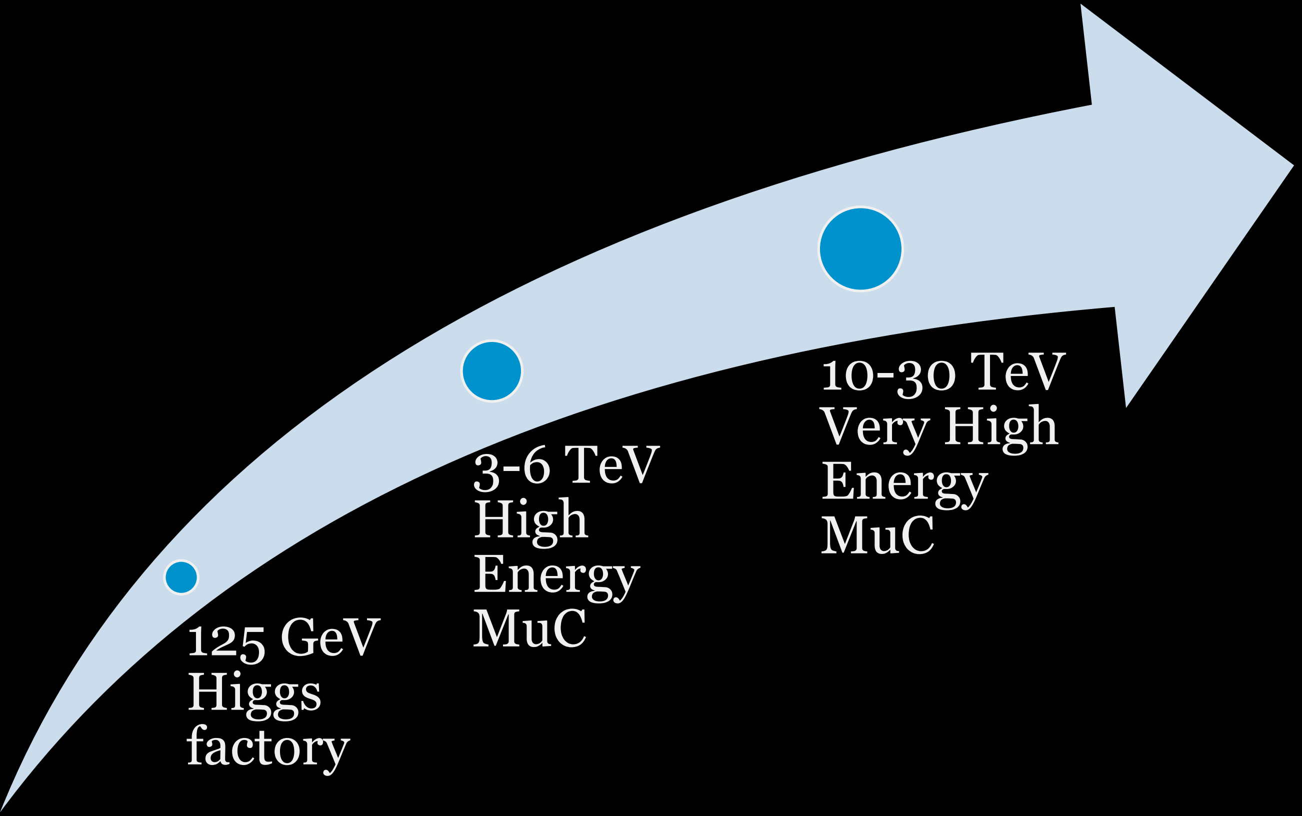
LPC Topic Of The Week (TOTW)

Physics Prospects at Muon Colliders

Zhen Liu
University of Maryland

07/14/2020

The Dream Machine

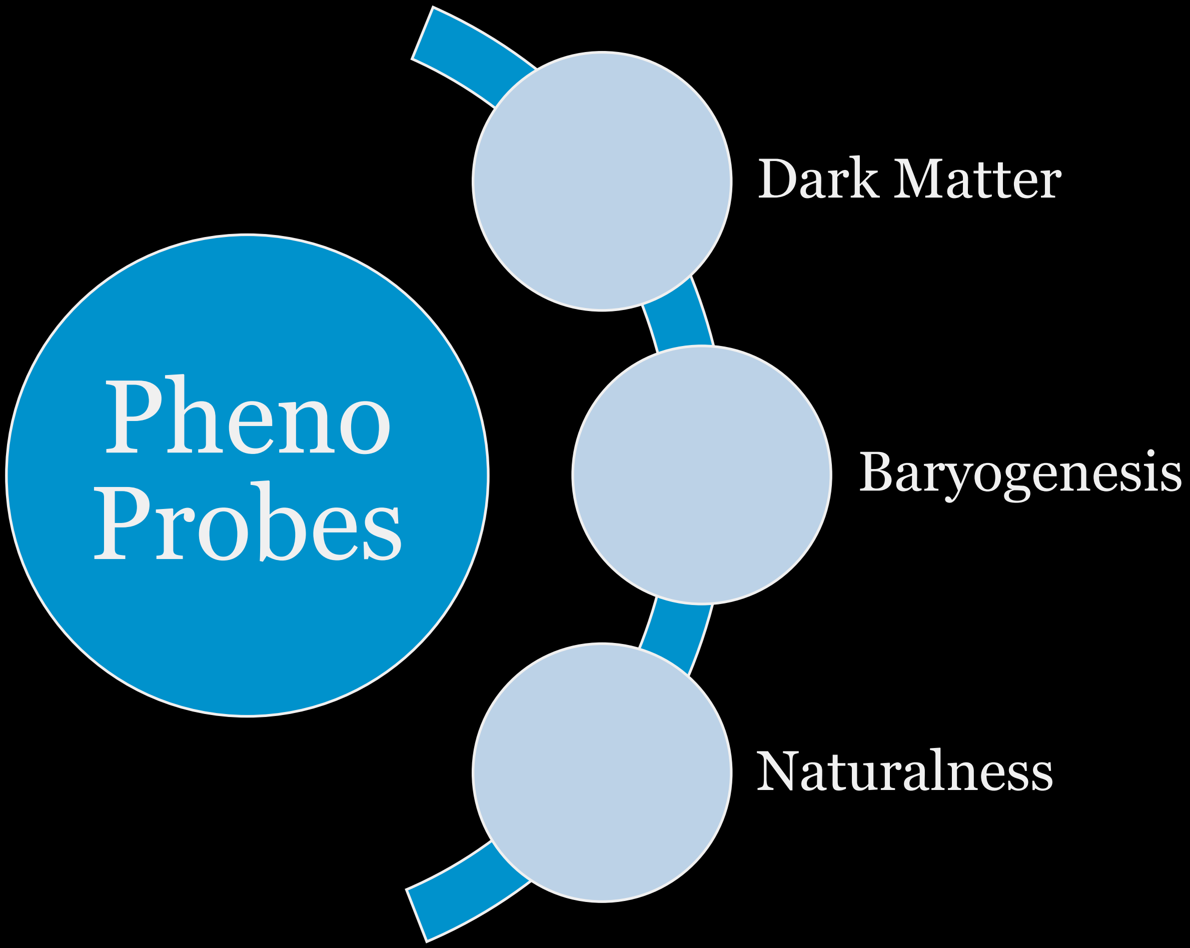


125 GeV
Higgs
factory

3-6 TeV
High
Energy
MuC

10-30 TeV
Very High
Energy
MuC

Physics Driver



Pheno
Probes

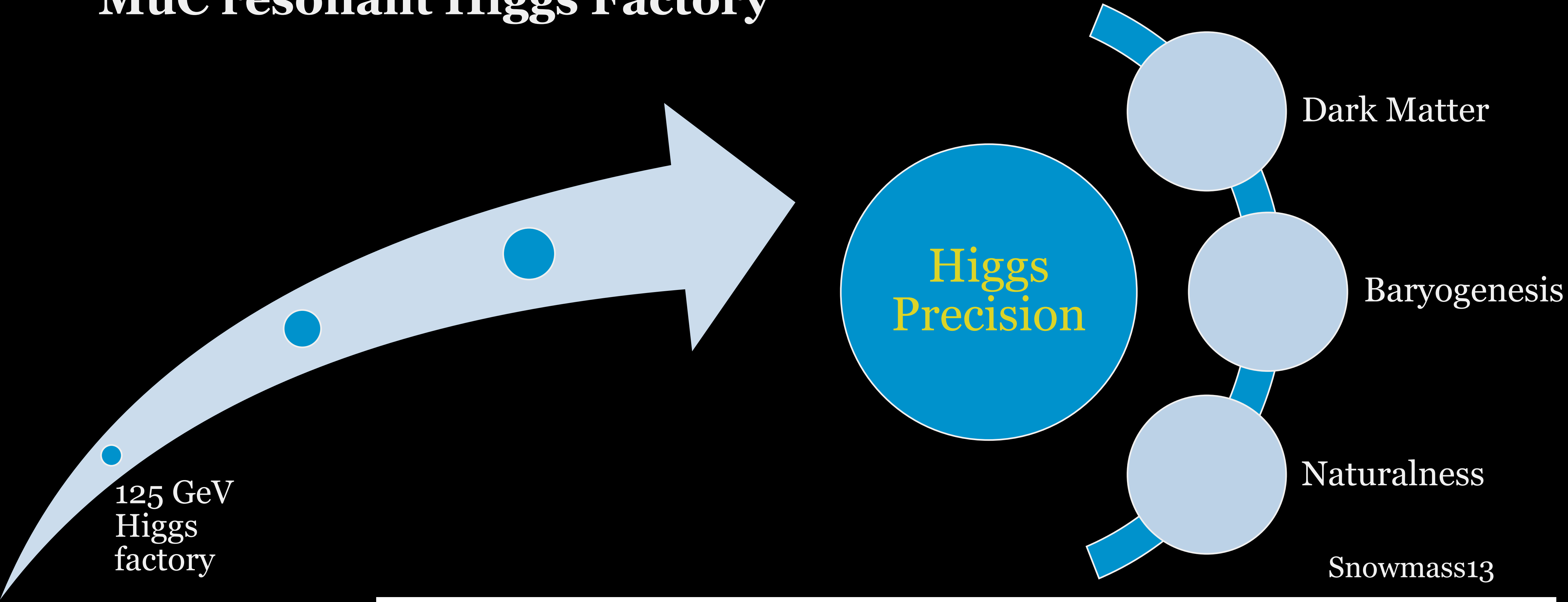
Dark Matter

Baryogenesis

Naturalness

We shall be open to new theory paradigm shift, and experimental new physics discoveries (cannot rely on that happening, though)

MuC resonant Higgs Factory



125 GeV Higgs factory

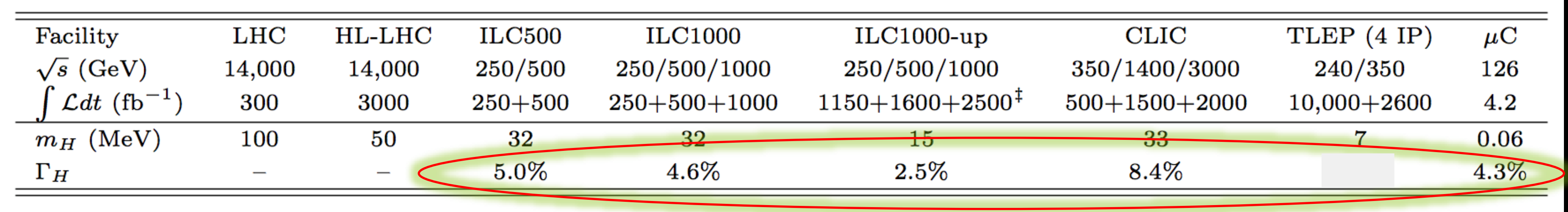
Higgs Precision

Dark Matter

Baryogenesis

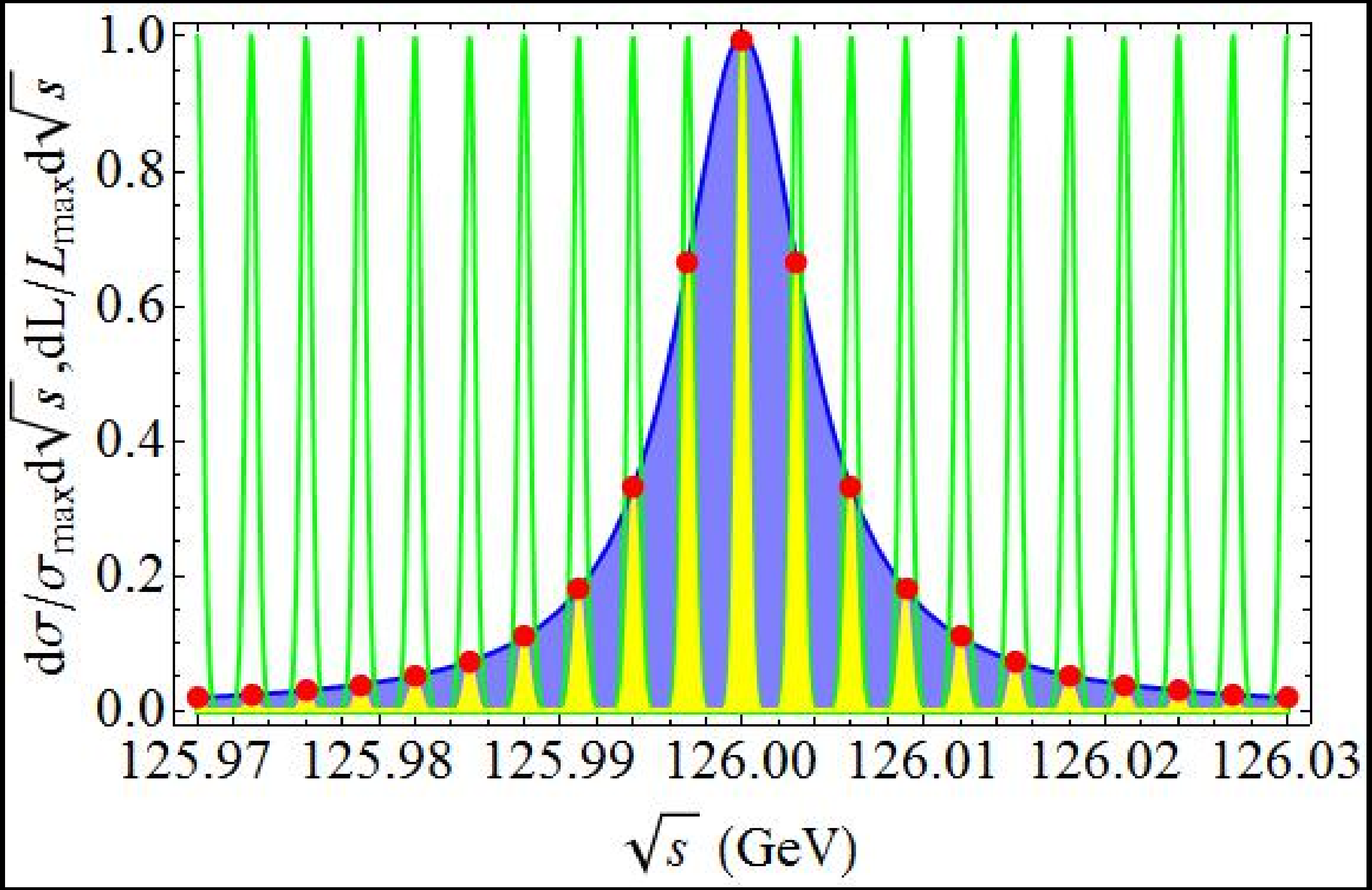
Naturalness

Snowmass13



Facility	LHC	HL-LHC	ILC500	ILC1000	ILC1000-up	CLIC	TLEP (4 IP)	μC
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350	126
$\int \mathcal{L}dt$ (fb^{-1})	300	3000	250+500	250+500+1000	1150+1600+2500‡	500+1500+2000	10,000+2600	4.2
m_H (MeV)	100	50	32	32	15	33	7	0.06
Γ_H	–	–	5.0%	4.6%	2.5%	8.4%	[redacted]	4.3%

Extreme (good) Case:



Energy Spread much narrower than the physical width:

$\Delta = 0.3$ MeV

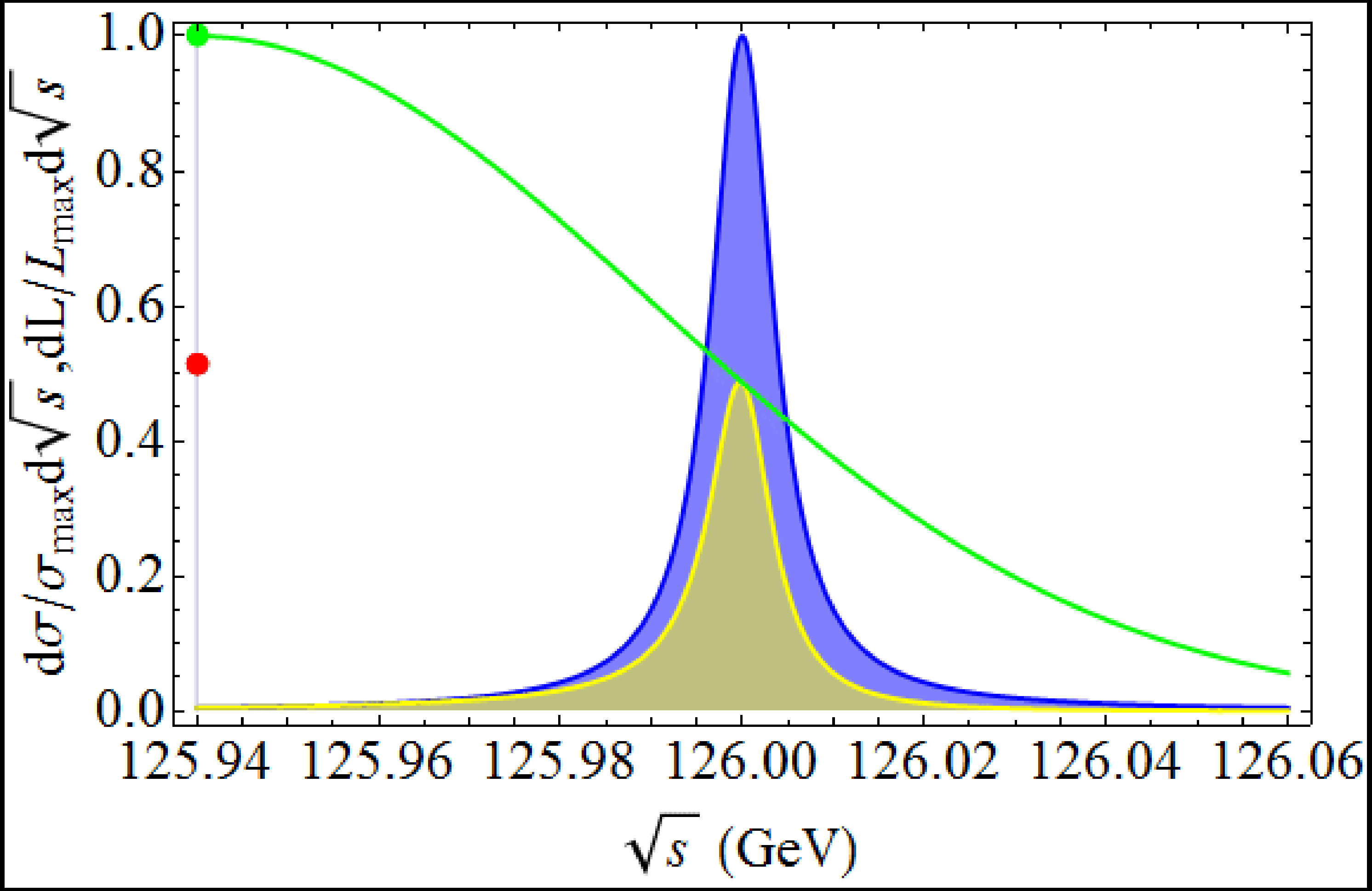
$\Gamma_h = 4.2$ MeV

Breit-Wigner
Gaussian Profile (beam)
Overlap (observable rate)
Effective cross section (observable scan)

Recall: Z scan @LEP

$\Gamma = 2.5$ GeV

Extreme (bad) Case:



Energy Spread much broader than the physical width:

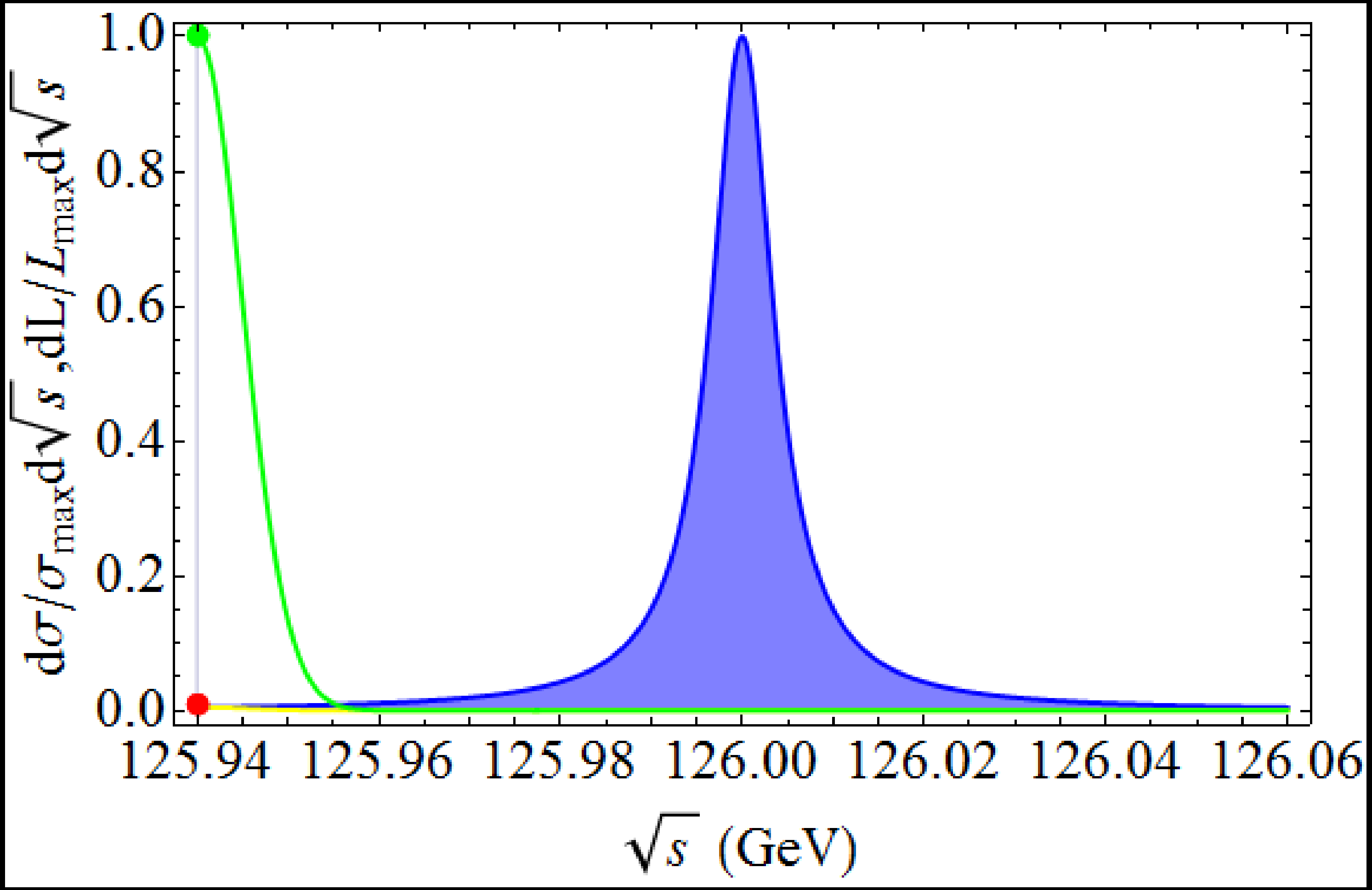
$\Delta = 50$ MeV

$\Gamma_h = 4.2$ MeV

Breit-Wigner
Gaussian Profile (beam)
Overlap (observable rate)
Effective cross section
(observable scan)

Recall: J/ψ scan $\Gamma \approx 93$ keV

Normal "Ideal" Case:



Energy Spread comparable to the physical width:

$\Delta = 5$ MeV

(R=0.003%)

$\Gamma_h = 4.2$ MeV

Breit-Wigner

Gaussian Profile (beam)

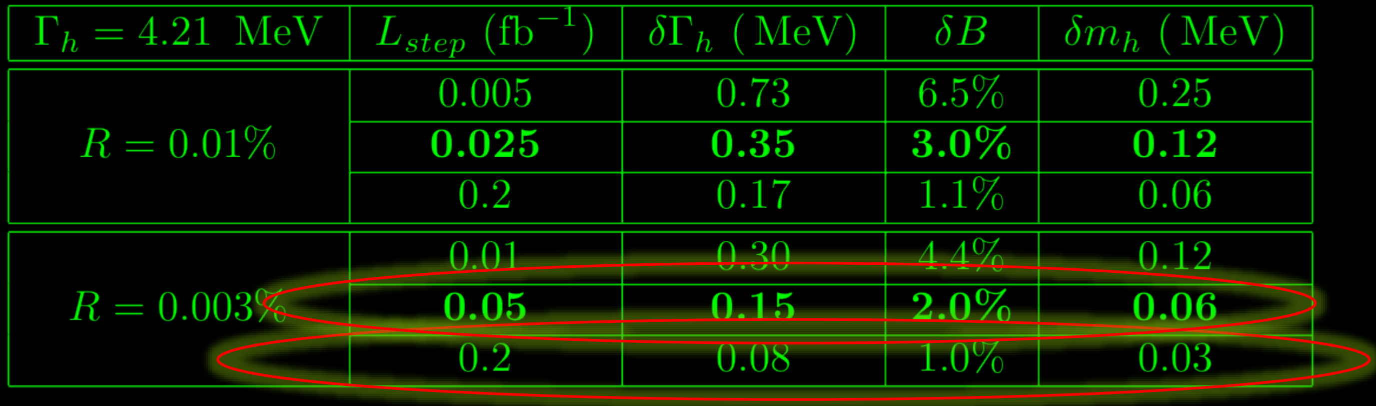
Overlap (observable rate)

Effective cross section (observable scan)

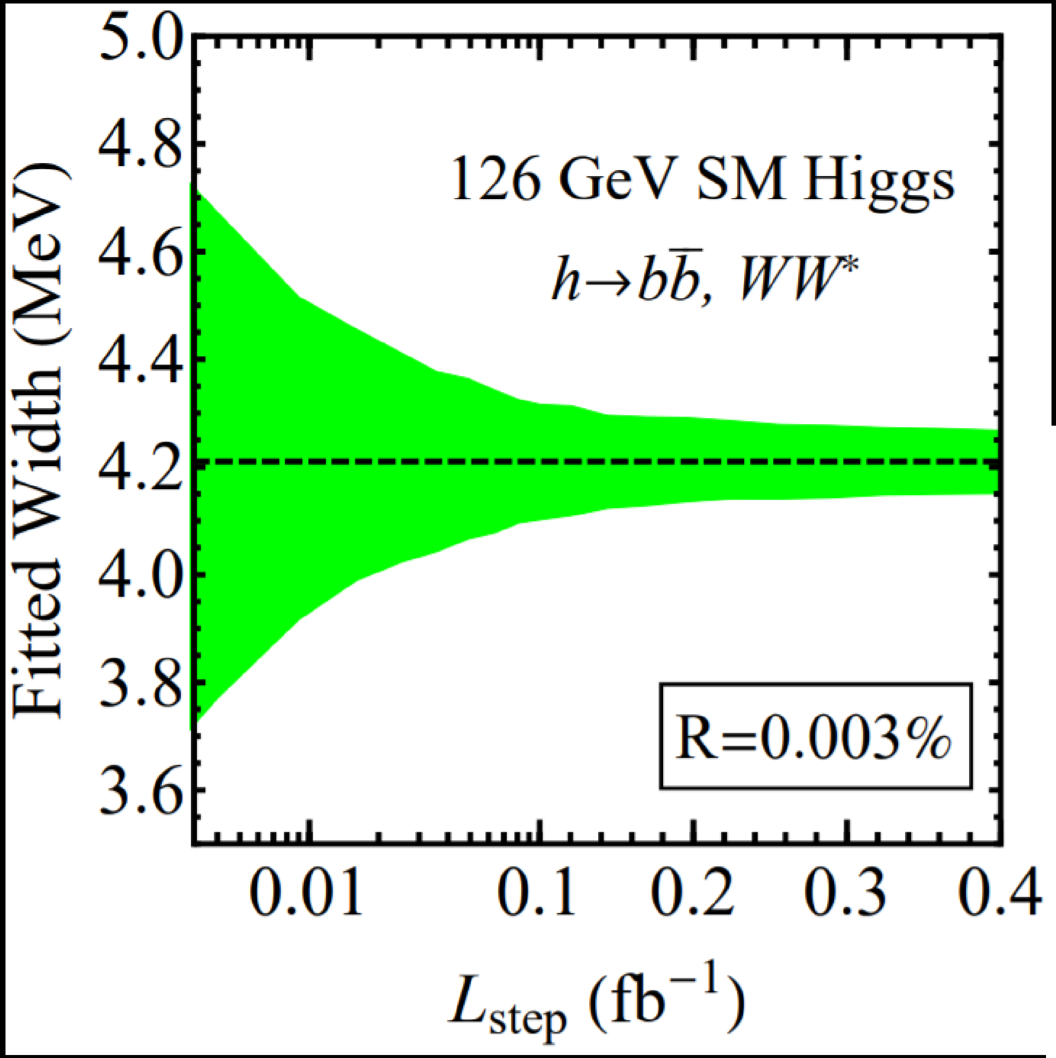
An optimal fitting would reveal Γ_h

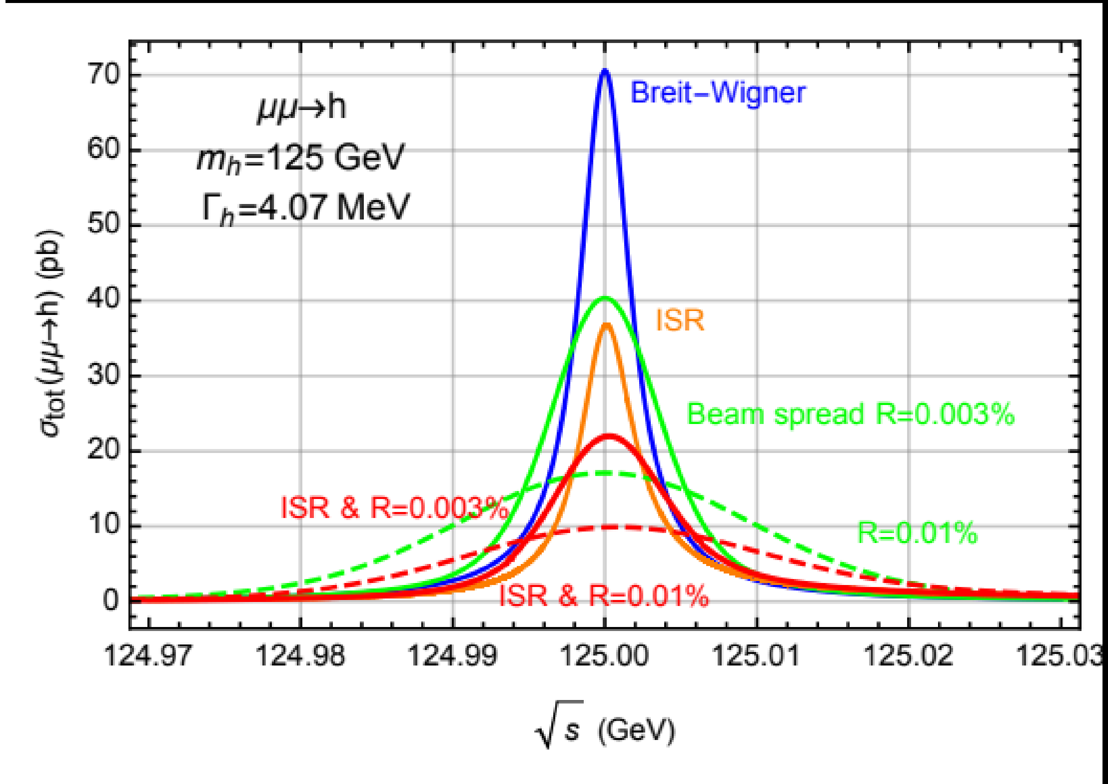
Fitting the **SM** Higgs

Han, ZL, 1210.7803; also see Conway, Wenzel 1304.5270



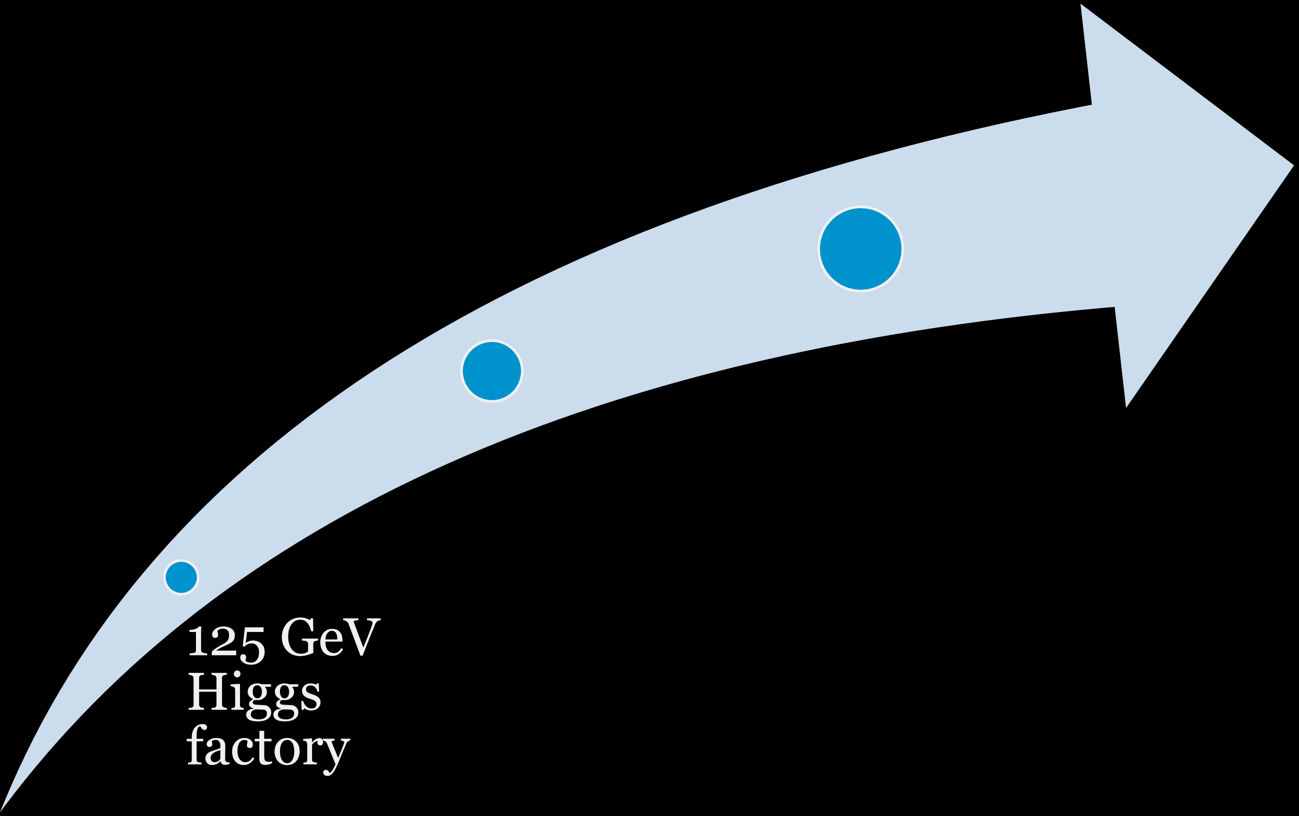
$\Gamma_h = 4.21$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	δm_h (MeV)
$R = 0.01\%$	0.005	0.73	6.5%	0.25
	0.025	**0.35**	**3.0%**	**0.12**
	0.2	0.17	1.1%	0.06
$R = 0.003\%$	0.01	0.30	4.4%	0.12
	0.05	**0.15**	**2.0%**	**0.06**
	0.2	0.08	1.0%	0.03





Greco, Han, ZL,
1607.03210
Resolving
interferences,
ZL, et al,
arXiv:1308.2143

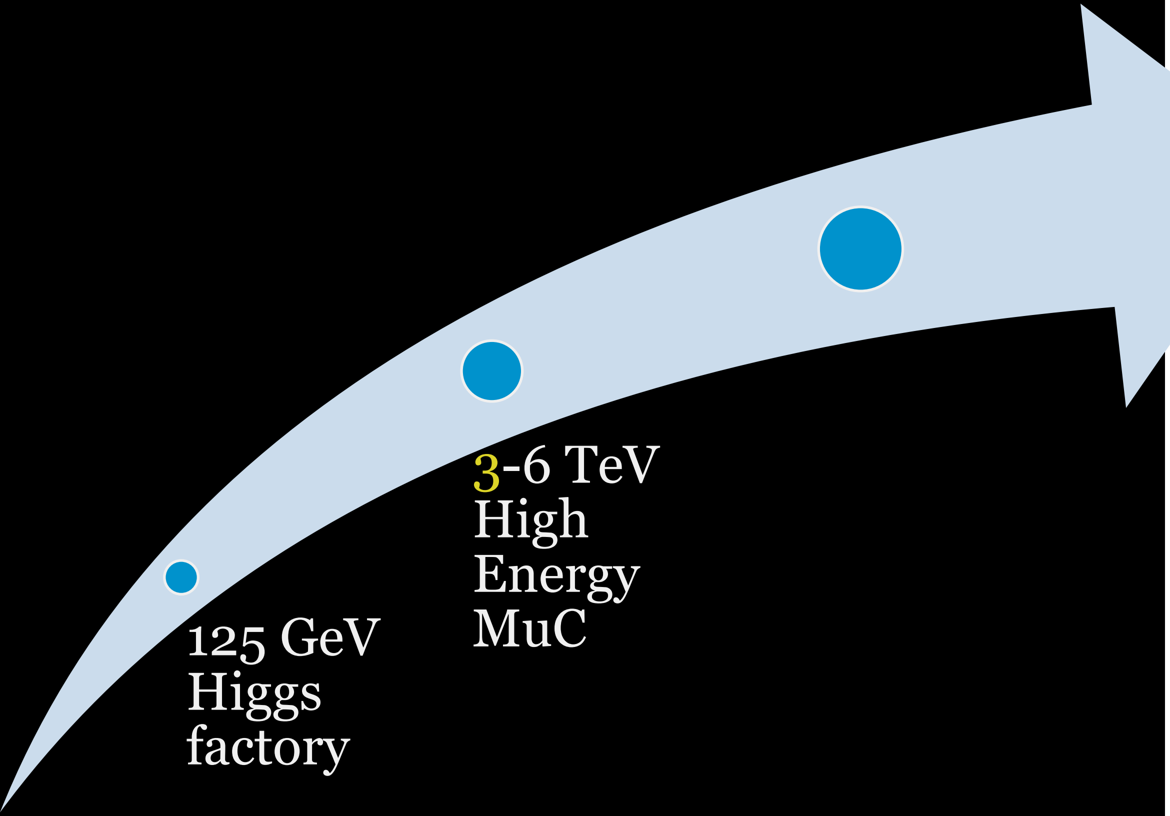
MuC resonant Higgs Factory Summary



- Unique Width determination method
  - similar precision as other lepton colliders, due to various reasons
- Uniquely great sensitivity to muonic Yukawa, at least 10 times better than any other Higgs factories
  - it would be very interesting if muonic anomalies continues, g-2, B meson, ~~muonic atom~~, etc.
  - No competitors
- Utlra-precise determination of Higgs mass
  - Associated challenge of finding the resonance
  - Resolve degenerate Higgs
  - No competitors (but it seems we do not need it now)
- 10 times less Higgs than other lepton colliders
  - Higgs coupling precision slightly less impressive
  - Do not worry about basis, EFT, kappa, etc.

3 TeV Muon Collider: dance with shackles

2013 Benchmark



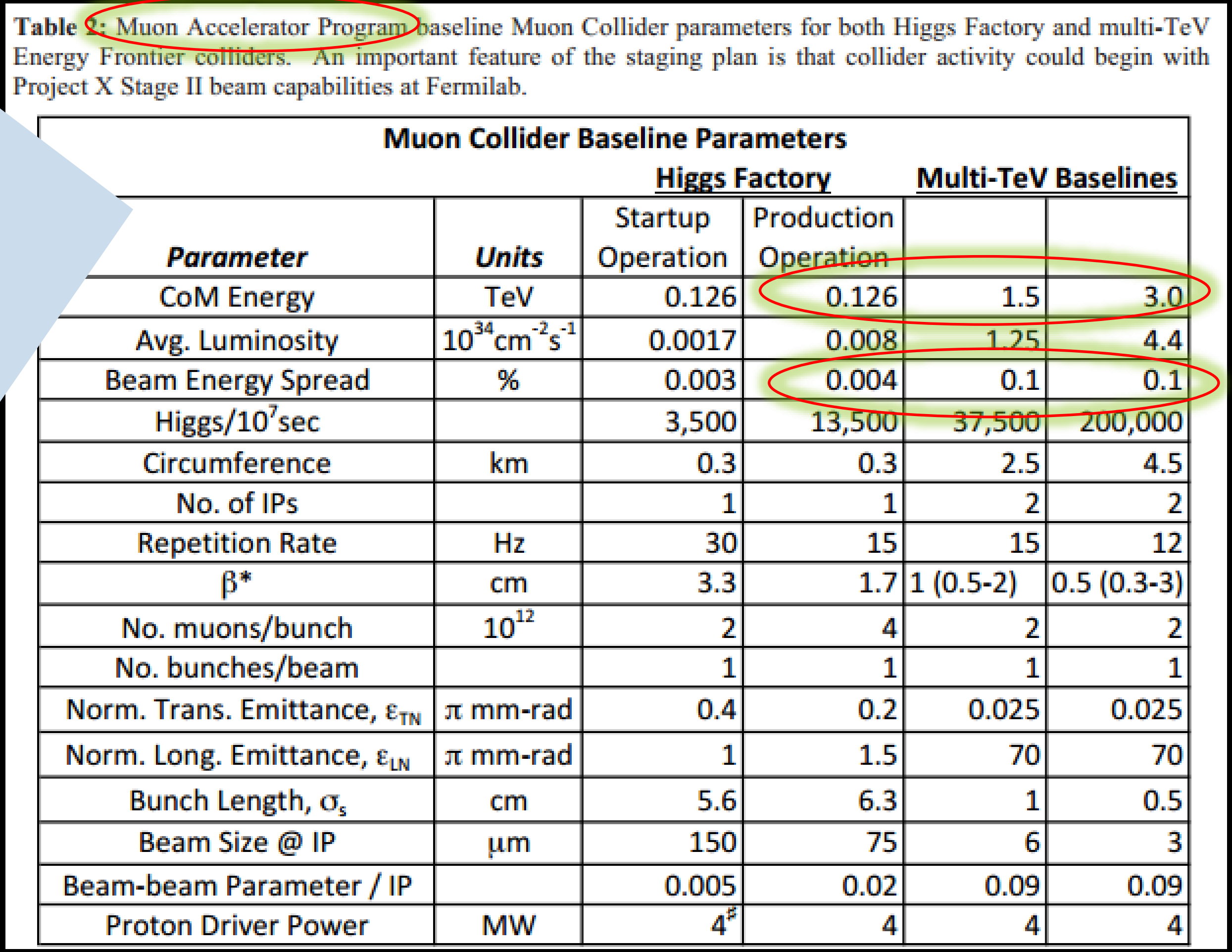


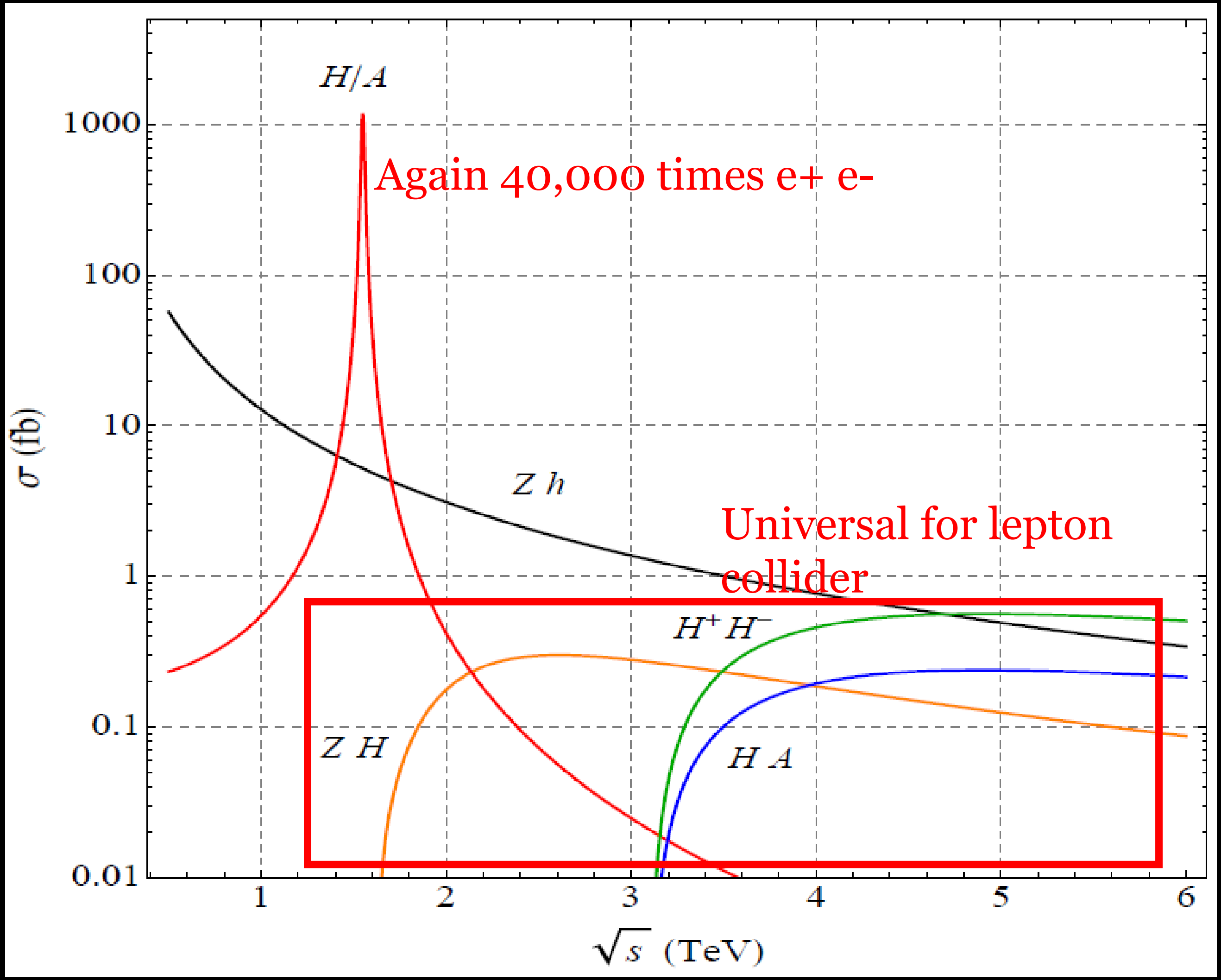
Table 2: Muon Accelerator Program baseline Muon Collider parameters for both Higgs Factory and multi-TeV Energy Frontier colliders. An important feature of the staging plan is that collider activity could begin with Project X Stage II beam capabilities at Fermilab.

Muon Collider Baseline Parameters

		Higgs Factory		**Multi-TeV Baselines**	
Parameter	***Units***	Startup Operation	Production Operation		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	$4^{\sharp}$	4	4	4

Exactly the same physics motivation as 3 TeV CLIC, with somewhat less luminosity and less technological maturity

Focused on something unique

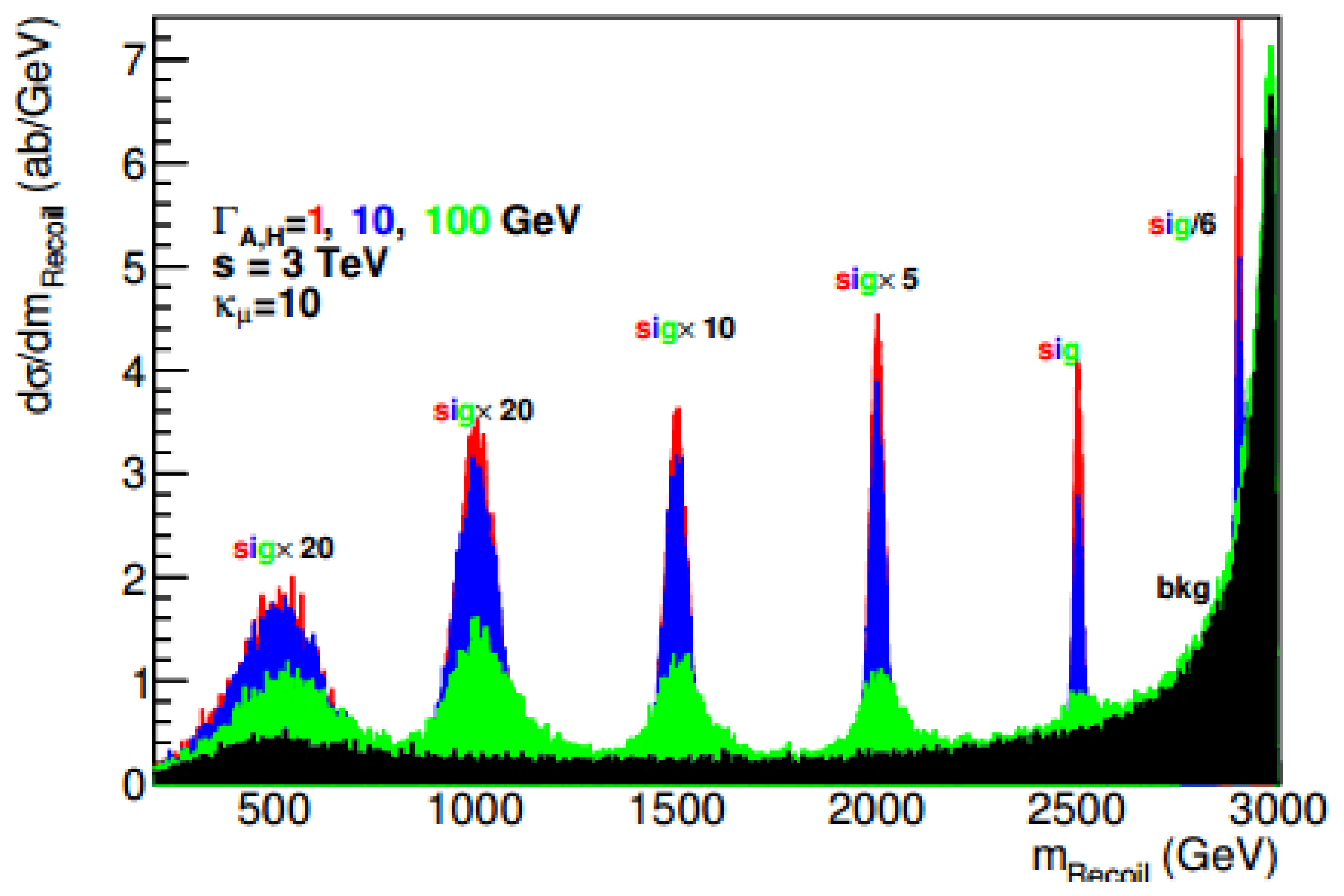


Again 40,000 times e+ e-

Universal for lepton collider

E. Eichten and A. Martin
arxiv: 1306.2609

Focused on something unique



MG5+Pythia+smearing

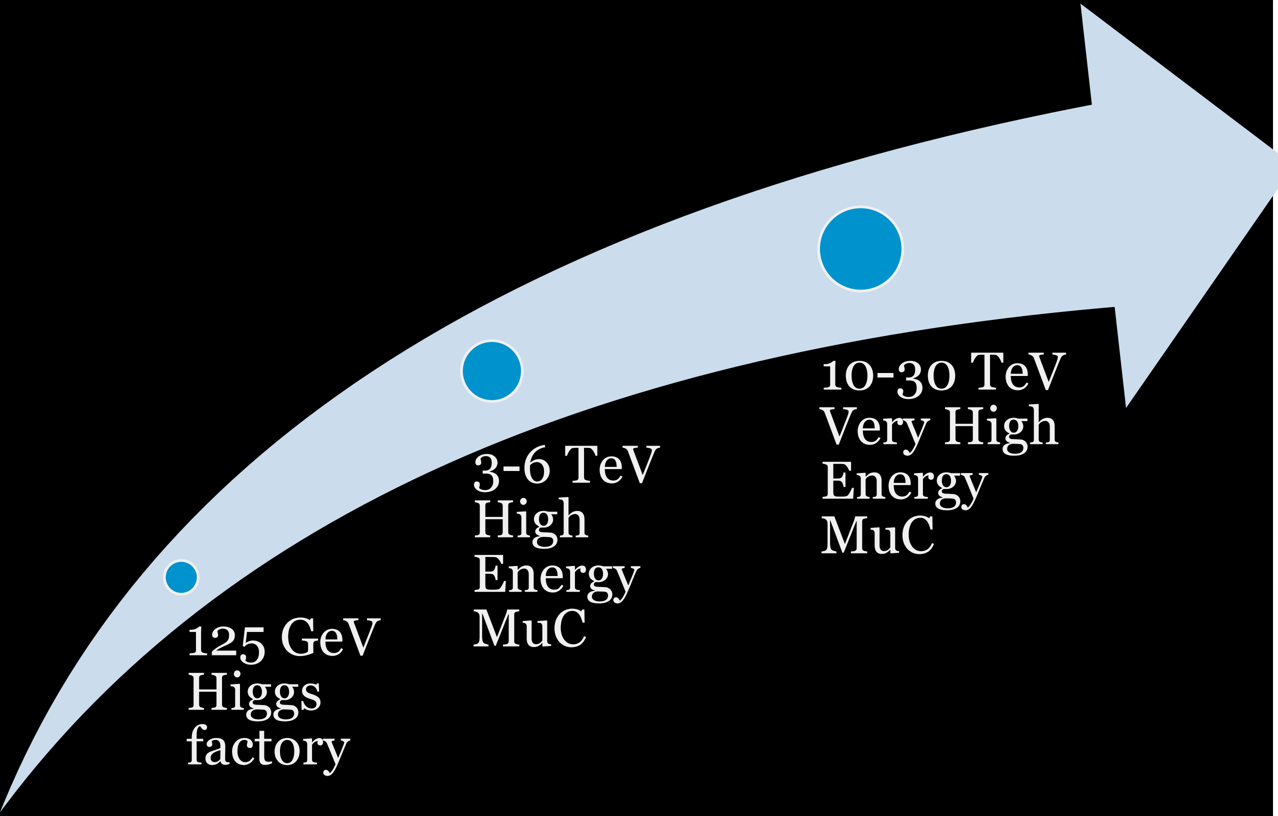
Black—background;
Red—1 GeV Width;
Blue—10 GeV Width;
Green—100 GeV Width;

N. Chakrabarty, T. Han, ZL, B. Mukhopadhyaya, 1408.5912

We don't know the resonant mass: radiating a photon can help us hit the resonance again!

Take bb decay mode for example,
Assuming 80% tagging efficiency on a heavy Higgs with Br to bb 80%.
Effectively 64%; can be interpreted (approximately) 64% of Heavy Higgs decay useful.

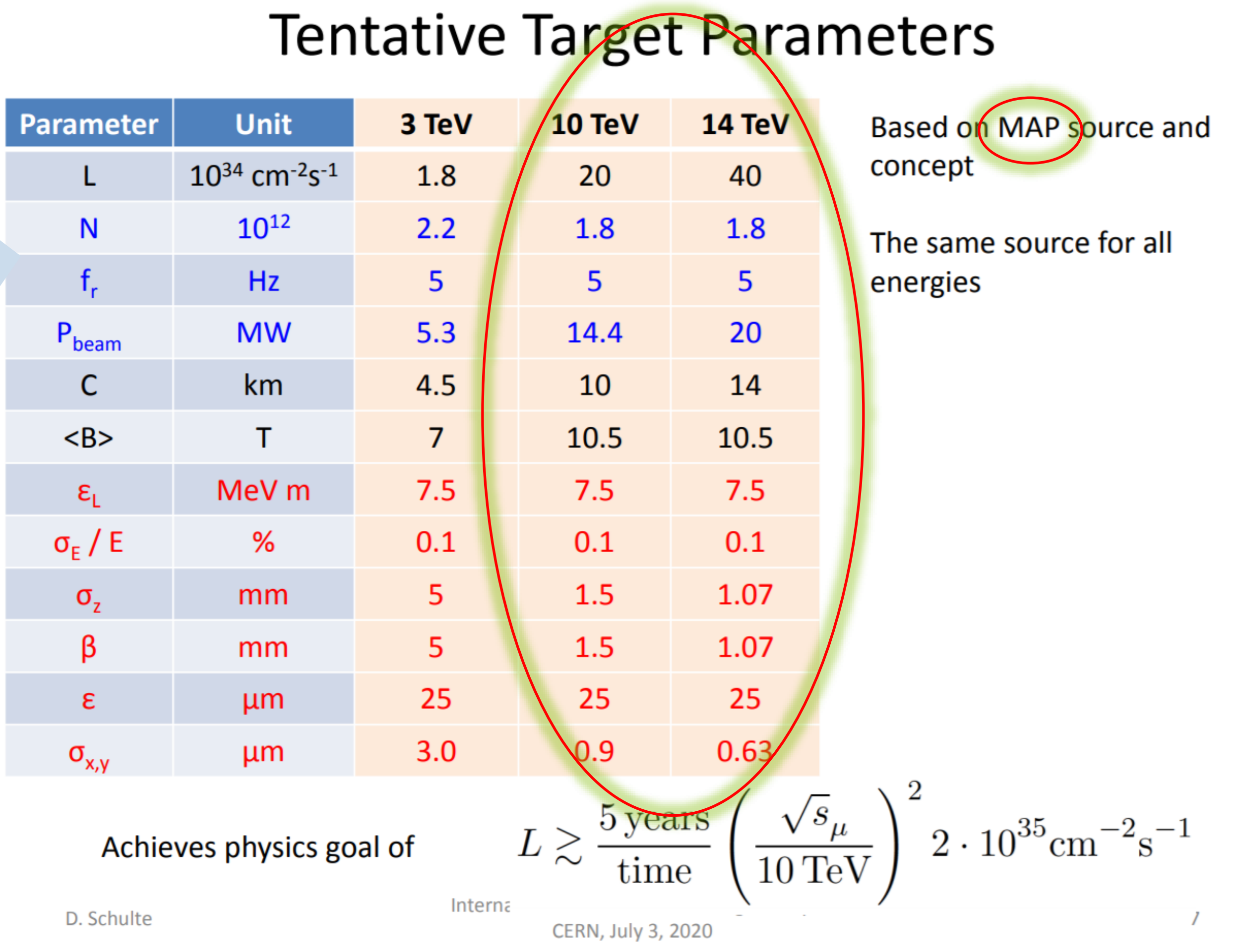
10+ TeV Muon Collider: game changer & dream machine



125 GeV
Higgs
factory

3-6 TeV
High
Energy
MuC

10-30 TeV
Very High
Energy
MuC



Tentative Target Parameters

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ \text{cm}^{-2}\text{s}^{-1}$	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

Based on MAP source and concept

The same source for all energies

Achieves physics goal of

$$L \gtrsim \frac{5\,\text{years}}{\text{time}}\left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}}\right)^2 2\cdot10^{35}\text{cm}^{-2}\text{s}^{-1}$$

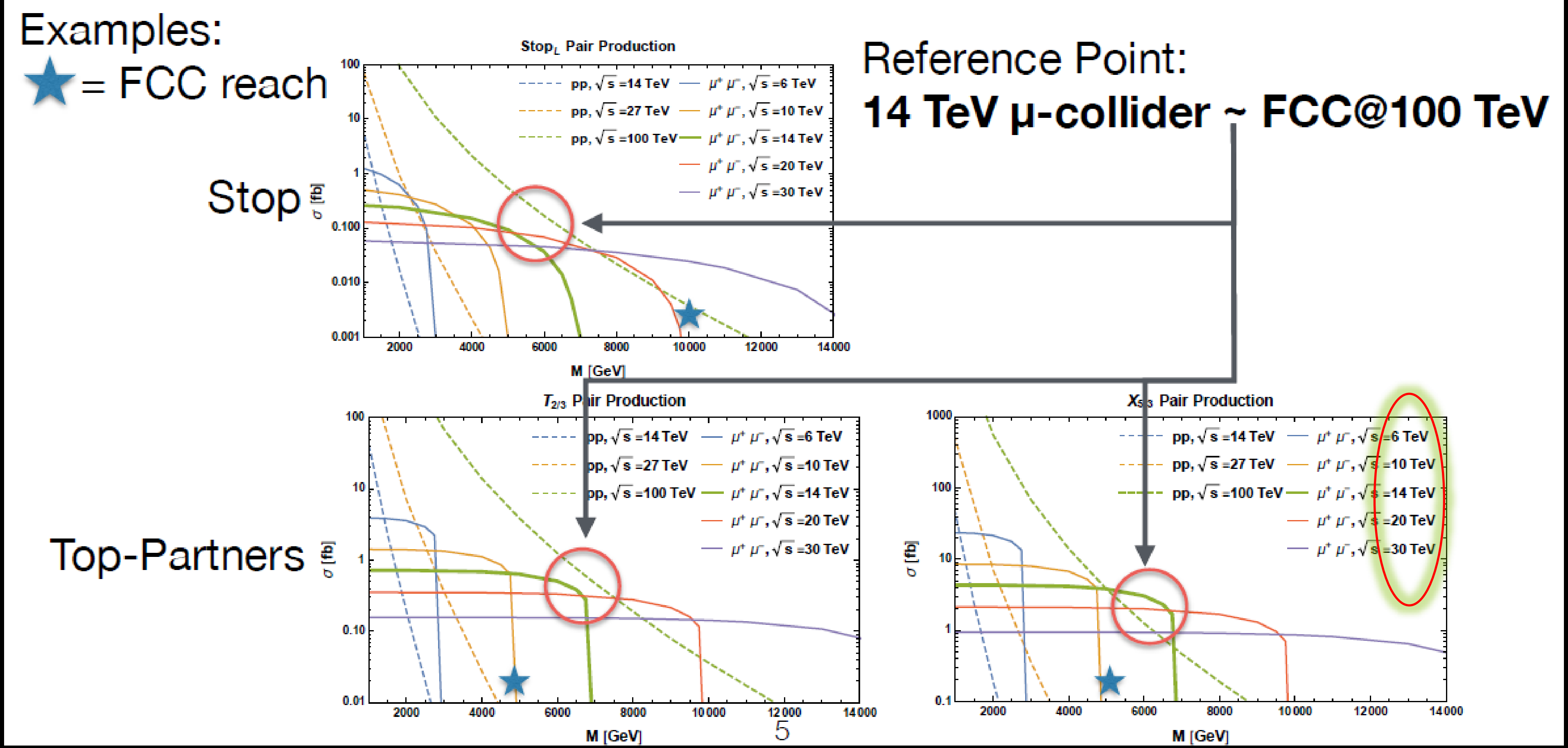
D. Schulte

Interna

CERN, July 3, 2020

Dream Machine: no rivals

High Energies—the dream machine



Examples:

★ = FCC reach

Reference Point:

14 TeV μ-collider ~ FCC@100 TeV

Stop

Top-Partners

Outperform 100 TeV collider in almost every aspect

(except for dijet resonances; particles only color charged, no EW charges)

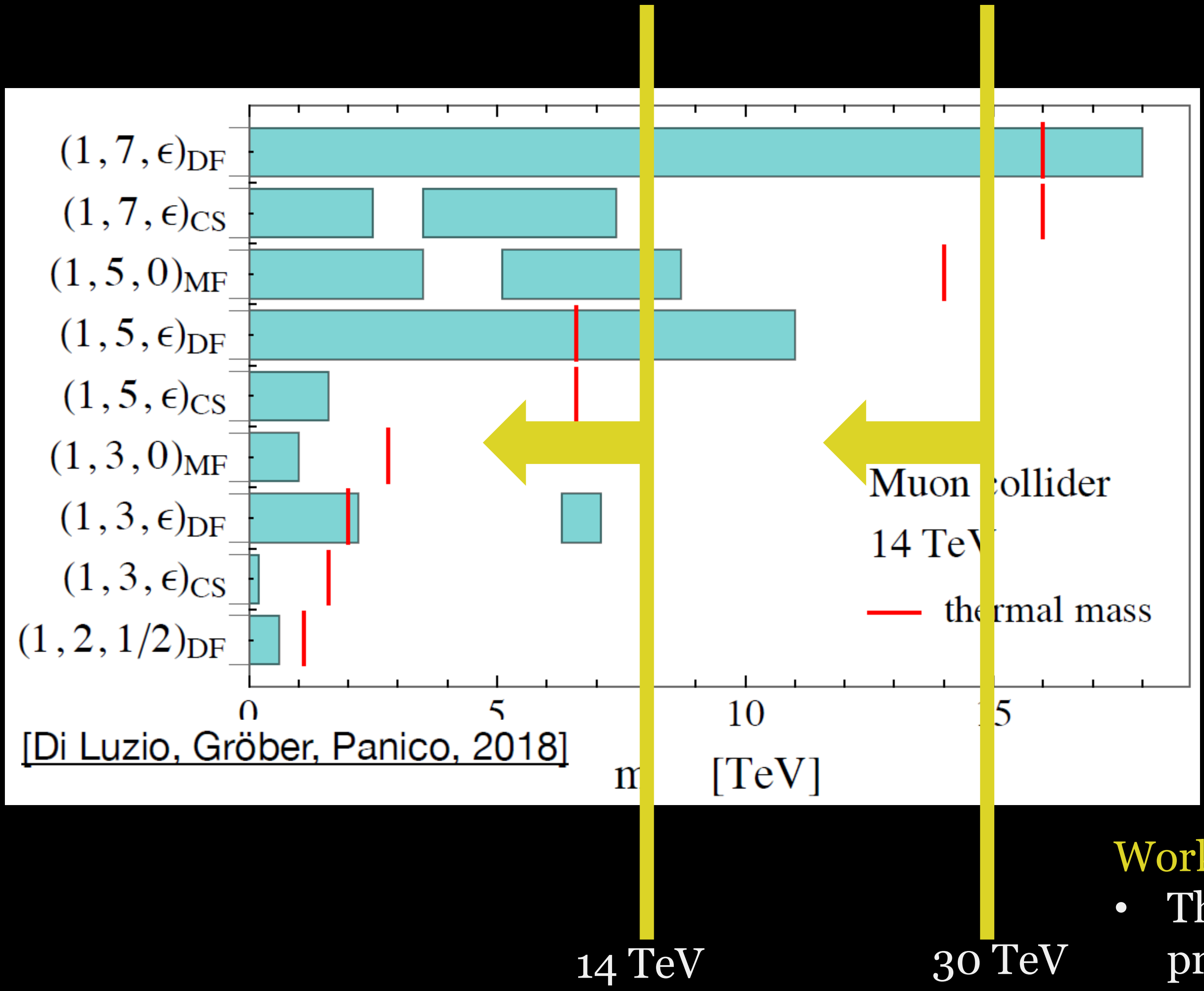
For electroweak states, already winning if MuC have 3+ TeV energy

Recall WIMP miracle & Unitarity bound (there are many exceptions)

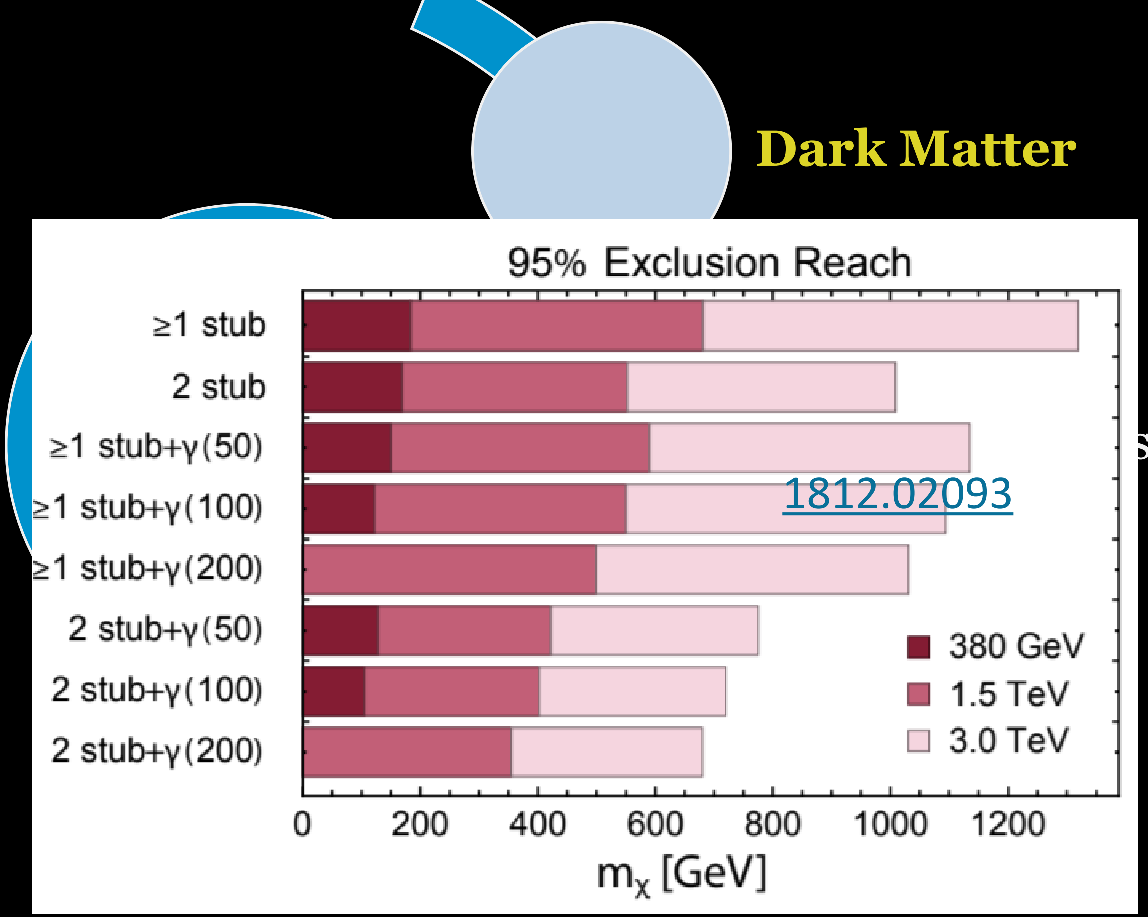
$$\langle \sigma v \rangle \approx \frac{\alpha_w^2}{1\ \text{TeV}^2}$$

$$m_\chi \lesssim 50 - 100\ \text{TeV}.$$

New physics pair productions: Dark Matter



[Di Luzio, Gröber, Panico, 2018]

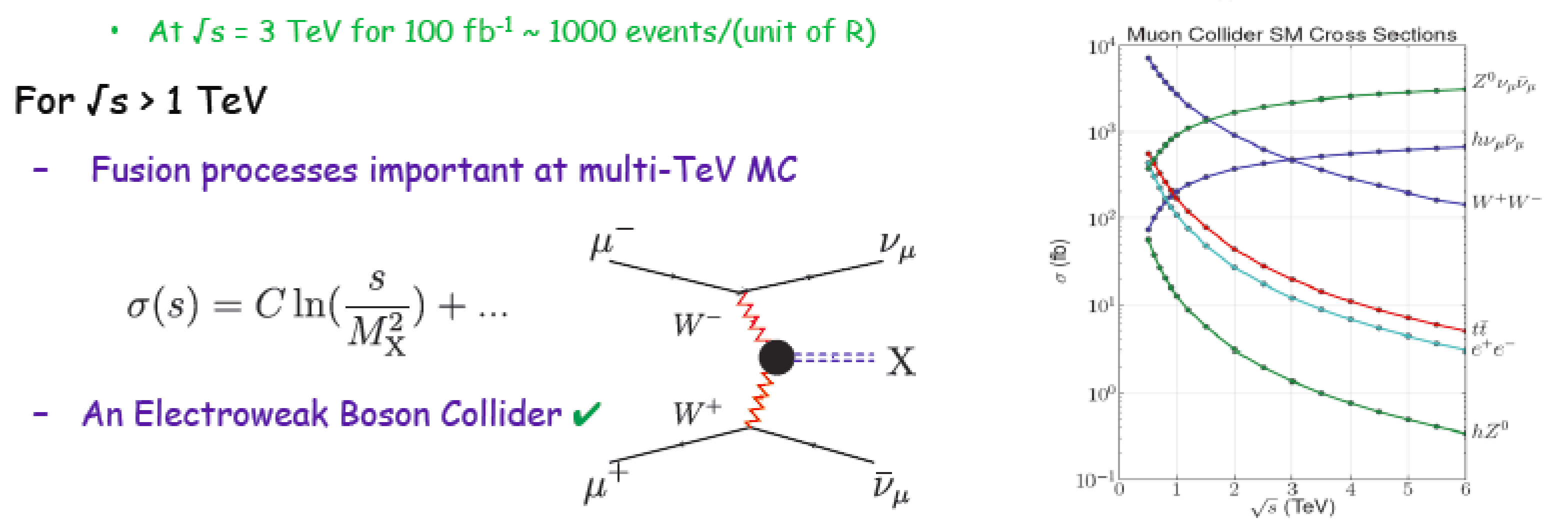


1812.02093

Work needed:

- Theoretical: deliver a comprehensive DM message and prioritize channels;
- Experimental: analyze leading channels, mono-photon, disappearing track, soft-particles, etc.

On Vector Boson Scattering (Fusion)



- At $\sqrt{s}$ = 3 TeV for 100 fb^{-1} ~ 1000 events/(unit of R)

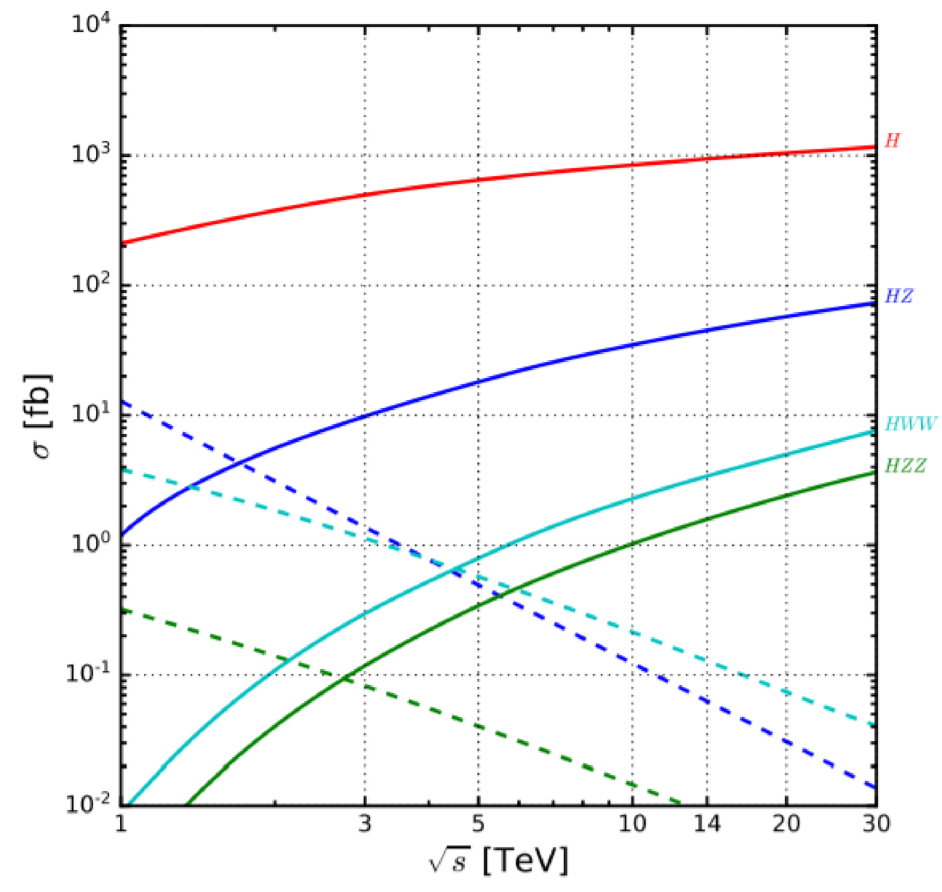
For $\sqrt{s} > 1$ TeV

- Fusion processes important at multi-TeV MC

$$\sigma(s) = C \ln(\frac{s}{M_X^2}) + \ldots$$

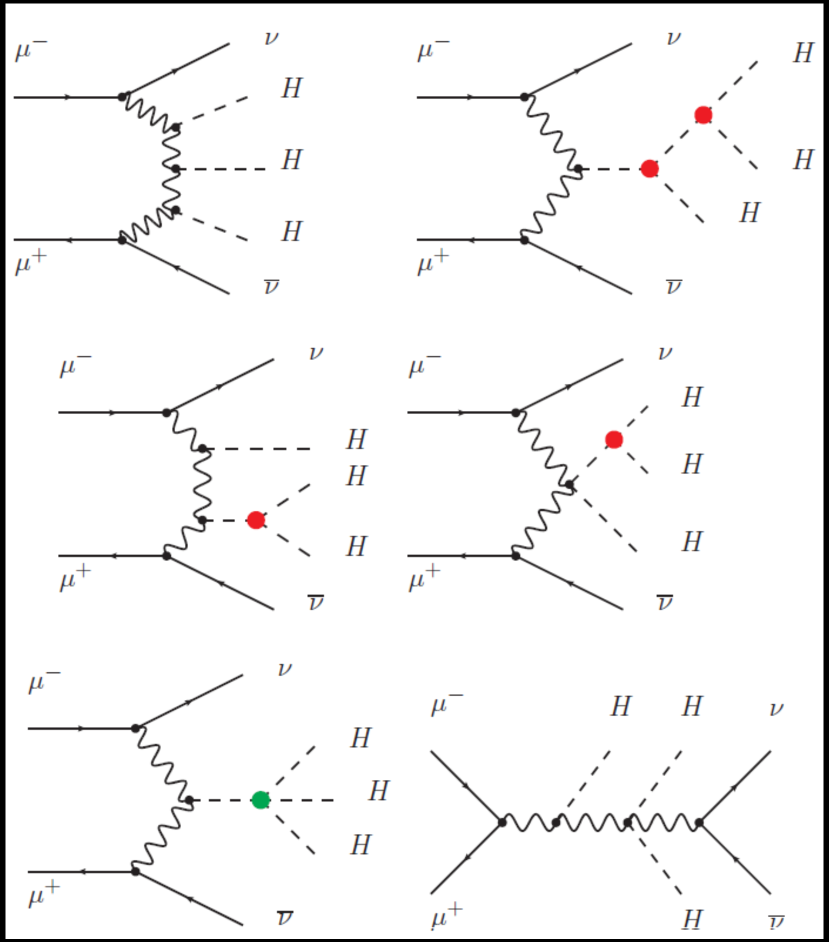
- An Electroweak Boson Collider ✓

From Eichten's Talk at MAP meetings (2013)

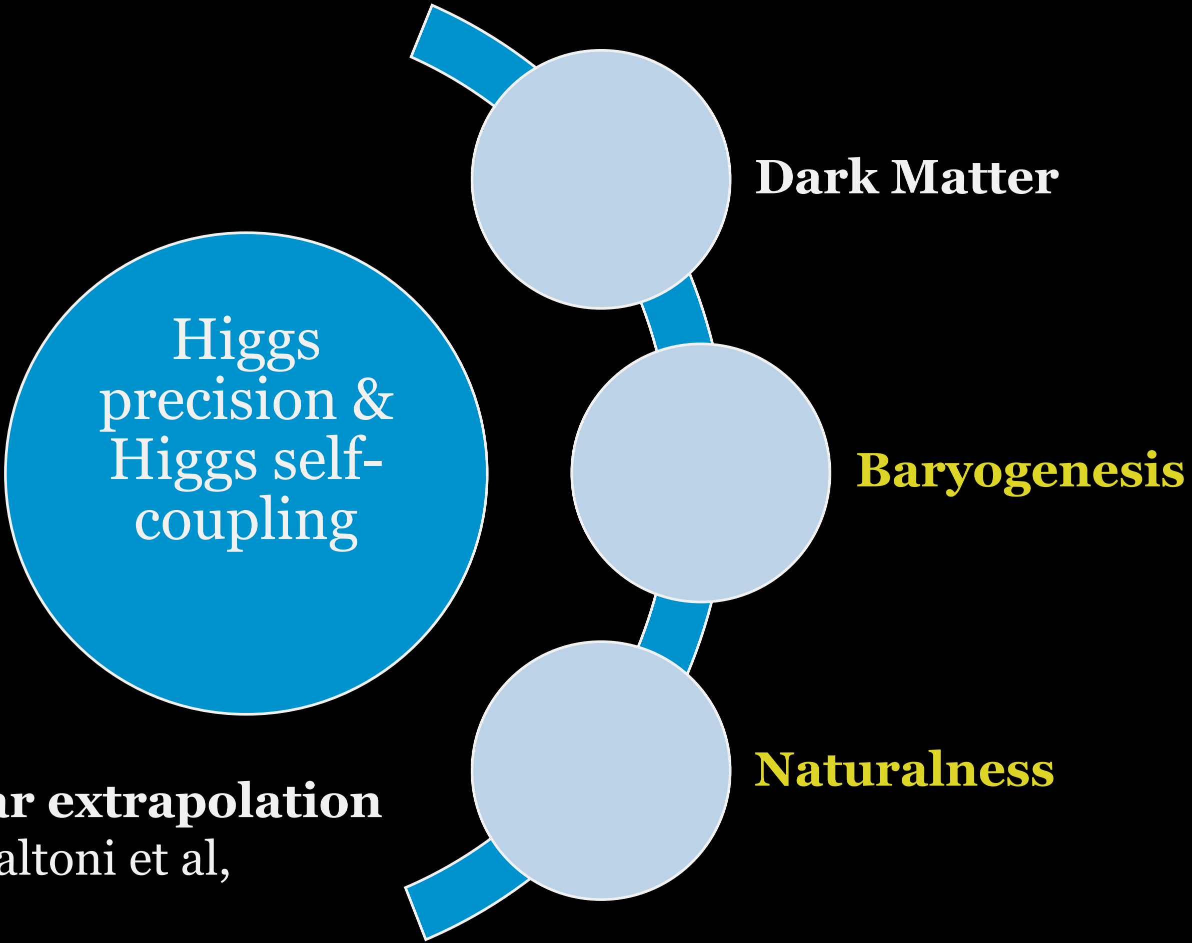


For instance, Maltoni et al, 2005.10289
Similar physics happens for electroweak pair productions, gauge boson productions, etc.

Higgs measurements

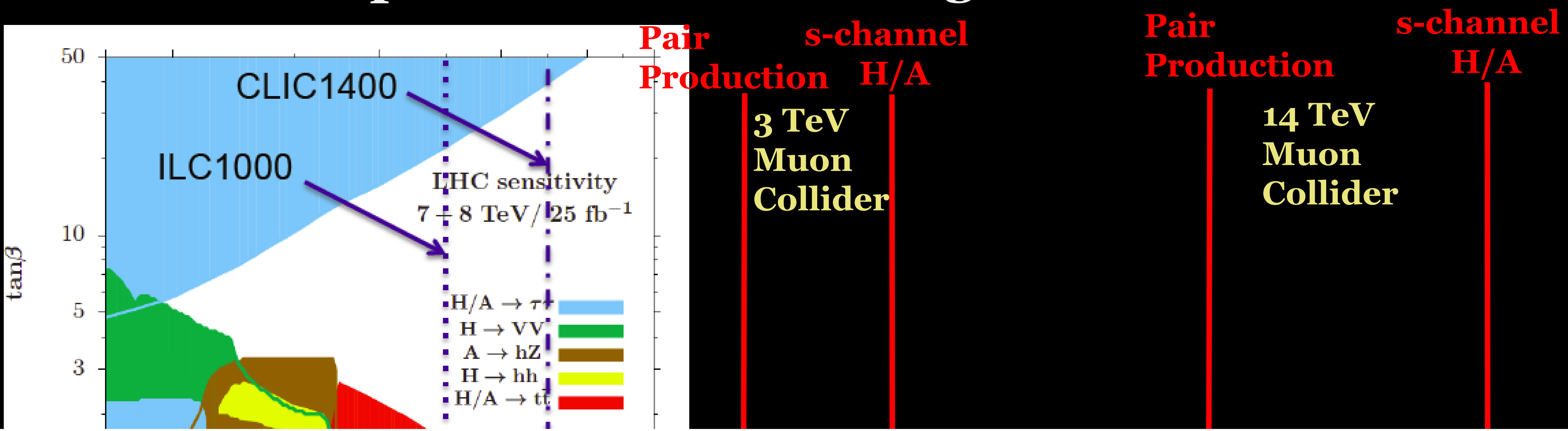


e.g., recent Higgs quartic study
Remove one or two H to get singlet
and double Higgs diagrams



Work needed:
A solid trilinear extrapolation
(1405.5910v1, Maltoni et al,
2003.13628)
A solid Higgs precision projection
needed (e.g., ZL et al 1711.03978)
So far things are only event counting
and varying kappa3 (see backup)

SUSY or Composite: infamous Wedge



Pair Production

s-channel H/A

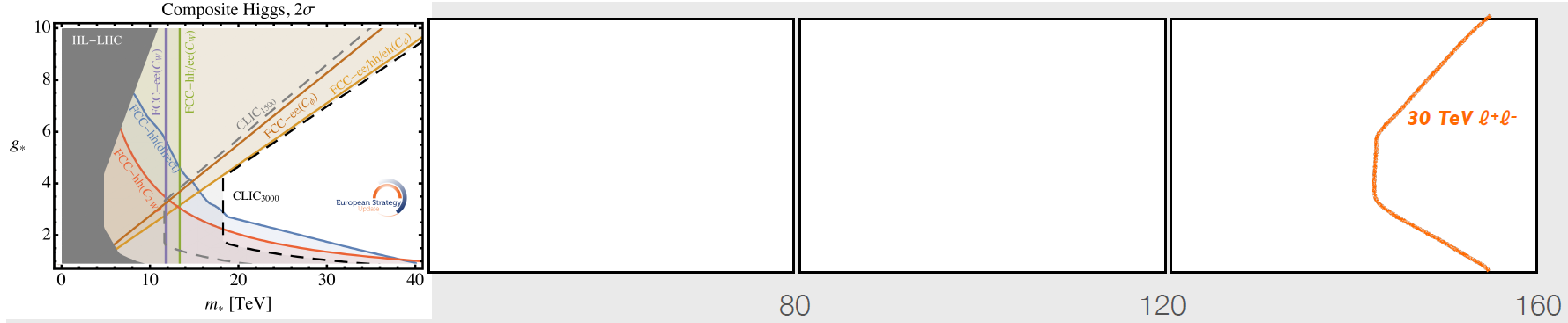
3 TeV Muon Collider

Pair Production

s-channel H/A

14 TeV Muon Collider

Courtesy of R.Franceschini



Suggested Studies (and things to pay attention to):

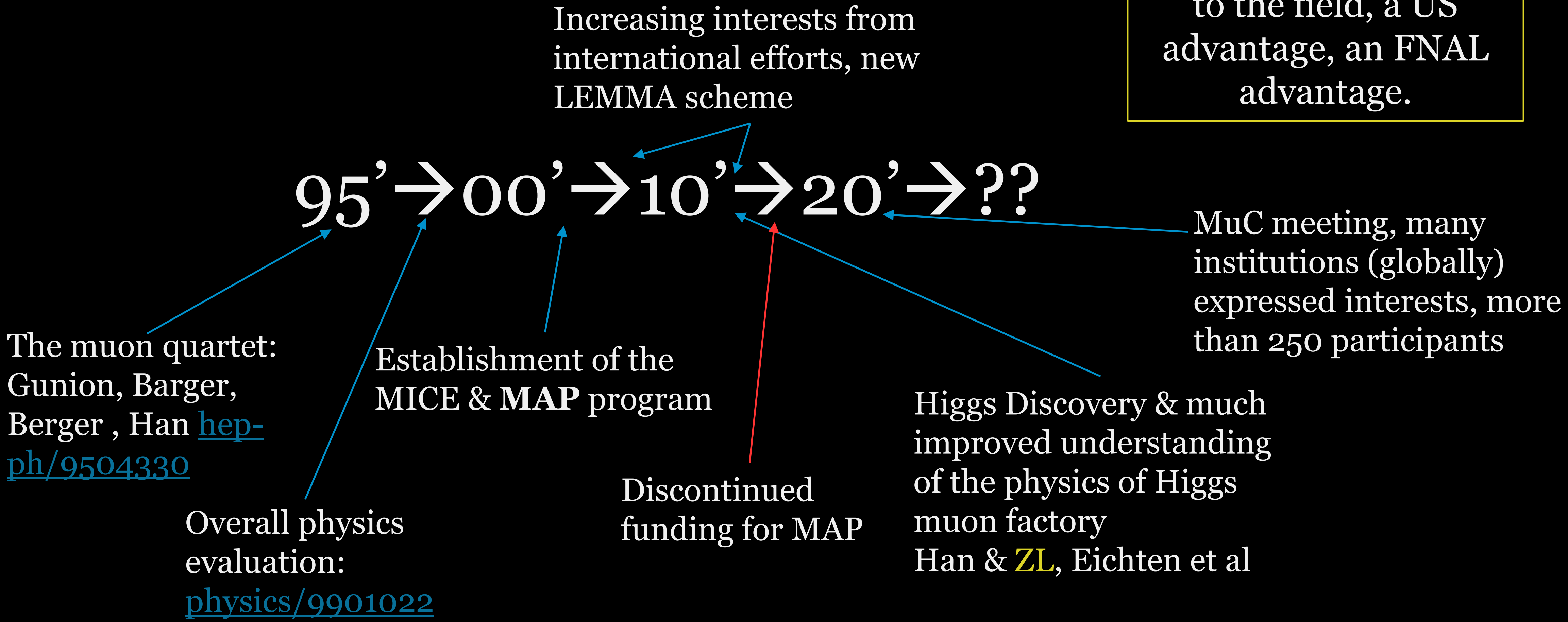
- Higgs trilinear extrapolation
  - (need solid prediction, with background, with some basic EFT treatment, e.g., simplified version of ZL et al, 1711.03978, Maltoni et al, 2003.13628)
- DM-motivated considerations and WIMP coverage
  - Mono-photon (consider beam spread and machine induced background)
  - Disappearing tracks (in the small lifetime region, in particular)
  - (in addition) soft particles plus missing momentum
  - (Refs, e.g., 1812.02093, 1805.00015, 1404.0682)
- Higgs precision projections (high energy measurement only)
  - Higgs factory projections reasonably understood (unless there is a new machine benchmark with orders of magnitude improvement in luminosity)
  - See the previous talk, more can be done to reach the robustness of the projections like in other colliders. Basically, one need to provide a list of projected sensitivities on different Higgs production and decay channels.
- Some generic Extensions of the SM
  - Zprime projections (through precision dilepton/dijet measurements, following ESU 1910.11775)
  - Heavy Higgs searches (somewhat known for 3 TeV, ZL et al 1408.5912)
- Naturalness-motivated consideration, top partner pair production pheno
  - (VBF matters) e.g., 2005.10289, Need to go beyond, 1901.06150

In all the above, pay attention to muon beam induced background & dare to work with the most optimistic machine parameters.

I compiled this list assuming the audience are more experimental oriented; for theorists, making more killer-cases (e.g., unique VBF for aQGC) and setting nice benchmarks for the following cases.

A side note

MAP is a extremely valuable contribution to the field, a US advantage, an FNAL advantage.



Increasing interests from international efforts, new LEMMA scheme

95’→00’→10’→20’→??

MuC meeting, many institutions (globally) expressed interests, more than 250 participants

The muon quartet: Gunion, Barger, Berger , Han hep-ph/9504330

Establishment of the MICE & **MAP** program

Overall physics evaluation: physics/9901022

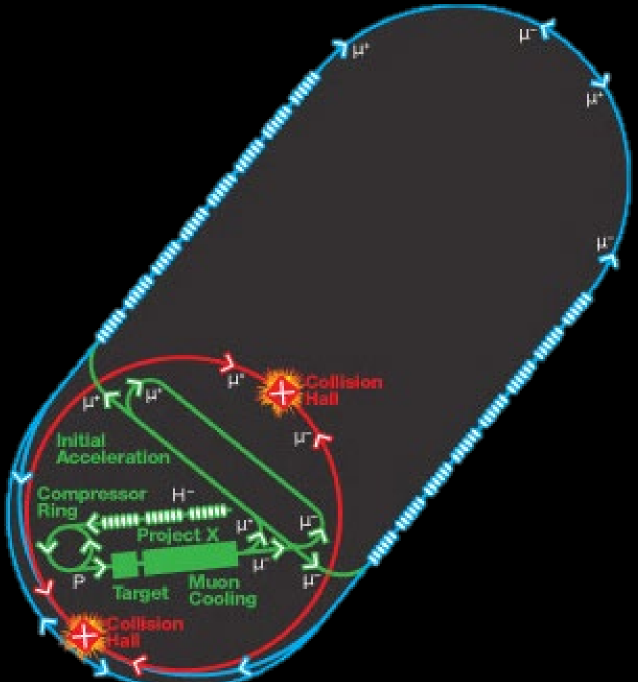
Discontinued funding for MAP

Higgs Discovery & much improved understanding of the physics of Higgs muon factory
Han & ZL, Eichten et al

You will always hear two leading “criticism” (excuse of not thinking) on muon colliders:

- Where is the beam? (cooling and luminosity)
  - Solution: participate, understand, appreciate the muon cooling researches (as well as LEMMA), and be optimistic
- Background from muons decaying in flight
  - Solution: try to estimate and convince yourself it won’t be a problem.


Fermilab Si

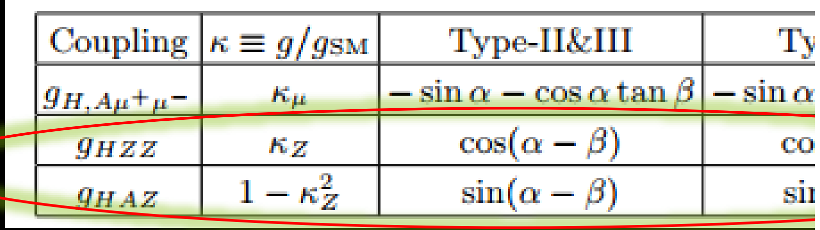

μ^+
μ^-
μ^+
μ^-
μ^+
μ^+
μ^+
Collision Hall
μ^-
Initial Acceleration
Compressor Ring
H^-
Project X
μ^+
μ^-
μ^+
μ^-
P
Target
Muon Cooling
Collision Hall

Thank you!

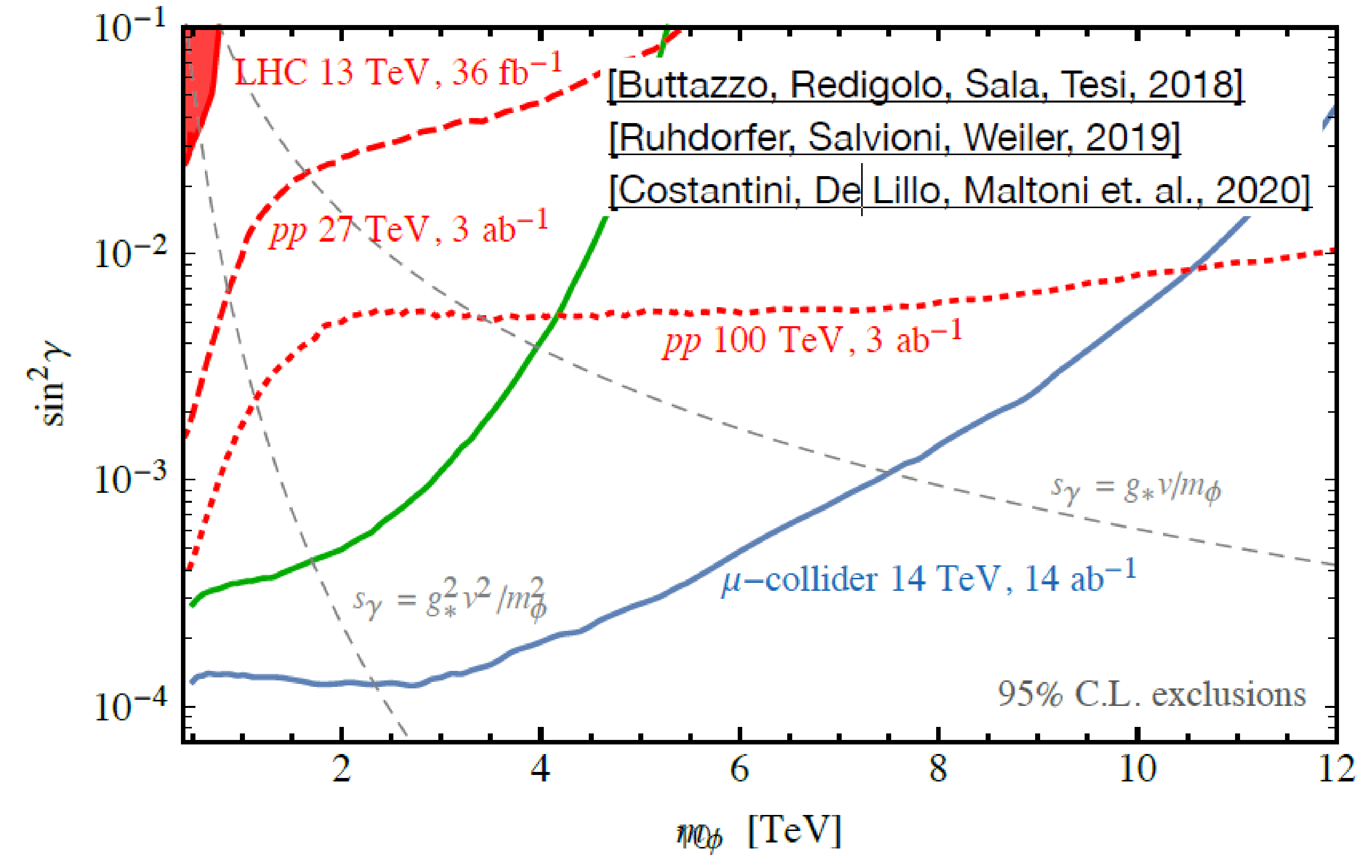
Back up

ZH associated Production
HA Pair production

- Two complimentary production me
- Both are limited by kinematics



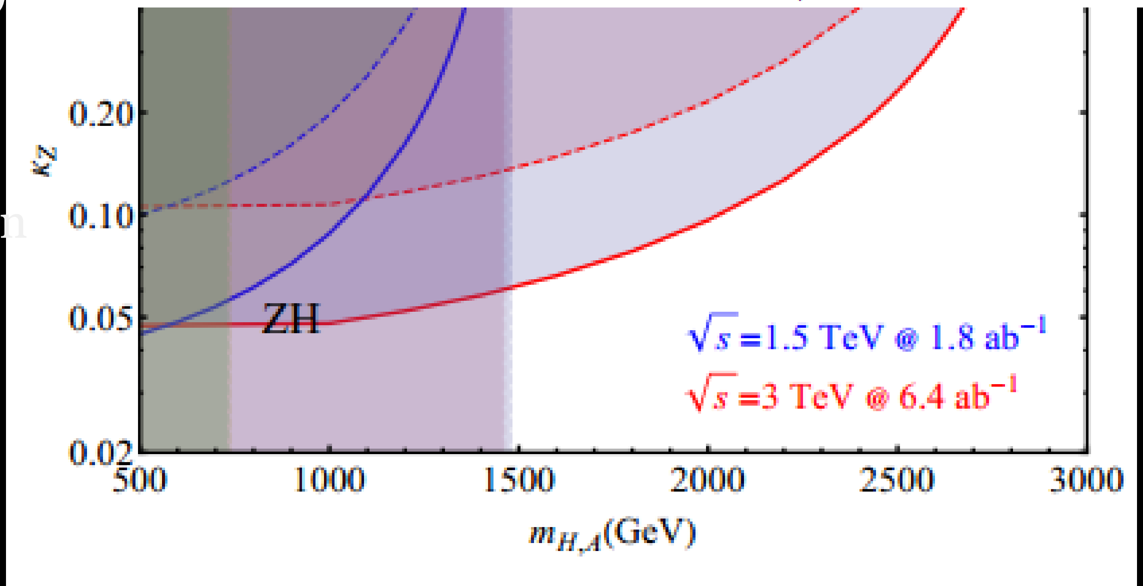
Coupling	$\kappa \equiv g/g_{\rm SM}$	Type-II&III	Ty
$g_{H,A\mu^+\mu^-}$	κ_μ	$-\sin\alpha - \cos\alpha\tan\beta$	$-\sin\alpha$
g_{HZZ}	κ_Z	$\cos(\alpha-\beta)$	co
g_{HAZ}	$1-\kappa_Z^2$	$\sin(\alpha-\beta)$	si



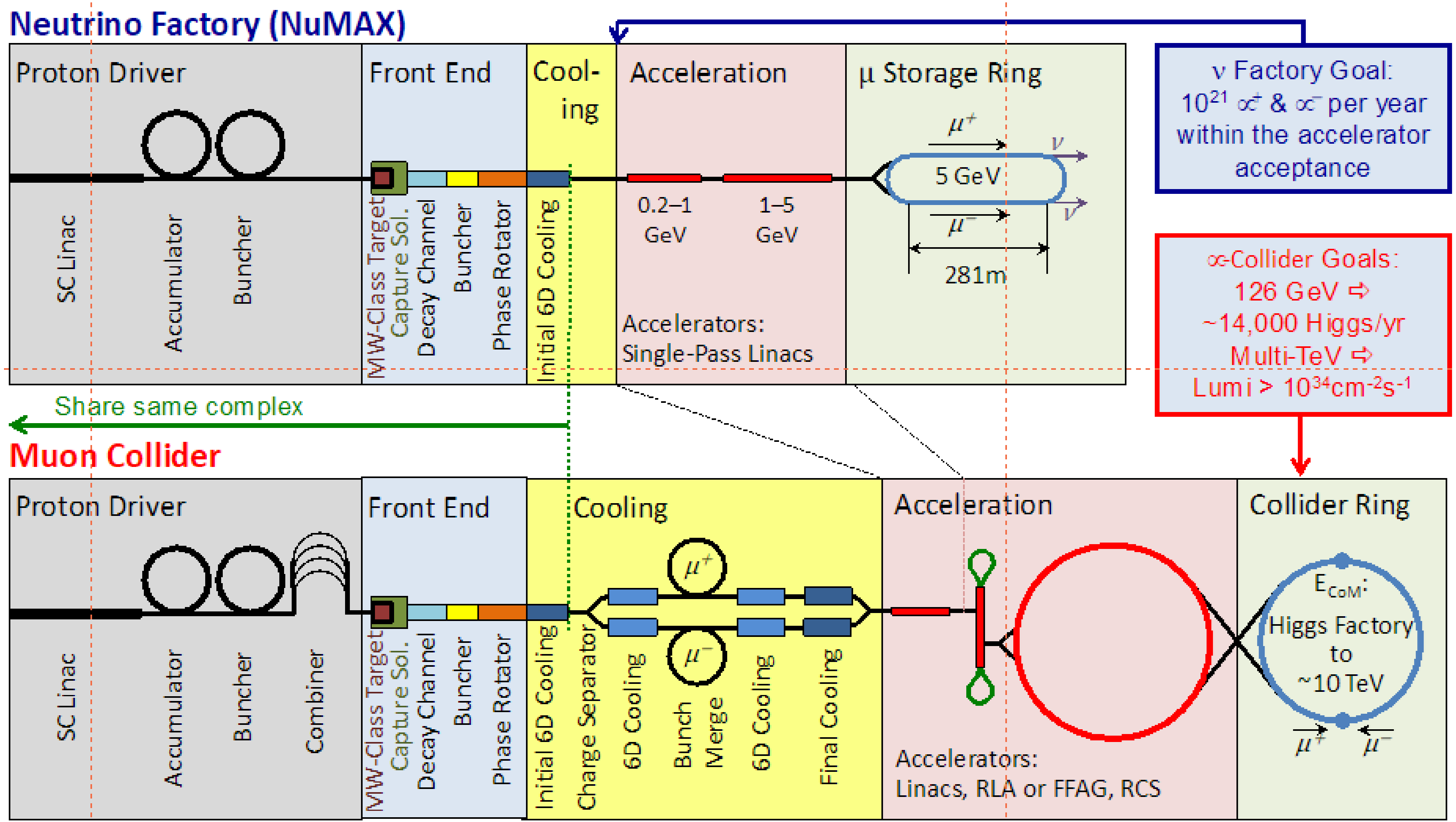
[Buttazzo, Redigolo, Sala, Tesi, 2018]
[Ruhdorfer, Salvioni, Weiler, 2019]
[Costantini, De Lillo, Maltoni et. al., 2020]

For simplicity, we consider H/A
nearly degenerate (as in the MSSM)

Shaded regions are
Parameter space covered by
Red/Blue– ZH associated production
Cyan/Pink-HA pair production
at 1.5/3 TeV Lepton Collider



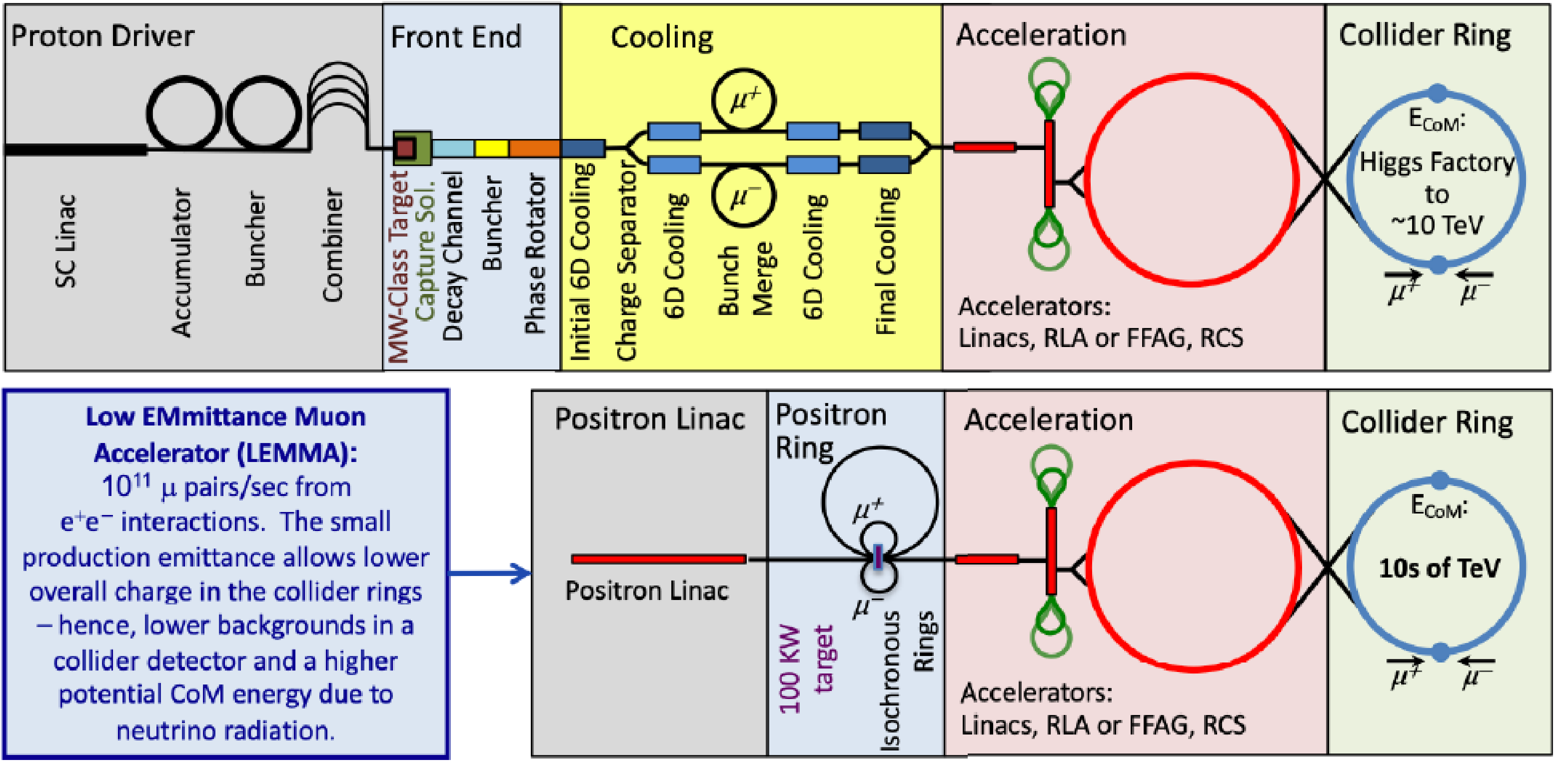
The US Muon Accelerator Program



ν Factory Goal:
10^{21} ∝+ & ∝− per year
within the accelerator
acceptance

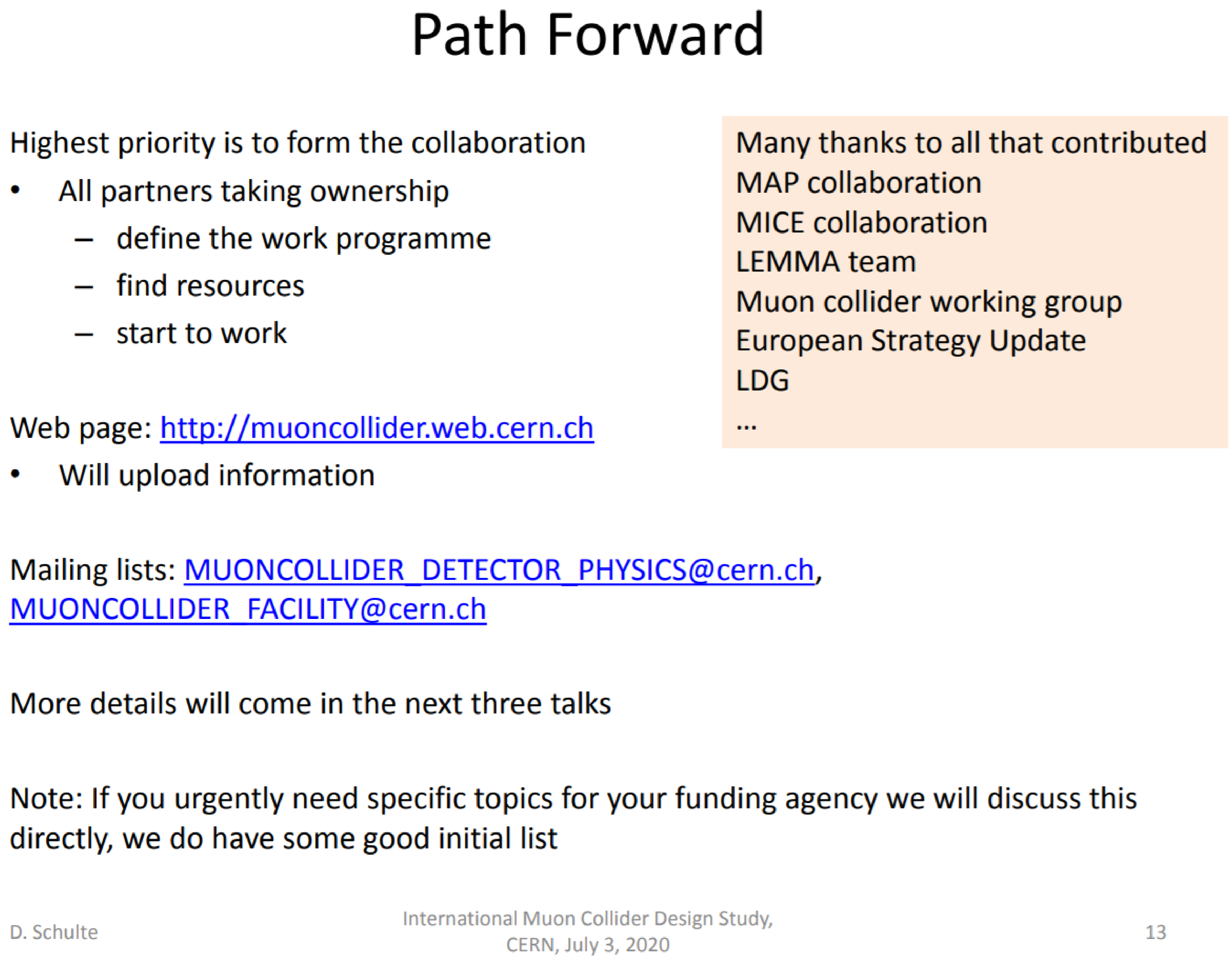
∝Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

- The members of the MAP effort can bring tremendous breadth and depth to a new international collaboration
  - > 20 institutions involved (including 6 national laboratories)
- MAP provided design concepts and technology feasibility studies
  - Including MICE
- Major feasibility outcomes provide a useful basis for moving forward with development of a CDR



Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

[Delahaye et al. arXiv:1901.06150]



Path Forward

Highest priority is to form the collaboration

- All partners taking ownership
  - define the work programme
  - find resources
  - start to work

Web page: http://muoncollider.web.cern.ch

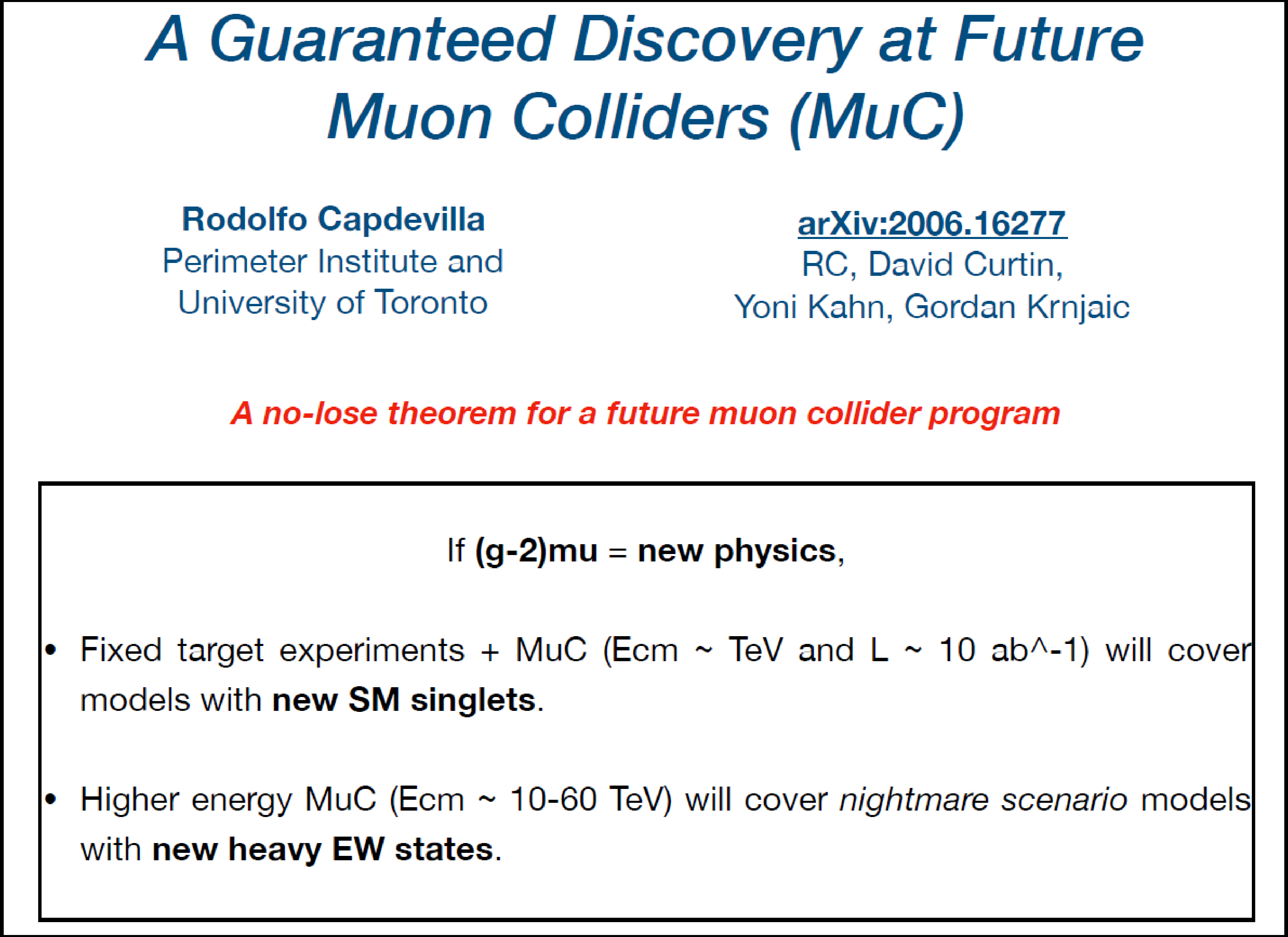
- Will upload information

Mailing lists: MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch, MUONCOLLIDER_FACILITY@cern.ch

More details will come in the next three talks

Note: If you urgently need specific topics for your funding agency we will discuss this directly, we do have some good initial list

Many thanks to all that contributed
MAP collaboration
MICE collaboration
LEMMA team
Muon collider working group
European Strategy Update
LDG
…



A Guaranteed Discovery at Future Muon Colliders (MuC)

Rodolfo Capdevilla
Perimeter Institute and
University of Toronto

arXiv:2006.16277
RC, David Curtin,
Yoni Kahn, Gordan Krnjaic

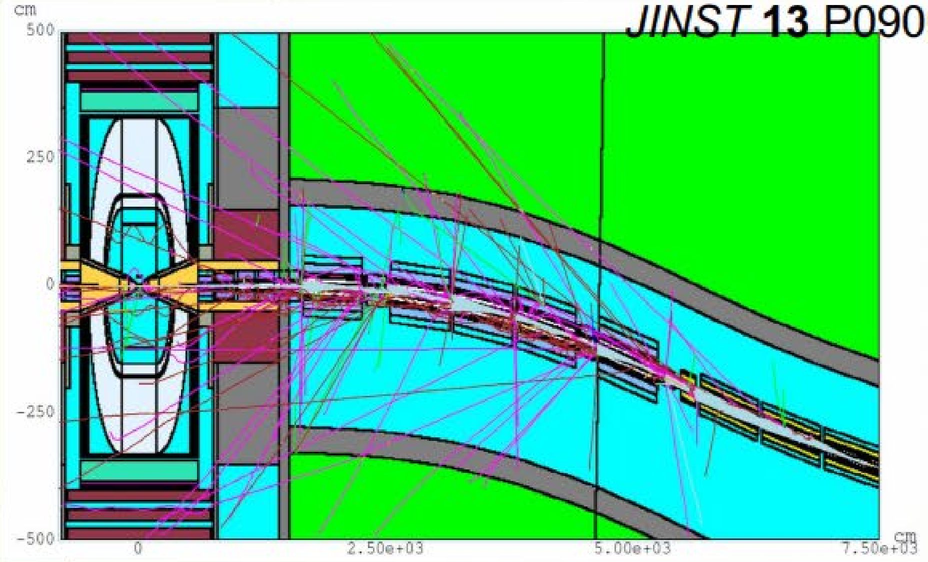
A no-lose theorem for a future muon collider program

If **(g-2)mu** = **new physics**,

- Fixed target experiments + MuC (Ecm ~ TeV and L ~ 10 ab^-1) will cover models with **new SM singlets**.
- Higher energy MuC (Ecm ~ 10-60 TeV) will cover *nightmare scenario* models with **new heavy EW states**.

Main Challenge

A muon collider experiment has to cope with the large beam-induced background (BIB).



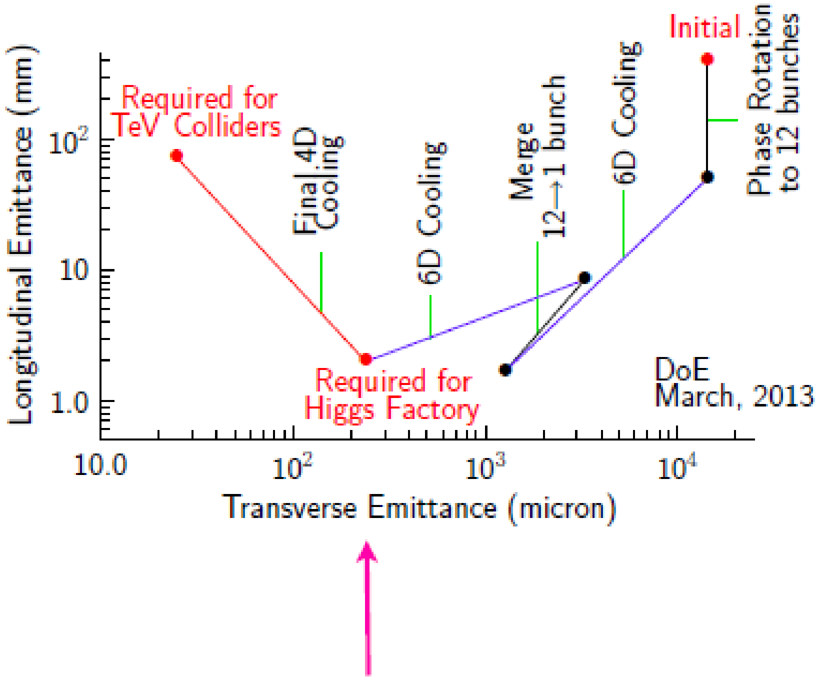
JINST **13** P09004

- ➢ MAP developed a realistic simulation of beam-induced backgrounds in the detector by implementing a model of the tunnel and accelerator ±200 m from the interaction point.
- ➢ Secondary and tertiary particles from muon decays are simulated with MARS15 then transported to the detector.
- ➢ Two tungsten nozzles play a crucial role in background mitigation inside the detector.

By using the MAP framework (thanks to A. Mazzacane, V. Di Benedetto) including the already simulated background, we demonstrated that challenging physics measurements are possible.

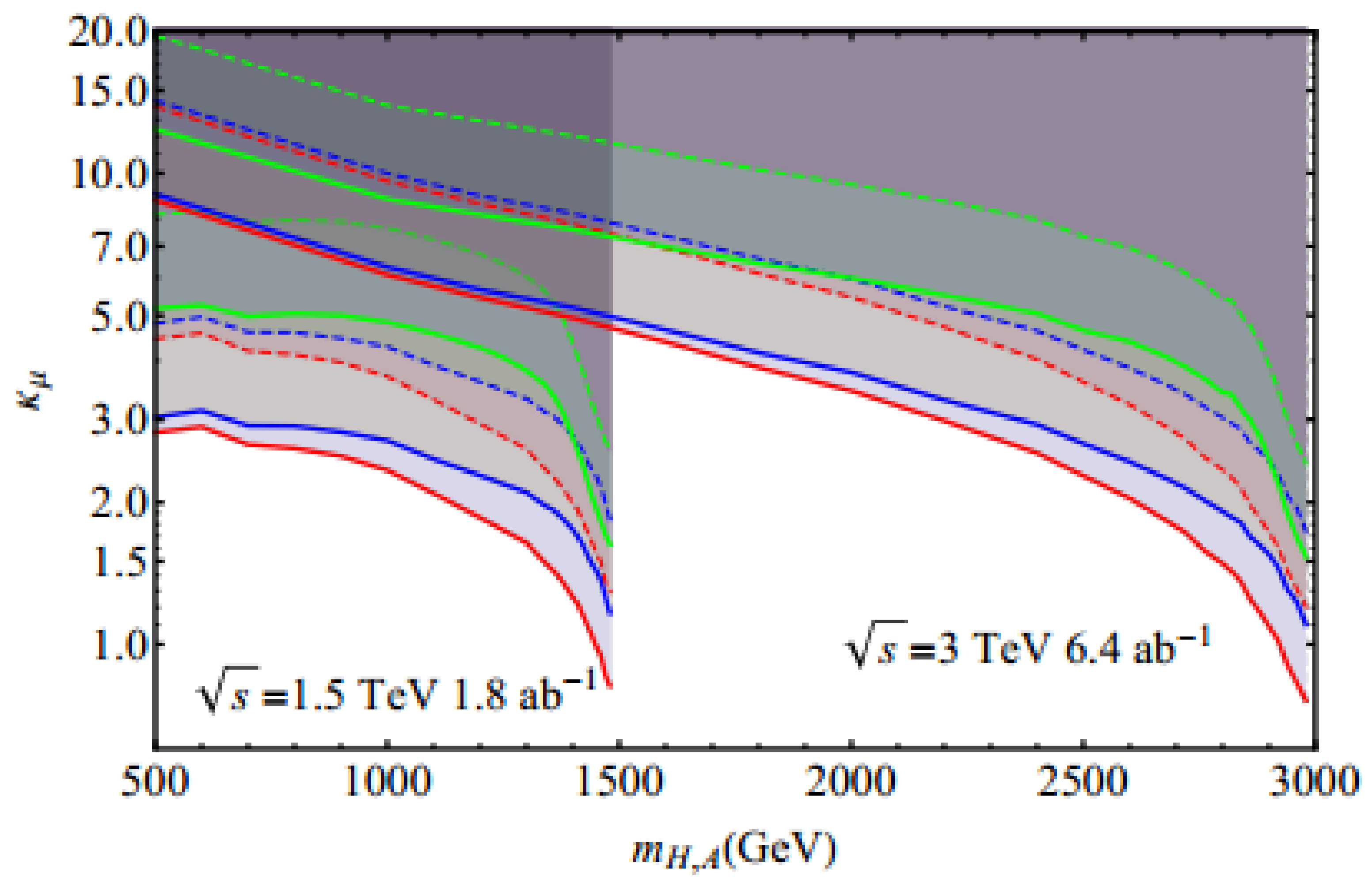
Muon Collider

- But muons decay:
  - The muon beams must be accelerated and cooled in phase space (factor ≈ 10^6) rapidly -> ionization cooling
  - requires a complex cooling scheme
  - The decay products (μ^- -> ν_μ ν_e e^-) have high energies.
    - Detector background issues
    - Neutrino beam issue for Ecm ≥ 4 TeV. Beam steering resolves this for Ecm ≲ 10 TeV.
- The issues need dedicated R&D
  - MICE
  - MAP
  - nuStorm - Definitive 6D cooling demo.



Higgs Factory

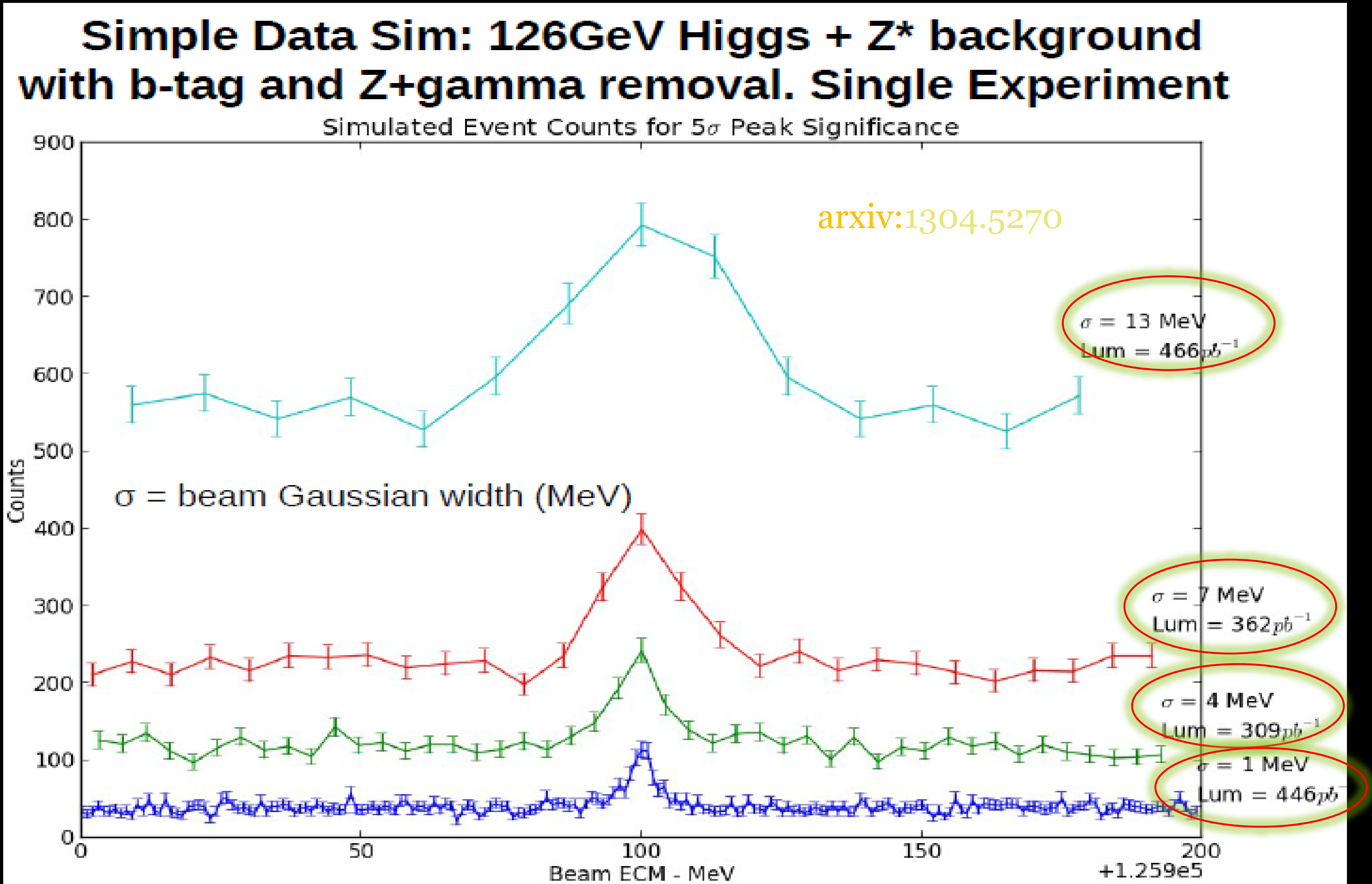
Sensitivities



Red, Blue, Green for 1, 10, 100 GeV Total Width
Solid, Dashed for 2-sigma 5-sigma significance
Bin size choice optimized for k_\mu=10

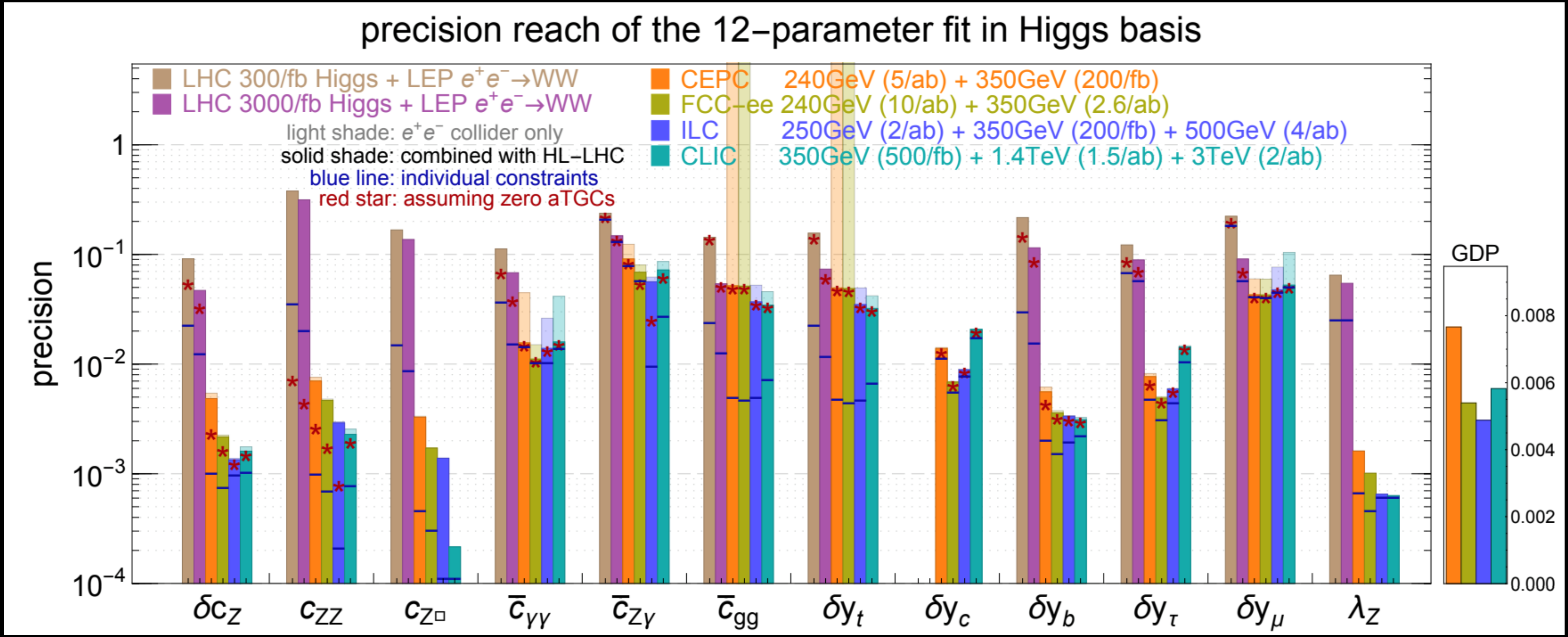
- global view on the Higgs self-coupling at lepton colliders
  S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon, JHEP02 (2018) 178, arXiv:1711.03978 [hep-ph] (2017)
- Learning from Higgs Physics at Future Higgs Factories
  J. Gu, H. Li, Z. Liu, S. Su, W. Su, JHEP 1712 (2017) 153, arXiv:1709.06103 [hep-ph] (2017)
- Exotic decays of the 125 GeV Higgs boson at future e+e− colliders
  Z. Liu, L.-T. Wang, H. Zhang, Chin.Phys. C41 (2017) no.6, 063102, arXiv:1612.09284 [hep-ph] (2016)
- ISR effects for resonant Higgs production at future lepton colliders, M. Greco, T. Han, Z. Liu, Phys.Lett. B763 (2016) 409-415, arXiv:1607.03210 [hep-ph] (2016)
- Beyond Higgs Couplings: Probing the Higgs with Angular Observables at Future e+e− Colliders, N. Craig, J. Gu, Z. Liu, K. Wang, JHEP 1603 (2016) 050, arXiv:1512.06877 [hep-ph] (2015)
- Improving Higgs coupling measurements through ZZ Fusion at the ILC, T. Han, Z. Liu, Z. Qian, J. Sayre, Phys. Rev. D 91, 113007, arXiv:1504.01399 [hep-ph] (2015)
- Radiative Return for Heavy Higgs Boson at a Muon Collider, N. Chakrabarty, T. Han, Z. Liu, B. Mukhopadhyaya, Phys.Rev. D91, 015008, arXiv:1408.5912 [hep-ph] (2014)
- Potential Precision on Higgs Couplings and Total Width at the ILC, T. Han, Z. Liu, J. Sayre, Phys. Rev. D 89 113006, arXiv:1311.7155 [hep-ph] (2013)
- Potential precision of a direct measurement of the Higgs boson total width at a muon collider, T. Han and Z. Liu, Phys.Rev. D87 (2013) 033007, arXiv:1210.7803 [hep-ph] (2012)
- Probing the Higgs with angular observables at future e+e− colliders Z. Liu, Int. J. Mod. Phys. A, 31, 1644005 (2016)
- CEPC-SppC Preliminary Conceptual Design Report Volume I: Physics and Detector. M. Ahmad et al., link [hep-ph] (2015)
- Diagnosis of a New Neutral Gauge Boson at the LHC and ILC for Snowmass 2013 T. Han, P. Langacker, Z. Liu and L.-T. Wang, arXiv:1308.2738 [hep-ph] (2013)
- Muon Collider Higgs Factory for Snowmass 2013, Y. Alexahin et al., arXiv:1308.2143 [hep-ph] (2013)
- The Case for a Muon Collider Higgs Factory,Y. Alexahin et al., arXiv:1307.6129 [hep-ph] (2013)

Pinning down the mass of the Higgs



Simple Data Sim: 126GeV Higgs + Z* background with b-tag and Z+gamma removal. Single Experiment

arxiv:1304.5270



Comparison between different lepton collider Higgs factories

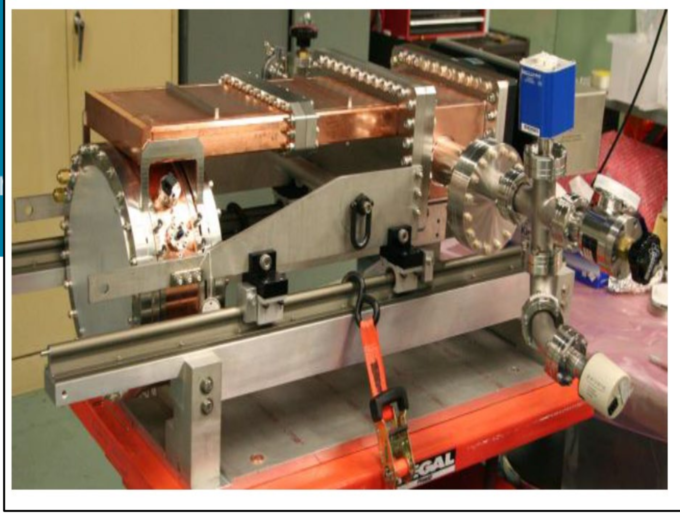
- Better than HL-LHC to 1% level
- Statistical limited (1 million Higgs roughly)

PHYSICAL REVIEW ACCELERATORS AND BEAMS

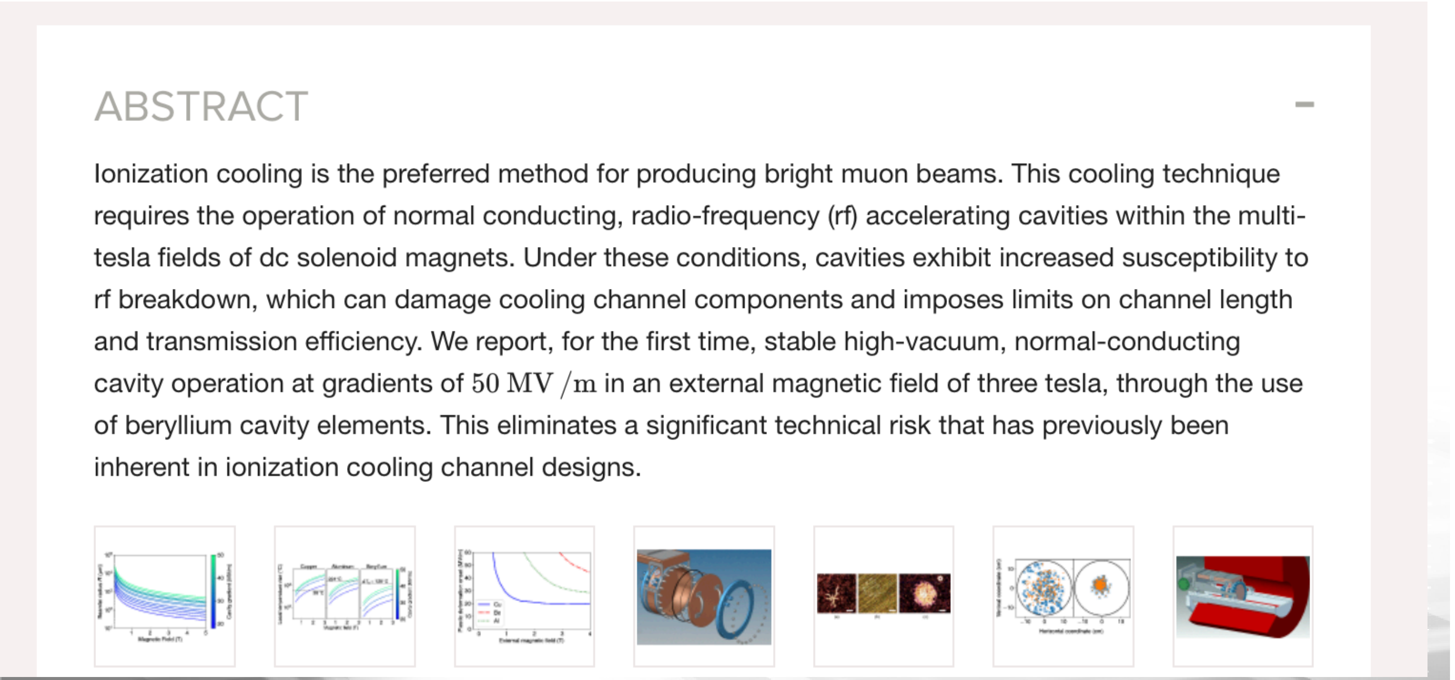
Operation of normal-conducting rf cavities in multi-Tesla magnetic fields for muon ionization cooling: A feasibility demonstration

D. Bowring, A. Bross, P. Lane, M. Leonova, A. Moretti, D. Neuffer, R. Pasquinelli, D. Peterson, M. Popovic, D. Stratakis, K. Yonehara, A. Kochemirovskiy, Y. Torun, C. Adolphsen, L. Ge, A. Haase, Z. Li, D. Martin, M. Chung, D. Li, T. Luo, B. Freemire, A. Liu, and M. Palmer

Phys. Rev. Accel. Beams **23**, 072001 – Published 2 July 2020

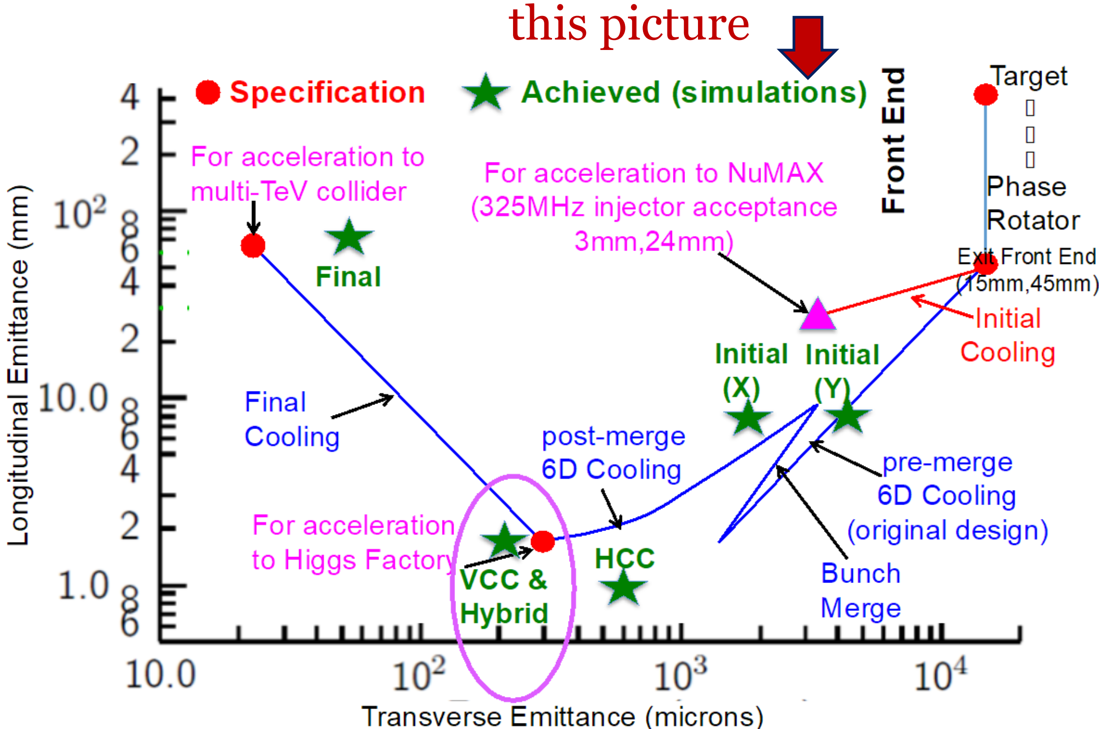


Performance with new RF gradient and magnet specifications can change this picture

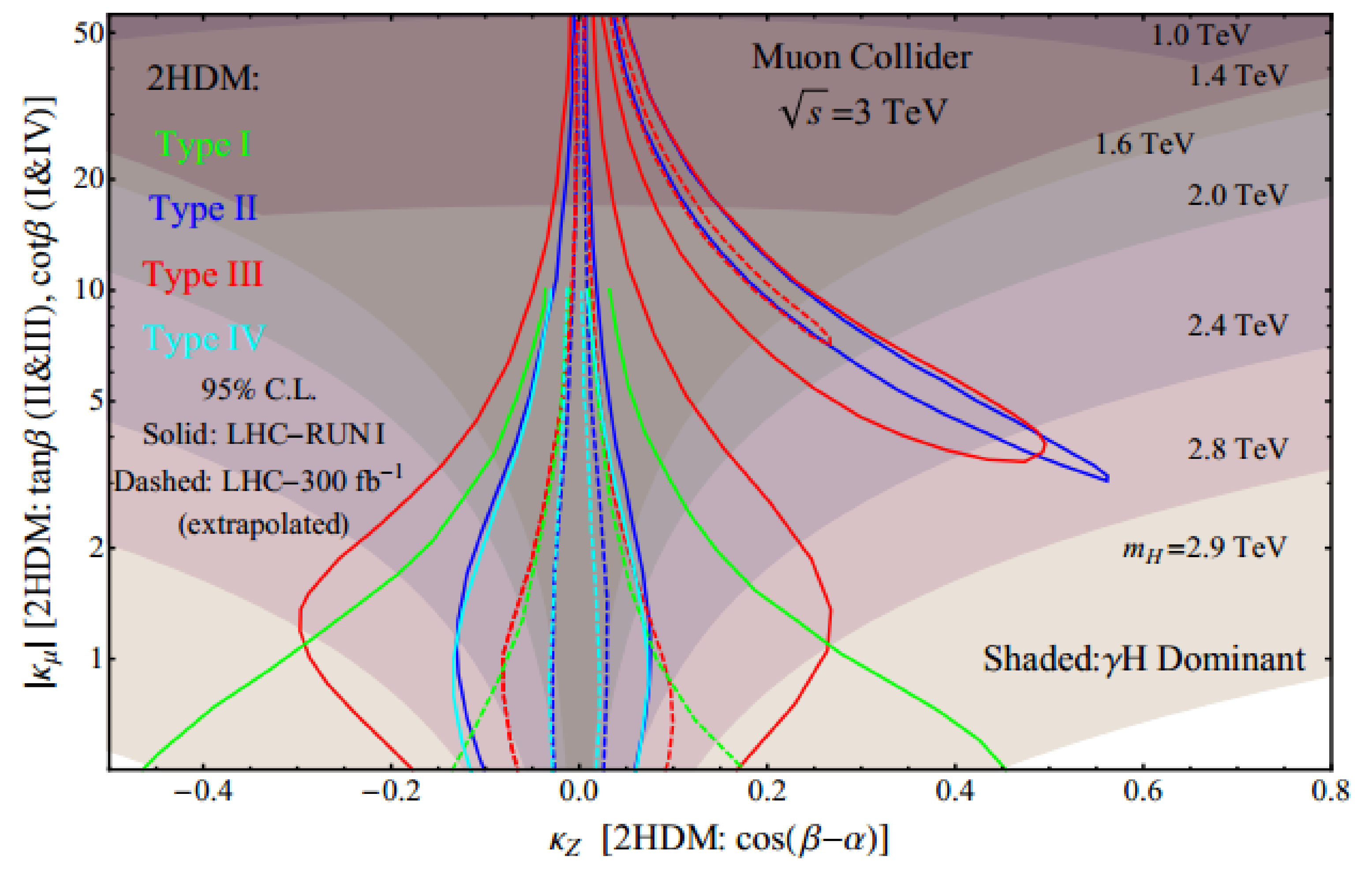


ABSTRACT

Ionization cooling is the preferred method for producing bright muon beams. This cooling technique requires the operation of normal conducting, radio-frequency (rf) accelerating cavities within the multi-tesla fields of dc solenoid magnets. Under these conditions, cavities exhibit increased susceptibility to rf breakdown, which can damage cooling channel components and imposes limits on channel length and transmission efficiency. We report, for the first time, stable high-vacuum, normal-conducting cavity operation at gradients of $50\ \mathrm{MV/m}$ in an external magnetic field of three tesla, through the use of beryllium cavity elements. This eliminates a significant technical risk that has previously been inherent in ionization cooling channel designs.

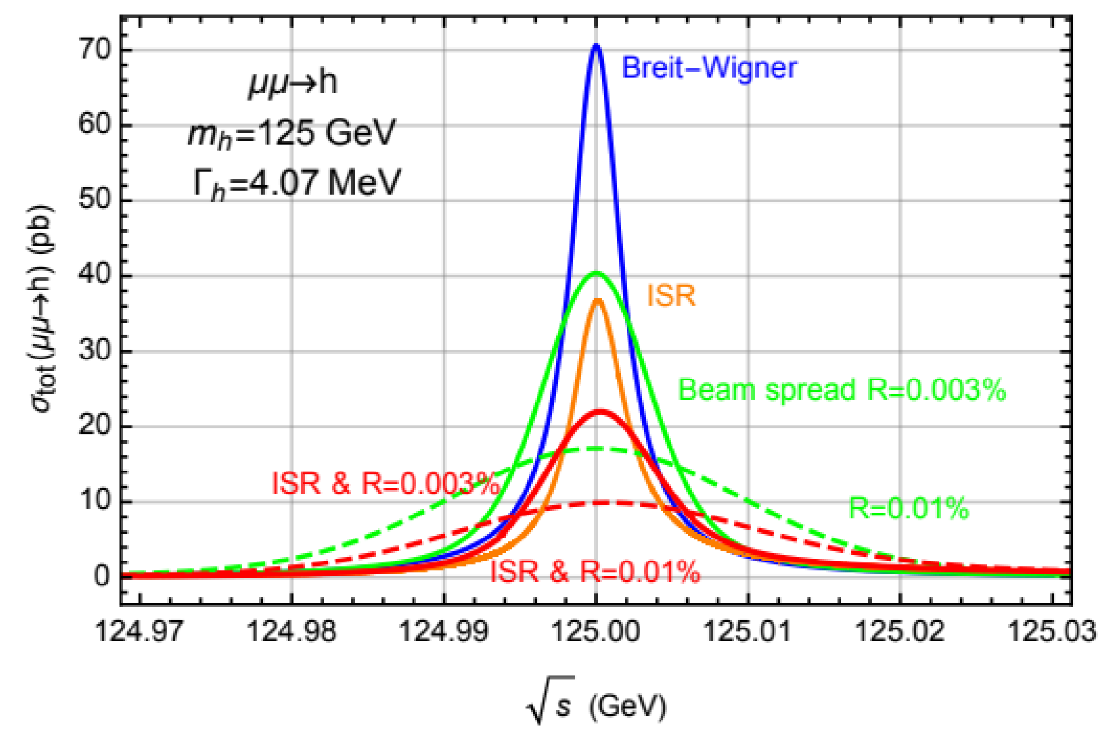


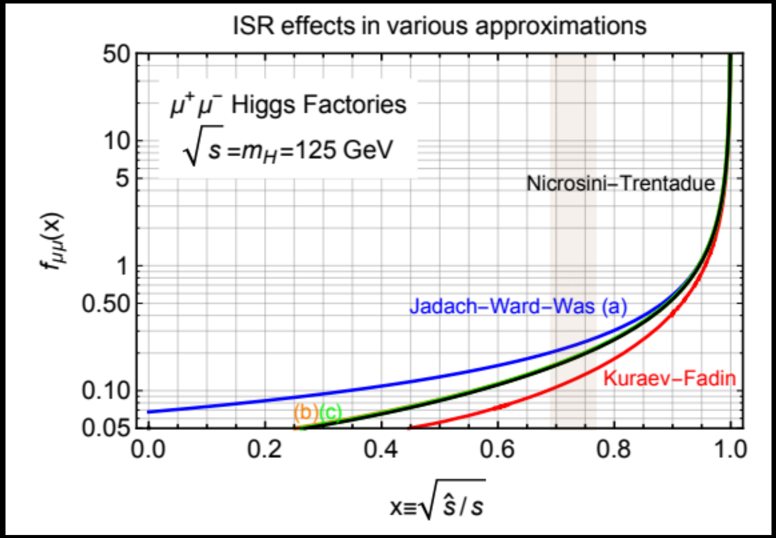
Comparison between Modes



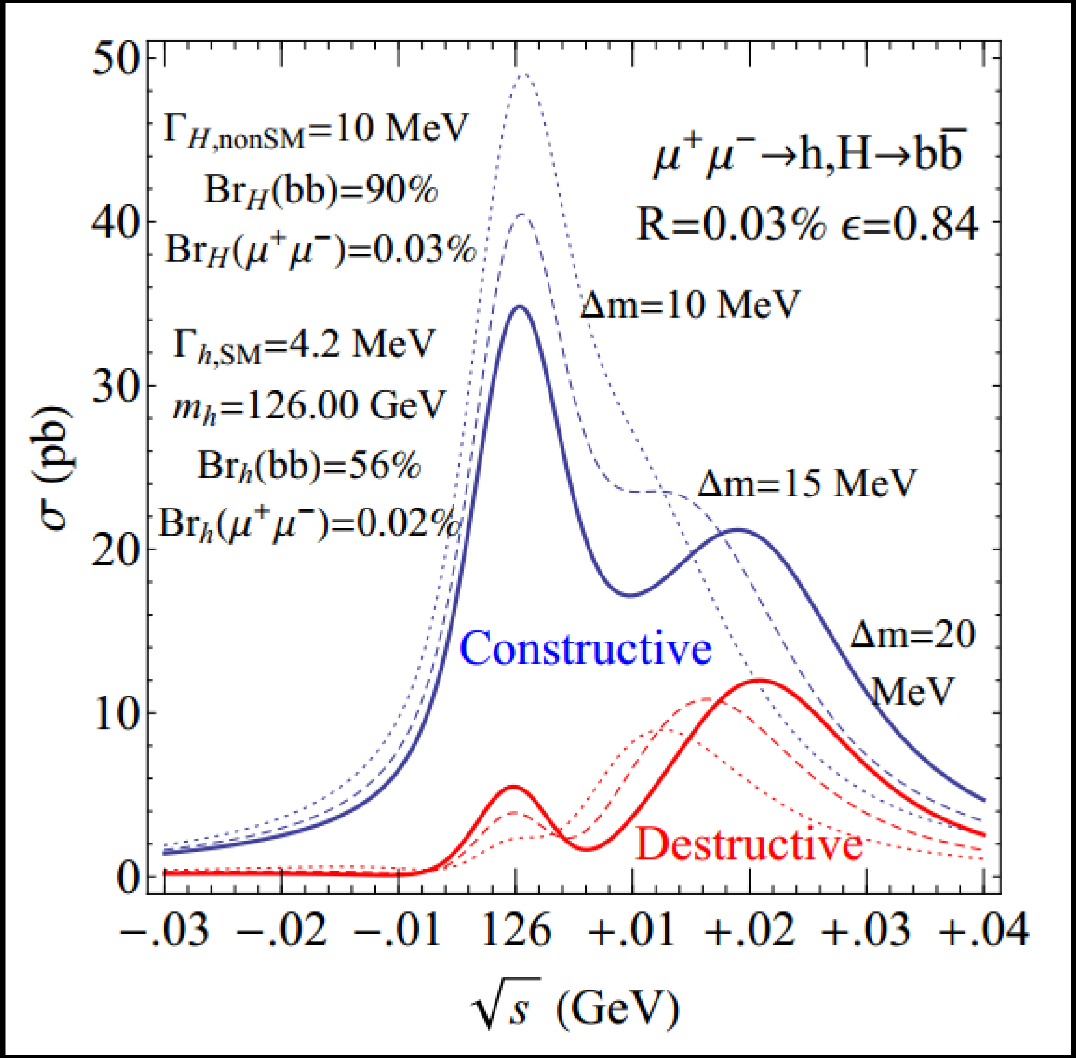
Shaded: photon H/A better than ZH and HA
The heavier the mass, the better photon+H/A
Dotted/dashed: allowed parameter regions by SM Higgs measurements
Current/projection of SM-like Higgs also favors photon+H/A strongly

Challenge of spread





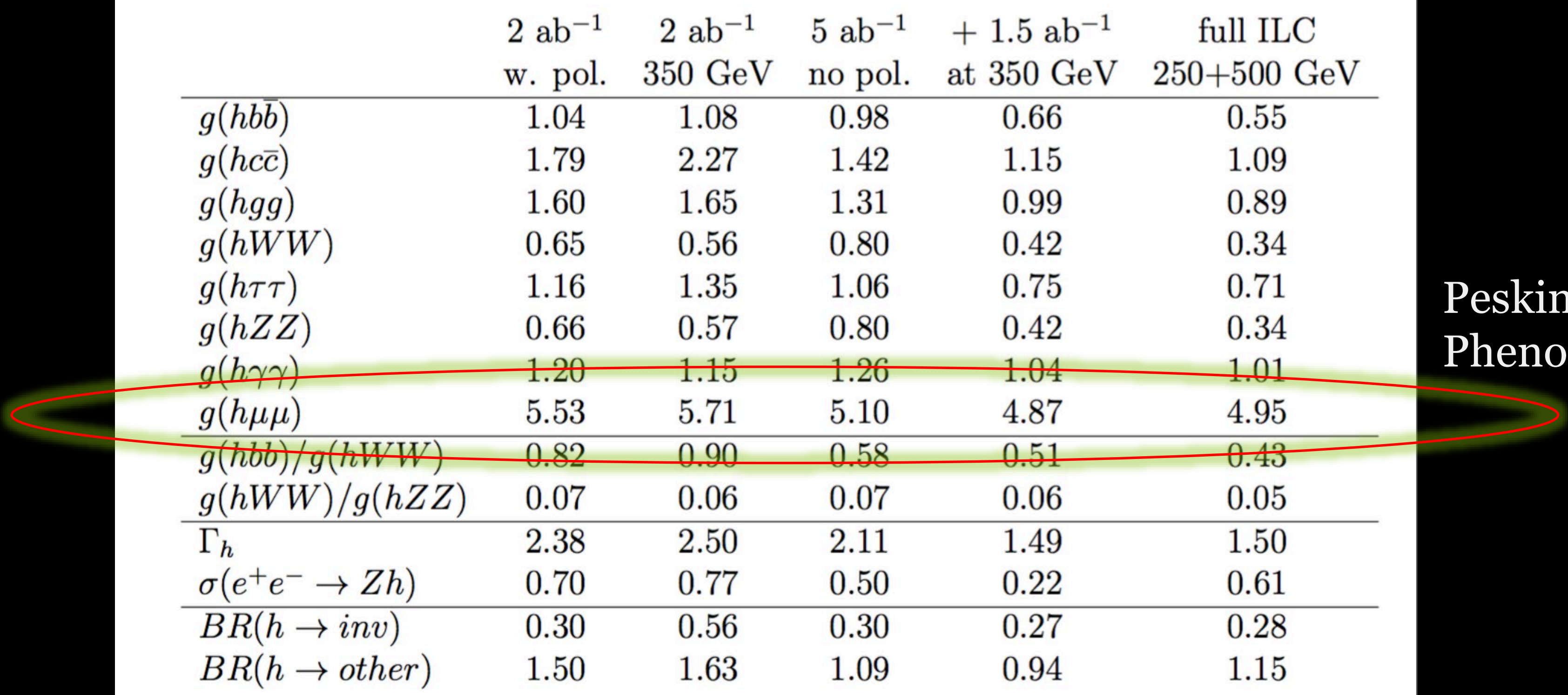
Breaking Mass Degeneracy



Amazing diagnosis power in breaking the near degeneracy to mass splitting order of the width

ZL, et al,
arXiv:1308.2143

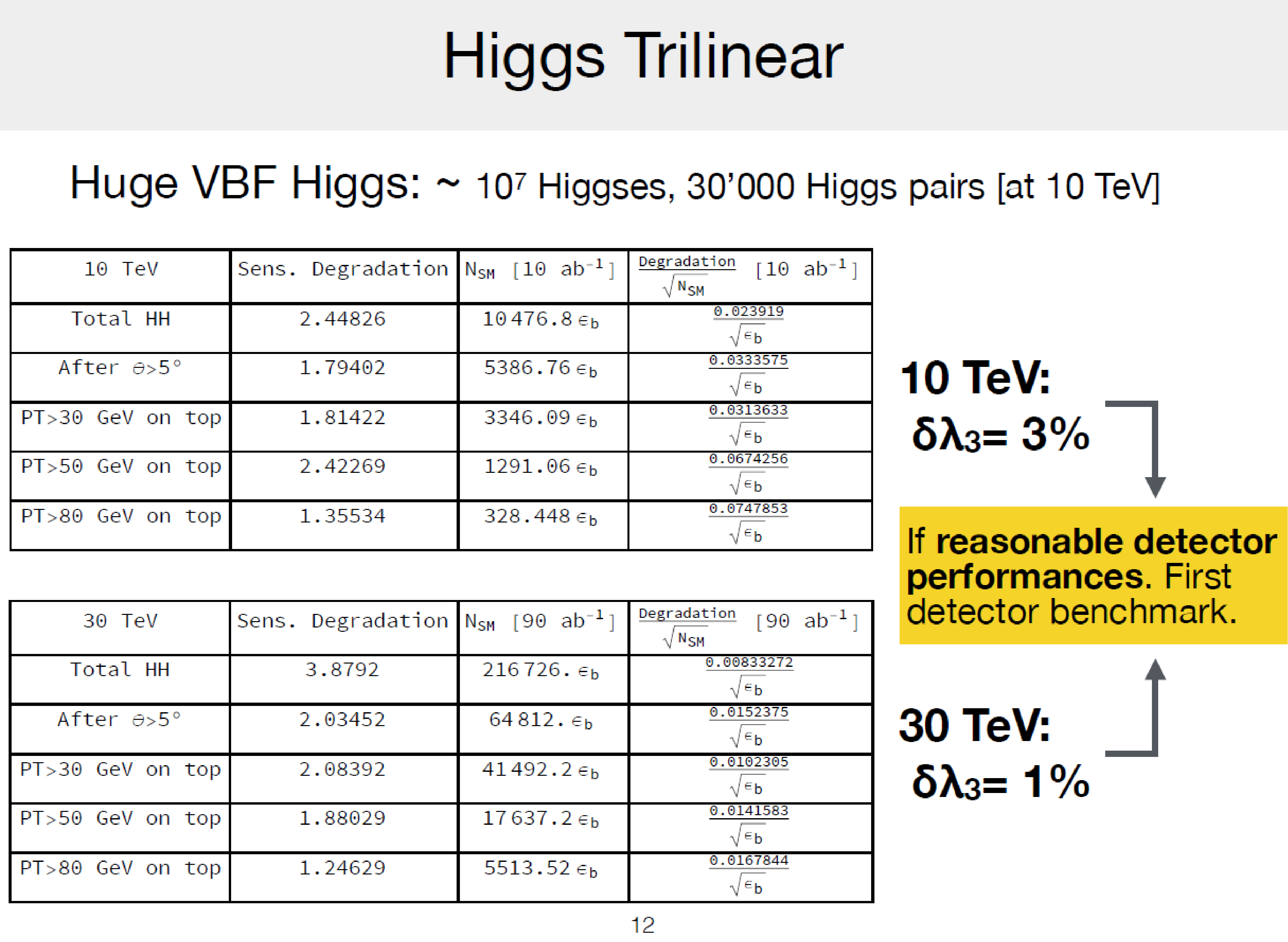
Here are coupling error estimates for various proposed e+e- colliders:



	ILC 250	CLIC	CEPC	FCC-ee	ILC 500
	2 ab^{-1} w. pol.	2 ab^{-1} 350 GeV	5 ab^{-1} no pol.	+ 1.5 ab^{-1} at 350 GeV	full ILC 250+500 GeV
$g(hb\bar{b})$	1.04	1.08	0.98	0.66	0.55
$g(hc\bar{c})$	1.79	2.27	1.42	1.15	1.09
$g(hgg)$	1.60	1.65	1.31	0.99	0.89
$g(hWW)$	0.65	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.16	1.35	1.06	0.75	0.71
$g(hZZ)$	0.66	0.57	0.80	0.42	0.34
$g(h\gamma\gamma)$	1.20	1.15	1.26	1.04	1.01
$g(h\mu\mu)$	5.53	5.71	5.10	4.87	4.95
$g(hbb)/g(hWW)$	0.82	0.90	0.58	0.51	0.43
$g(hWW)/g(hZZ)$	0.07	0.06	0.07	0.06	0.05
Γ_h	2.38	2.50	2.11	1.49	1.50
$\sigma(e^+e^- \to Zh)$	0.70	0.77	0.50	0.22	0.61
$BR(h \to inv)$	0.30	0.56	0.30	0.27	0.28
$BR(h \to other)$	1.50	1.63	1.09	0.94	1.15

errors in %

Peskin
Pheno18



Higgs Trilinear

Huge VBF Higgs: ~ 10^7 Higgses, 30’000 Higgs pairs [at 10 TeV]

10 TeV	Sens. Degradation	N_{SM} [10 ab^{-1}]	$\frac{\text{Degradation}}{\sqrt{N_{SM}}}$ [10 ab^{-1}]
Total HH	2.44826	$10\,476.8\,\epsilon_b$	$\frac{0.023919}{\sqrt{\epsilon_b}}$
After $\theta>5^\circ$	1.79402	$5386.76\,\epsilon_b$	$\frac{0.0333575}{\sqrt{\epsilon_b}}$
PT>30 GeV on top	1.81422	$3346.09\,\epsilon_b$	$\frac{0.0313633}{\sqrt{\epsilon_b}}$
PT>50 GeV on top	2.42269	$1291.06\,\epsilon_b$	$\frac{0.0674256}{\sqrt{\epsilon_b}}$
PT>80 GeV on top	1.35534	$328.448\,\epsilon_b$	$\frac{0.0747853}{\sqrt{\epsilon_b}}$

30 TeV	Sens. Degradation	N_{SM} [90 ab^{-1}]	$\frac{\text{Degradation}}{\sqrt{N_{SM}}}$ [90 ab^{-1}]
Total HH	3.8792	$216\,726.\,\epsilon_b$	$\frac{0.00833272}{\sqrt{\epsilon_b}}$
After $\theta>5^\circ$	2.03452	$64\,812.\,\epsilon_b$	$\frac{0.0152375}{\sqrt{\epsilon_b}}$
PT>30 GeV on top	2.08392	$41\,492.2\,\epsilon_b$	$\frac{0.0102305}{\sqrt{\epsilon_b}}$
PT>50 GeV on top	1.88029	$17\,637.2\,\epsilon_b$	$\frac{0.0141583}{\sqrt{\epsilon_b}}$
PT>80 GeV on top	1.24629	$5513.52\,\epsilon_b$	$\frac{0.0167844}{\sqrt{\epsilon_b}}$

10 TeV:
$\delta\lambda_3$= 3%

If **reasonable detector performances**. First detector benchmark.

30 TeV:
$\delta\lambda_3$= 1%

12

Wulzer’s talk two weeks ago