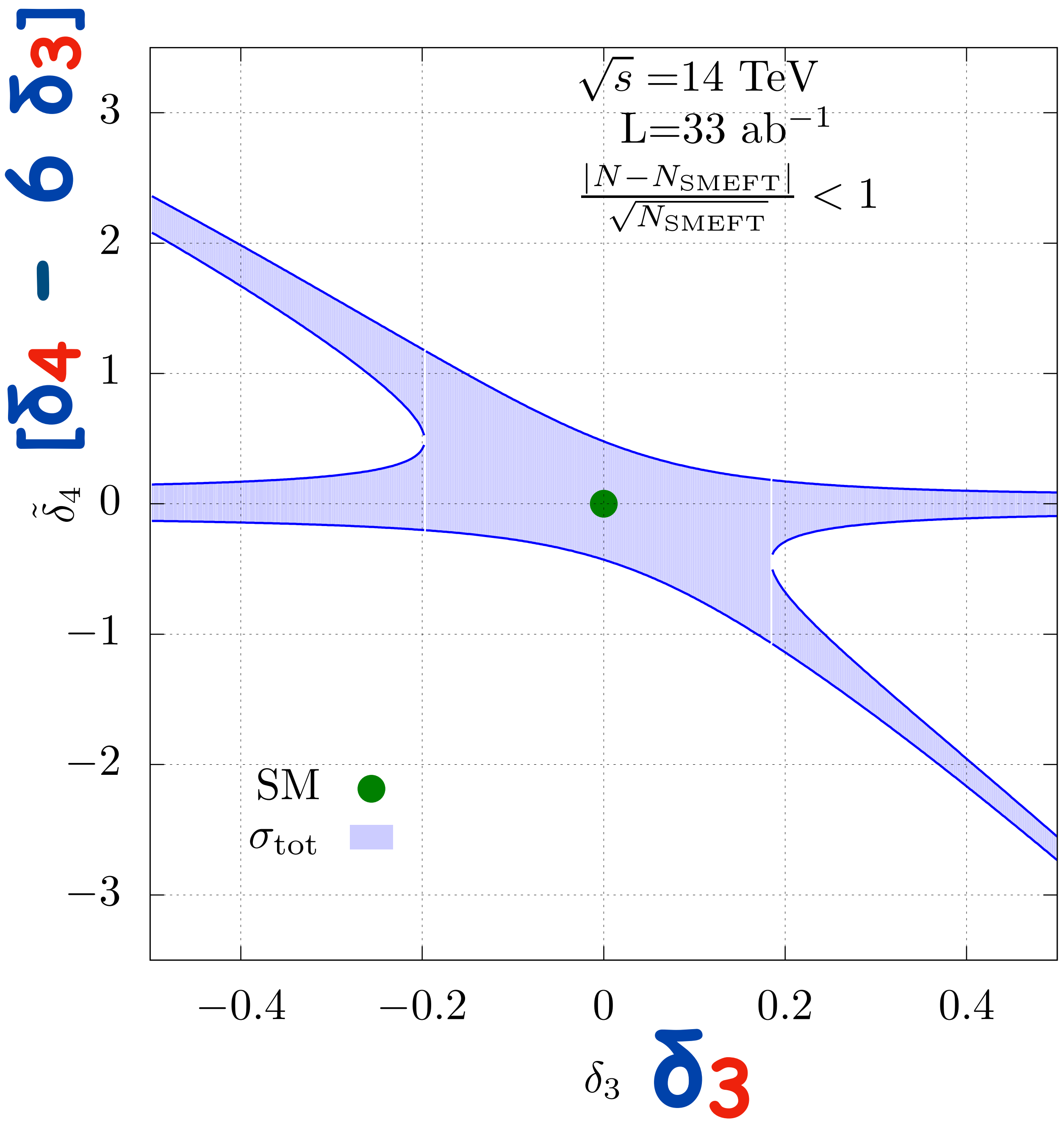
~20 x $L_{(CLIC)}$!!

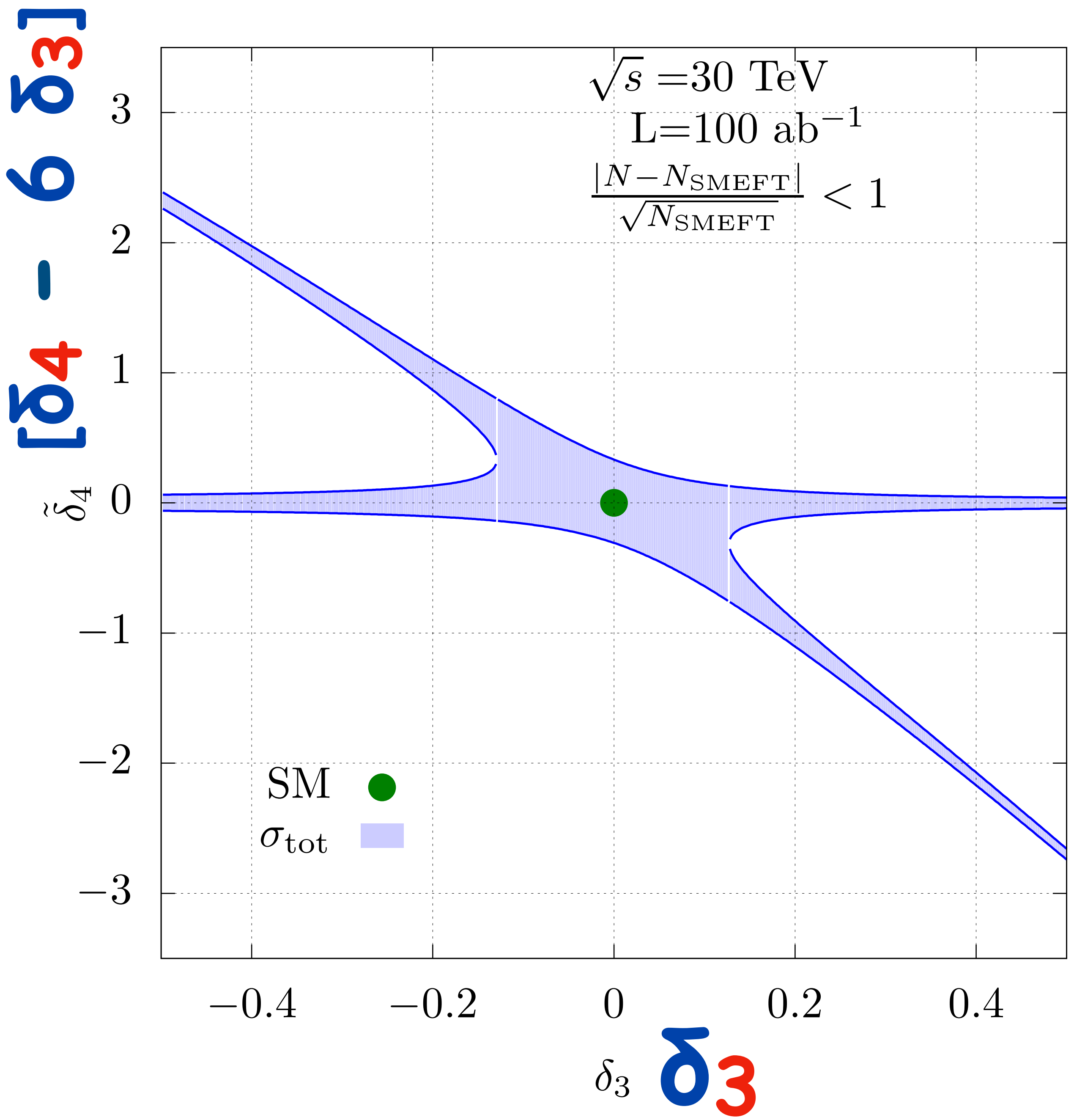


- full HHH statistics
- no background
- no optimization from kinem. features of (δ_3,δ_4)-depending sub-amplitudes

for $\delta_3 \neq 0$, can constrain deviations from SMEFT configuration $[\delta_4 \sim 6\,\delta_3]$

$$|N(\delta_3, \tilde{\delta}_4 + 6\delta_3) - N(\delta_3, 6\delta_3)| / \sqrt{N(\delta_3, 6\delta_3)} < 1$$

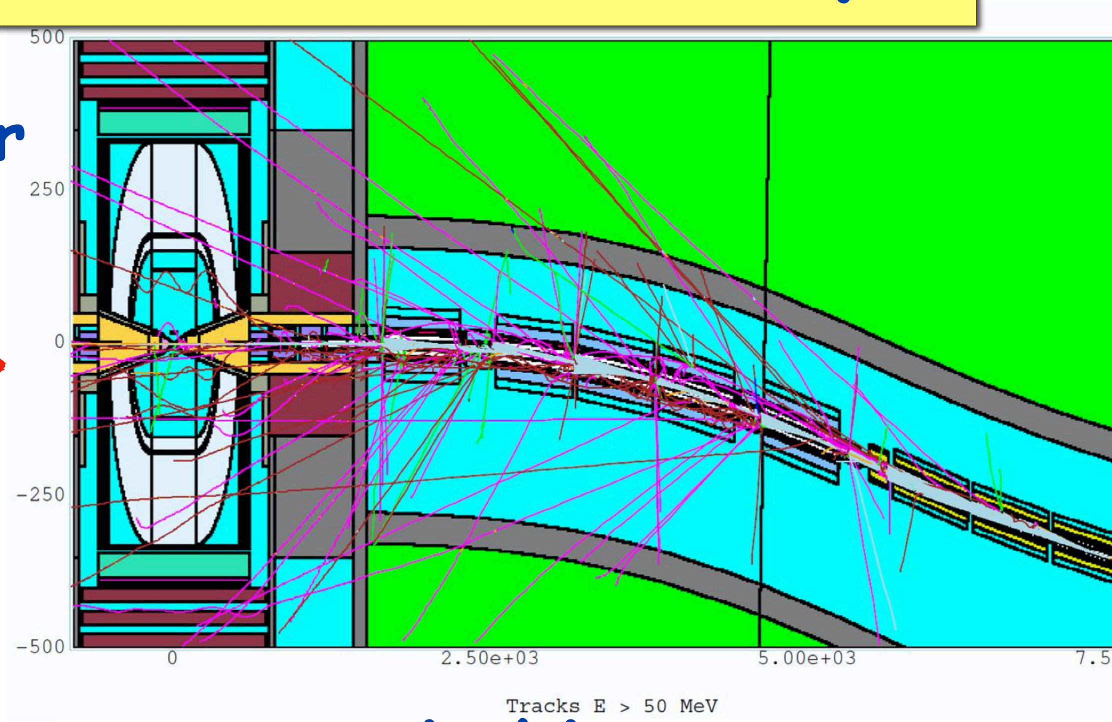




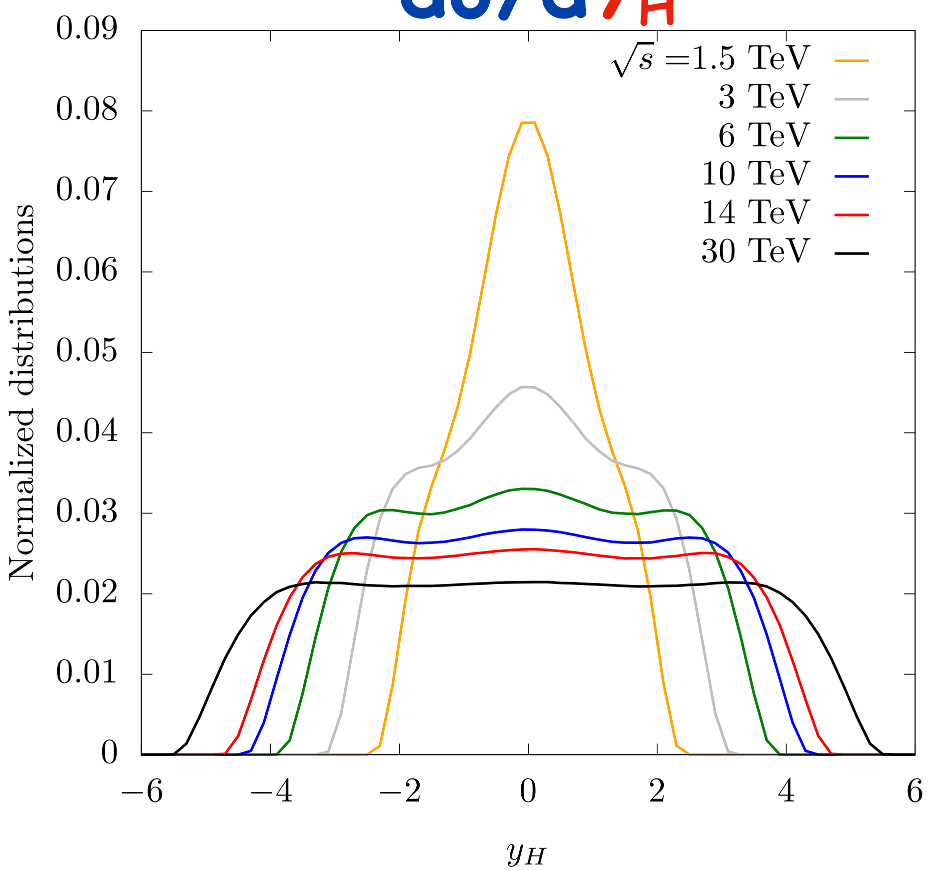
Beam Induced Bckgr (BIB) from muons' decay

two tungsten nozzles can mitigate BIB in detector
→ → reduced acceptance in forward regions

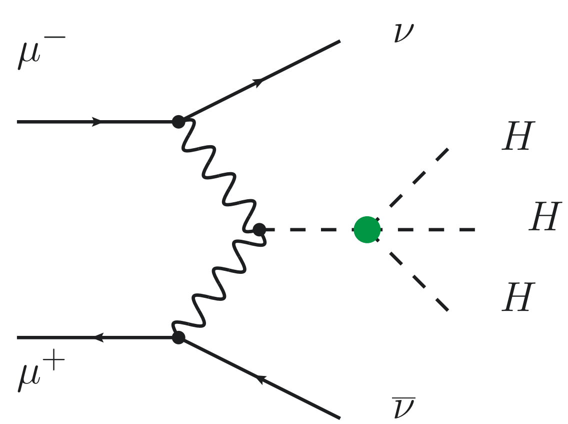
(MAP studies at $\sqrt{S_{\mu\mu}}$~1.5 TeV
+ recent studies in IMCC)



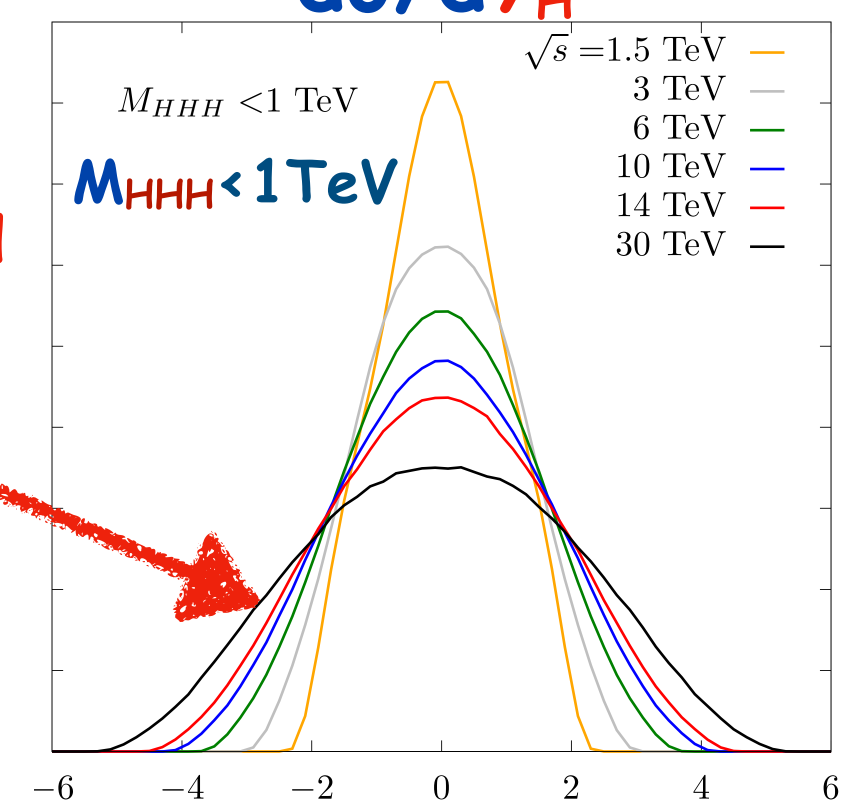
$d\sigma/dy_H$



δ_4 sensitivity enhanced for M_{HHH}<1TeV where final p.les are more centrally produced



$d\sigma/dy_H$



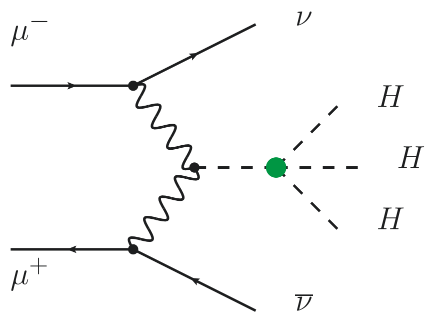
→→ cutting off small angles could increase sensitivity !

δ_4 bounds [δ_3=0] → σ_{tot} vs $\sigma_{[reduced\ accept.]}$

$\sqrt{s}$ (TeV)	Lumi (ab^{-1})	x-sec [tot] 1 σ	p_T >20 GeV, $\lvert\eta\rvert < 3$ 1 σ
6	12	$[-0.60, 0.75]$	$[-0.50, 0.70]$
10	20	$[-0.50, 0.55]$	$[-0.37, 0.54]$
14	33	$[-0.45, 0.50]$	$[-0.28, 0.43]$
30	100	$[-0.30, 0.35]$	$[-0.15, 0.30]$
3	100	$[-0.35, 0.60]$	$[-0.34, 0.64]$

δ_4

* geometrical selection on H → bb decay products
  (in principle inclusive on H → bb,cc,gg,ττ...) → no BR applied
* killing acceptance in forward regions increases sensitivity !

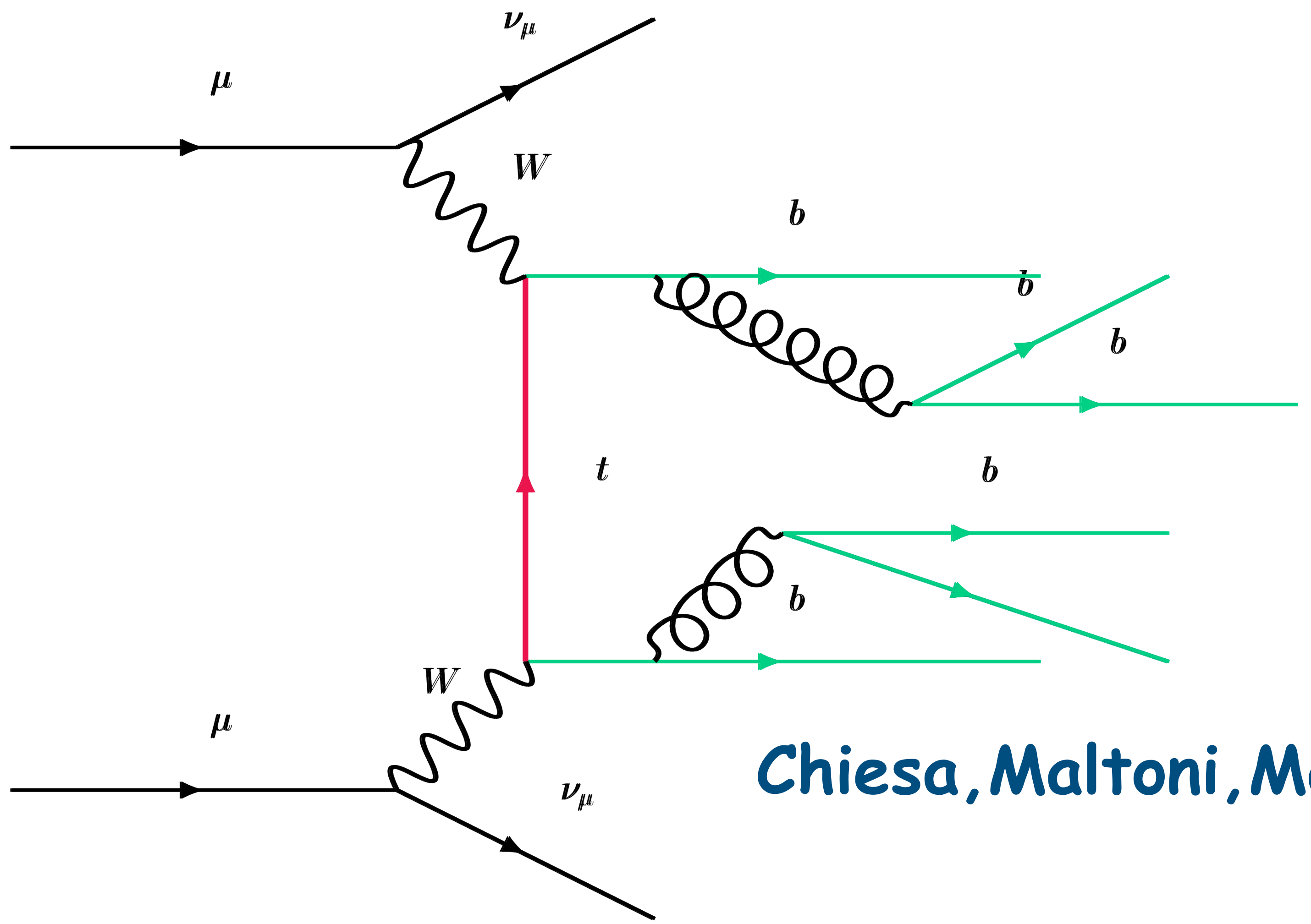


relative weight increases !

self-coupling measurement robust against beam-induced bckgr effects !!!

"Physics" bckgds to VBF → HHH

- all HHH decay modes with sizeble BR's are relevant !
- 8-body final states (at least !)
  → hard in general to evaluate via MC's
- 6b-jet bckgr moderate at FCC-hh [arXiv:1801.10157]
- might be S/B > 1 at multi-TeV muon colliders... → →



Chiesa, Maltoni, Mantani, BM, Moretti, Piccinini, Zhao
(in progress)

VBF → HHH background estimate [with b-tagging]

$$\mu^+\mu^- \to HHb\bar{b}\nu\bar{\nu}$$

→ Madgraph or Whizard (with on-shell H decay)

$$\mu^+\mu^- \to Hb\bar{b}b\bar{b}\nu\bar{\nu}$$

→ Madgraph or Whizard (?)

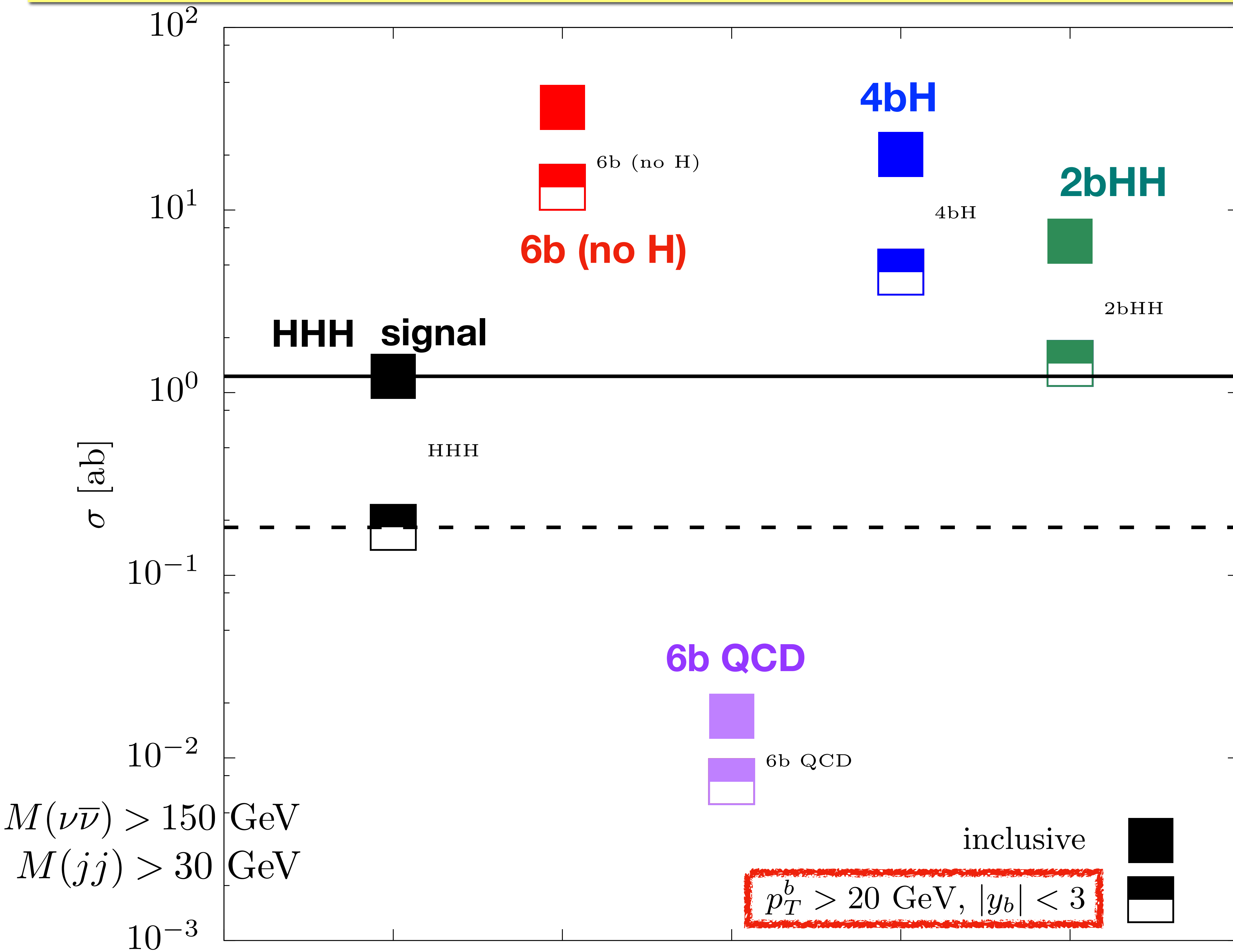
$$\mu^+\mu^- \to b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$$

(????)

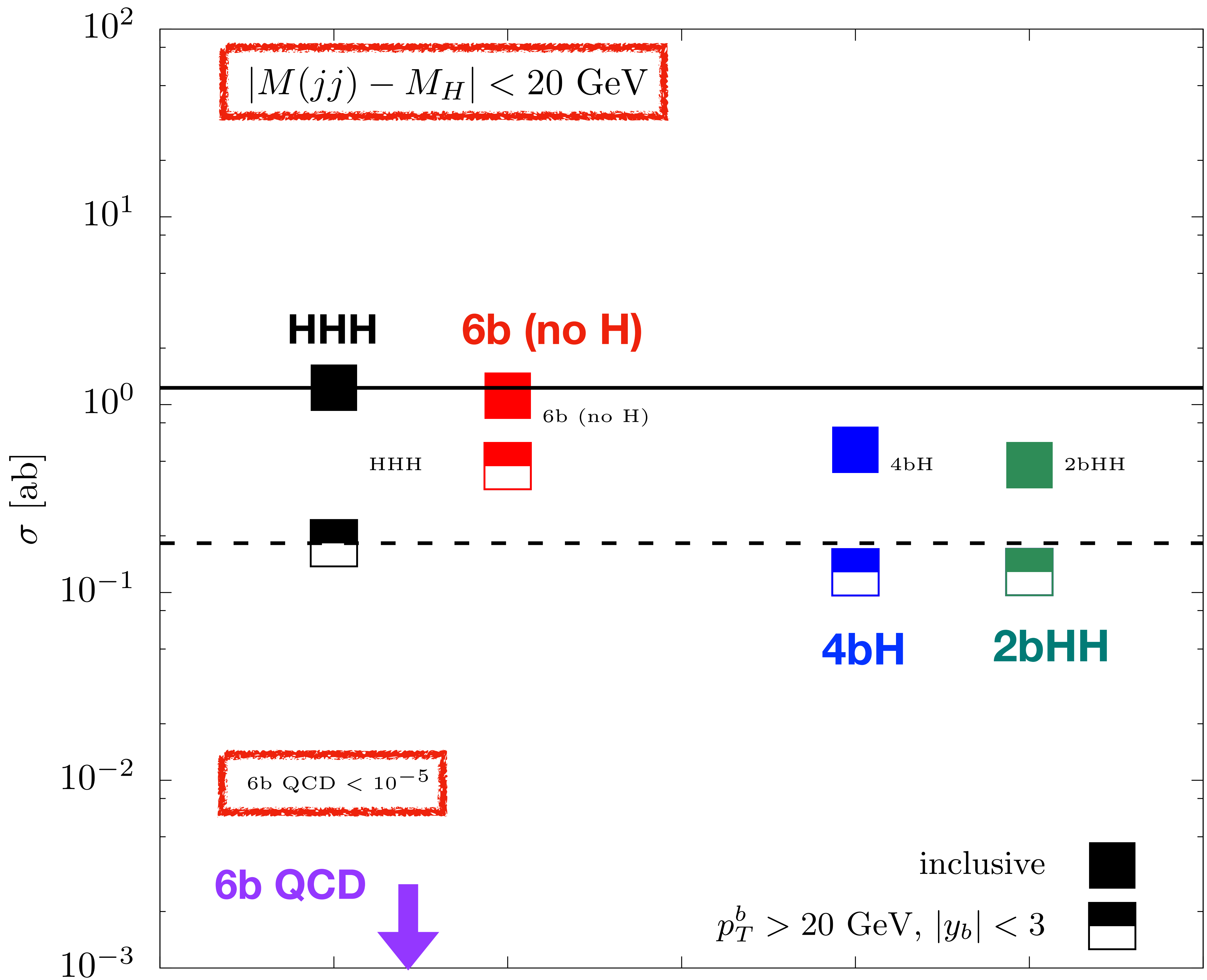
→ private version of Alpgen

* in HHH signal $BR_{(bb)}^3 \sim 1/5$ suppression !

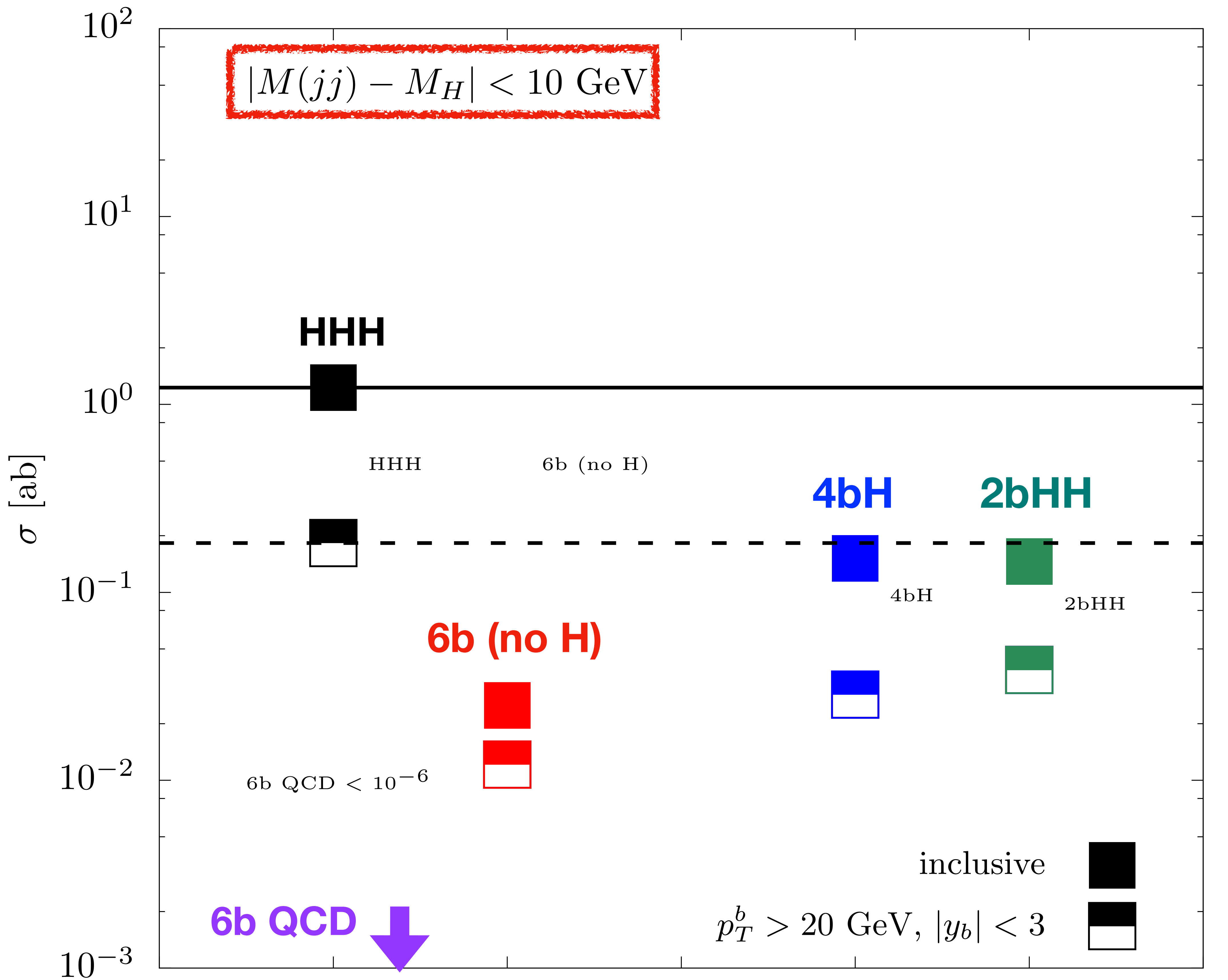
$\sqrt{S}_{\mu\mu}$ =14TeV (without m_H reconstruction)



with m_H reconstruction (20GeV)



with m_H reconstruction (10GeV)



no b-tagging (HHH → 6jets signal)

$\mu^+\mu^- \to t\bar{t}\nu\bar{\nu}$, with $t \to bW$ and $W \to jj$

$\mu^+\mu^- \to WWZ\nu\bar{\nu}$, if $W \to jj$ and $Z \to jj$

$\mu^+\mu^- \to WWH\nu\bar{\nu}$, if $W \to jj$ and $H \to jj$

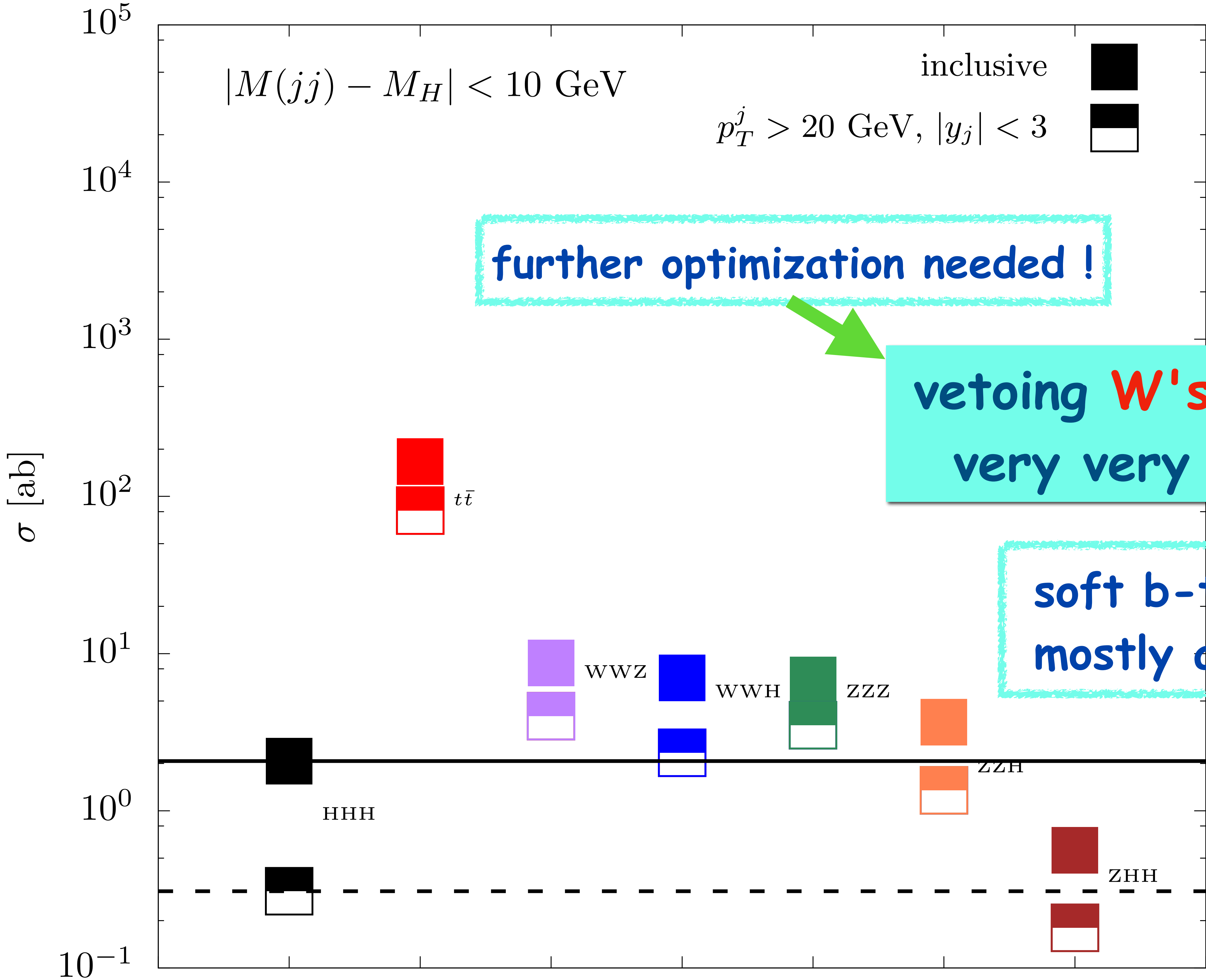
$\mu^+\mu^- \to ZZZ\nu\bar{\nu}$, if $Z \to jj$

$\mu^+\mu^- \to ZZH\nu\bar{\nu}$, if $Z \to jj$ and $H \to jj$

$\mu^+\mu^- \to ZHH\nu\bar{\nu}$, if $Z \to jj$ and $H \to jj$

* Madgraph or Whizard can make it (narrow width approx.)

BR($H \to jj$)^3 ~ 1/3



further optimization needed !

vetoing **W's** and/or **Z's** very very efficient !

soft b-tagging ?
mostly affects bckgr…

outlook

* testing Higgs potential via Higgs self-coupling measurement of paramount importance !
* triple Higgs production only direct access to quartic self-coupling
* projections at FCC-hh can give few-% accuracy on λ_3 but only mild bounds on λ_4 ($\delta\lambda_4/\lambda_4 \sim 10$) at present
* first indications that μ colliders @10+TeV with $L \sim 10^{35} cm^{-2} s^{-1}$ might provide a λ_4 determination with few-10% accuracy ($\delta\lambda_4/\lambda_4 \sim 1$)
  → → significantly better that other future projects !
* physics bckgds expected mild (also for hadronic final states) → preliminary detailed simulations confirm !
  optimal bckgd suppression requires good resolution in M(jj) reconstruction !