an introductory talk on

Standard Model and Beyond

at (future) *pp* machines

ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)

OCT. 4 2024, LNF FRASCATI

ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Roma3

Workshop on High Luminosity LHC and Hadron Colliders

1–4 Oct 2024
Laboratori Nazionali di Frascati (Rome), Italy

an introductory talk on

Standard Model and Beyond

at (future) *pp* machines

FRIDAY, OCTOBER 4

9:00 AM → 1:10 PM **Standard Model and Beyond**
Conveners: Davide Pagani, Livia Soffi, Ramona Groeber, Roberto Di Nardo

9:00 AM	**Introductory talk** **Speaker:** Roberto Franceschini (Istituto Nazionale di Fisica Nucleare)	1h
10:00 AM	**Experimental: exotica + SMEFT(Higgs, Top, EW)** **Speaker:** LIVIA SOFFI (Istituto Nazionale di Fisica Nucleare)	40m
10:40 AM	**Coffee break**	30m
11:10 AM	**Theory: SMEFT (Top and EW)** **Speaker:** Víctor Miralles (University of Manchester)	40m
11:50 AM	**Theory: Higgs** **Speaker:** Giuseppe Degrassi (Istituto Nazionale di Fisica Nucleare)	40m
12:30 PM	**Theory: Exotica (ALPs, DM, Light states, ..)** **Speaker:** Enrico Bertuzzo (University of Modena)	40m

2:30 PM → 3:50 PM **Machine Learning**

2:30 PM	**Machine learning in high energy physics: from experiment to theory** **Speaker:** Francesco Armando Di Bello (Istituto Nazionale di Fisica Nucleare)	40m
3:10 PM	**Machine learning in high energy physics: from theory to discovery** **Speaker:** Marco Letizia (Istituto Nazionale di Fisica Nucleare)	40m

3:50 PM → 4:10 PM **Final Discussion** 20m

4:10 PM → 4:40 PM **Coffee break** 30m

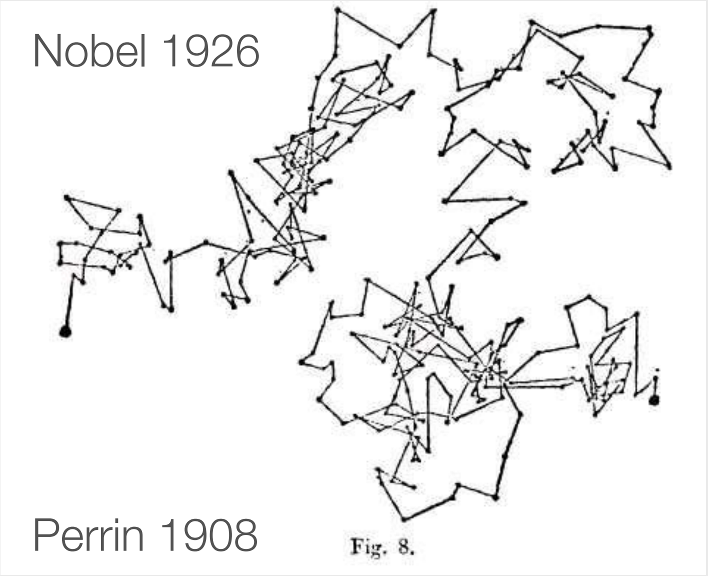
Workshop o … l Hadron Colliders

1–4 Oct 2024
Laboratori Nazionali di Frascati (Rome), Italy

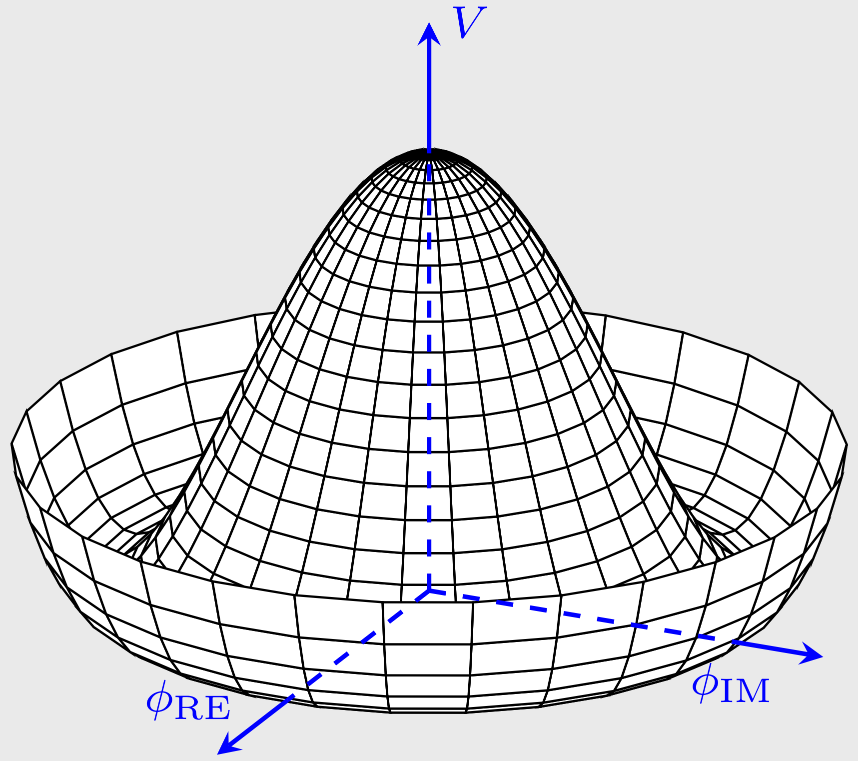
Short-Distance, the unreasonable effectiveness of

BSM is widely associated with short-distance (**high energy**) because of the inherent prejudice that at the microscopic scale we will understand the most fundamental aspects of Nature. The idea is that if you know the *micro* you can derive the *macro* … not trivial at all.
Explaining the *macro* using the *micro* has lead us a long way, and seemingly it does not stop to work. “To work” means that we understand new layers of Nature, but, even more important, the acquired knowledge raises **ever deeper questions on the next layer** of understanding of Nature.

- **Atoms**, that were the micro-physics BSM of the mid/late-19th century, opened up questions on the time-reversibility of the basic laws of physics. Maybe solved today, maybe not, I am not in position to judge.



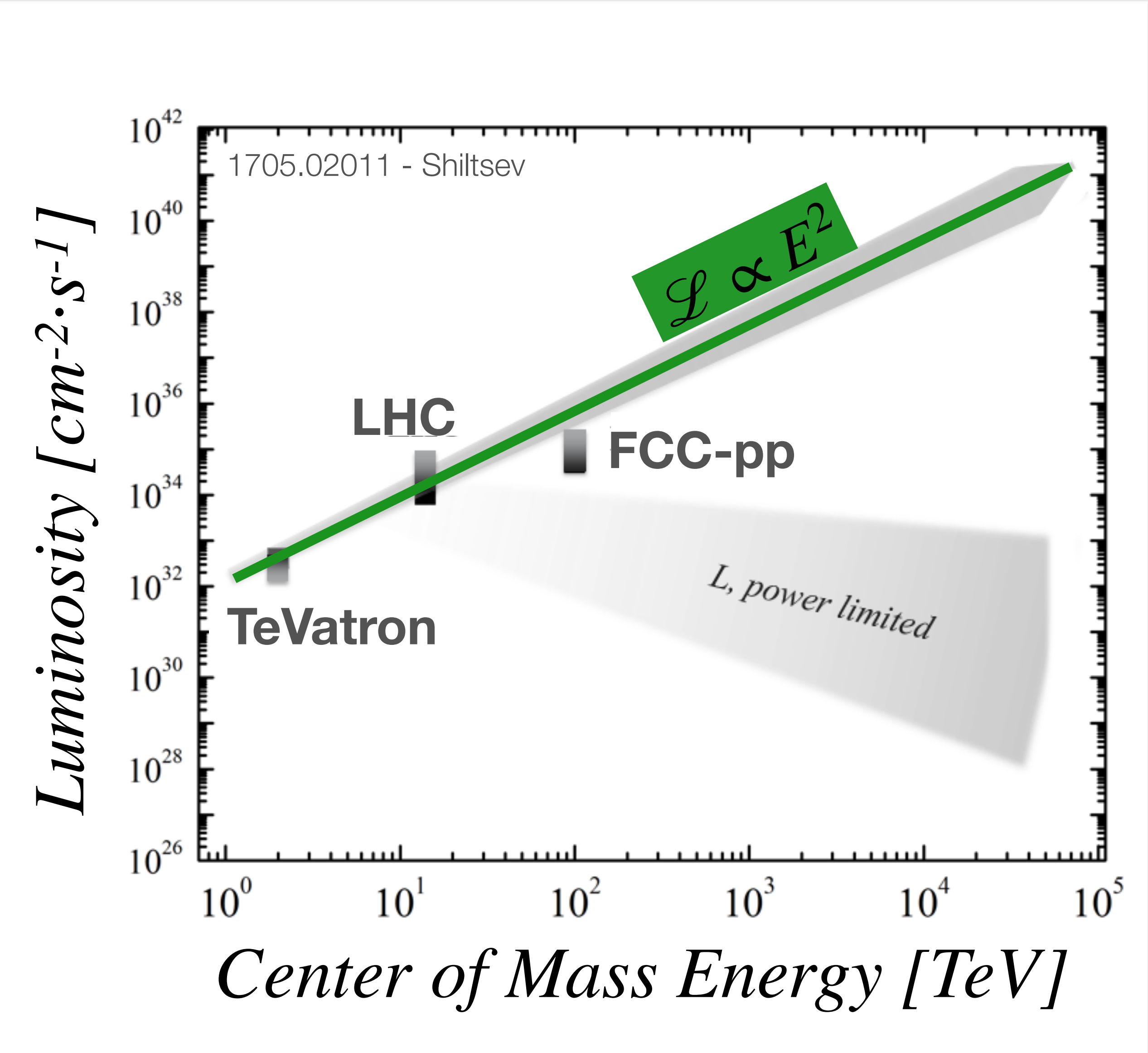
- Advocating for **symmetry** to explain the fundamental interactions worked out great. We are now lead to the question *“**how the symmetry was broken?**”* .This is “the” question about the next layer for our* generation, in my humble opinion, to be applied to the **electroweak** gauge symmetry, **flavor** symmetry, **accidental** baryon/lepton number, … That is also the flip side of asking what role symmetry still has to play in increasing our understanding of the Universe, not trivial to answer.



Page-1

Given we want to explore the shortest distances, then *pp* machines fill many checkboxes of the ideal tools:

- beams are relatively easy to handle (do not decay, do not annihilate, radiation is suppressed by m_p^{-4}, …) thus can reach the highest energies, which is nearly all we seem to care about.
- of course there is an issue with **luminosity** if you get down to numbers



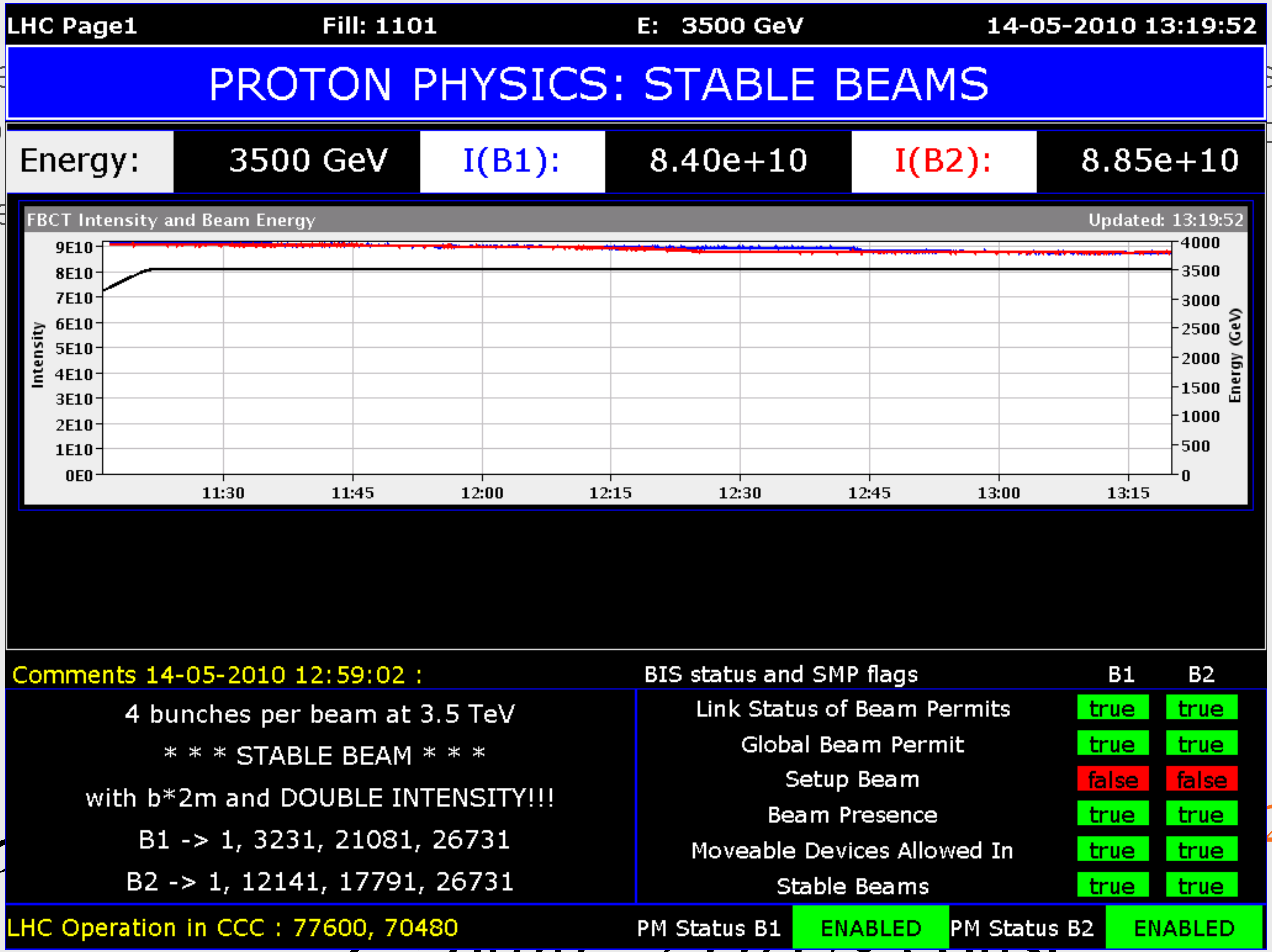
$$\sigma(ab \to cd) \sim 1/E^2 \Rightarrow \text{you want } \mathscr{L} \sim E^2$$

$$\mathscr{L} \cdot \sigma(ab \to cd) \sim \text{const}$$

Page-1

Given we want to explore the shortest distances, then *pp* machines fill many checkboxes of the ideal tools:

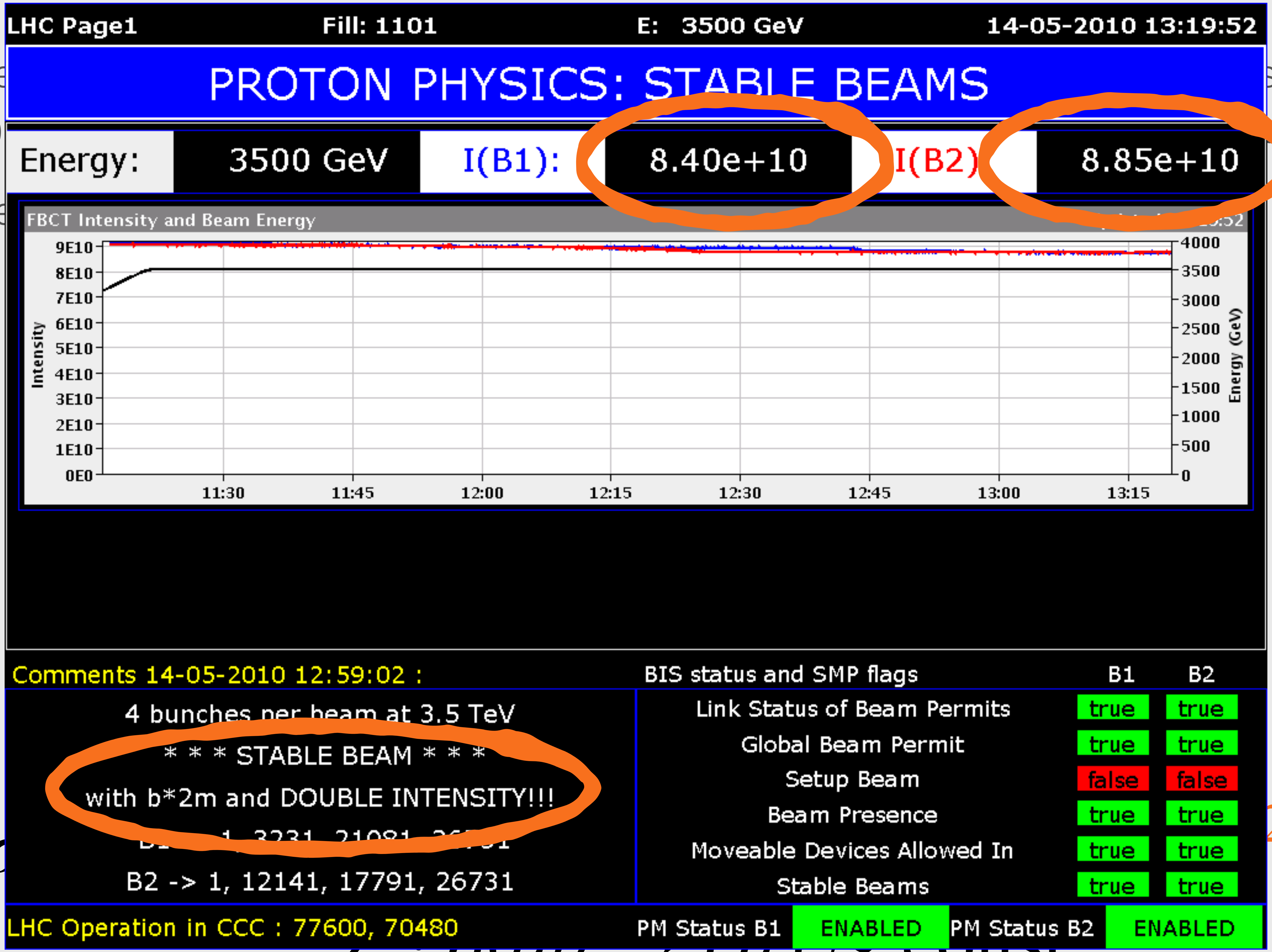
- beams are re… …ssed by m_p^{-4}, …) …bout.
- of course the…



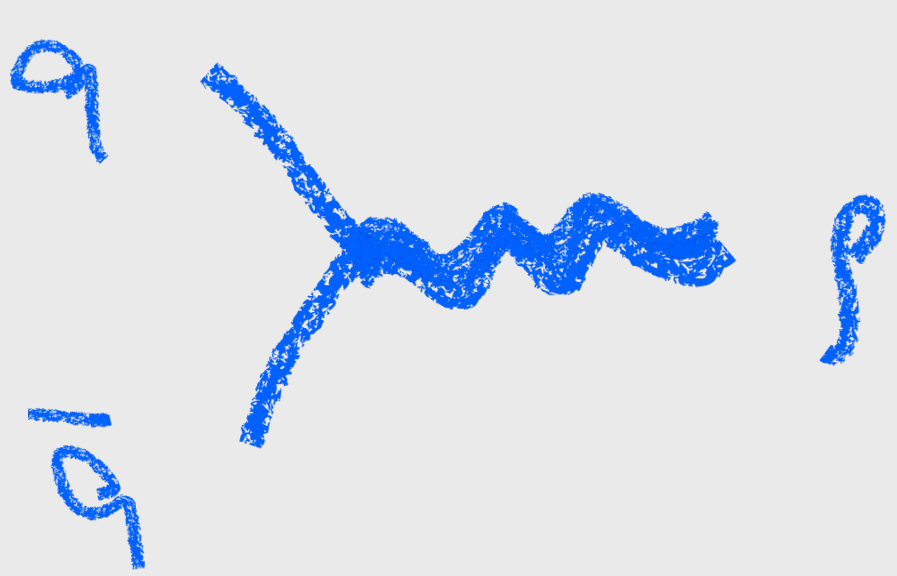
Page-1

Given we want to explore the shortest distances, then *pp* machines fill many checkboxes of the ideal tools:

- beams are re… ssed by m_p^{-4}, …) … out.
- of course the

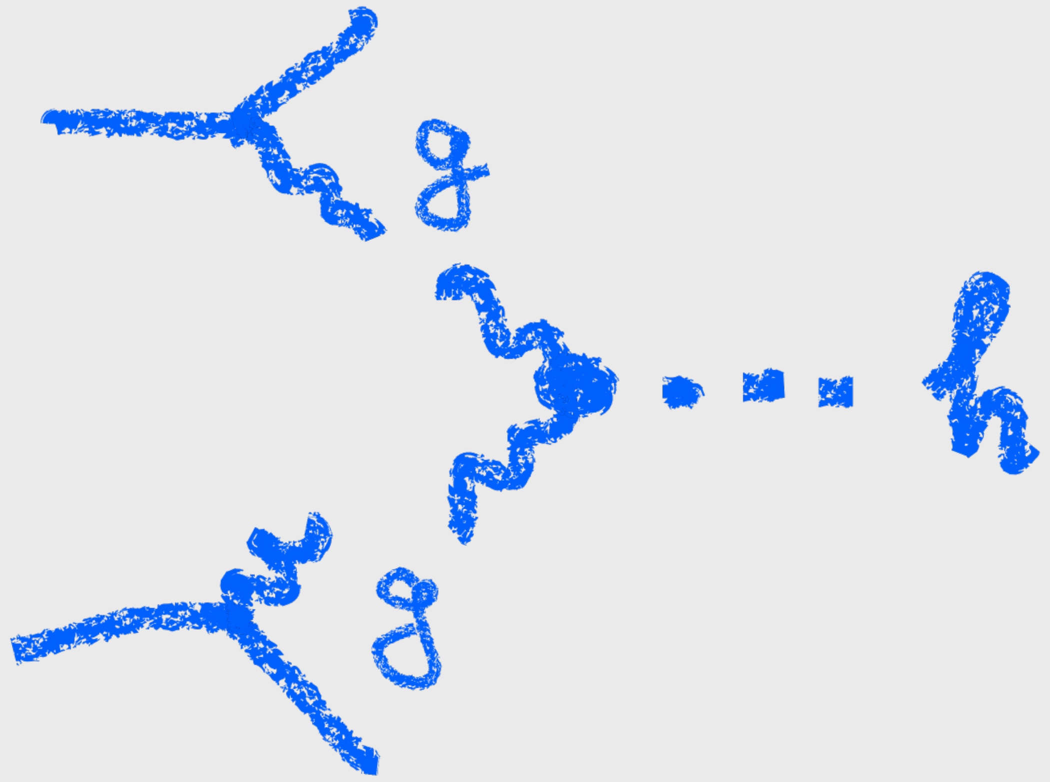


What kind of BSM can we look for at a *pp* machine?

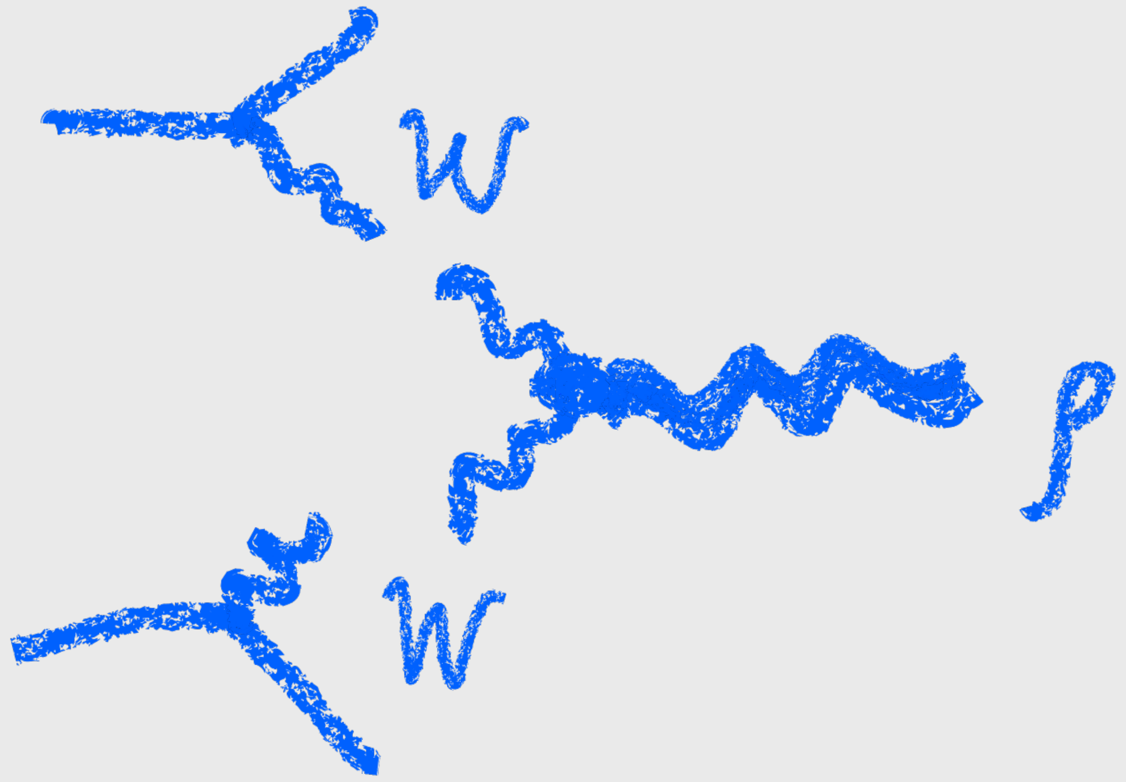


sea-valence

valence-valence



colored sea



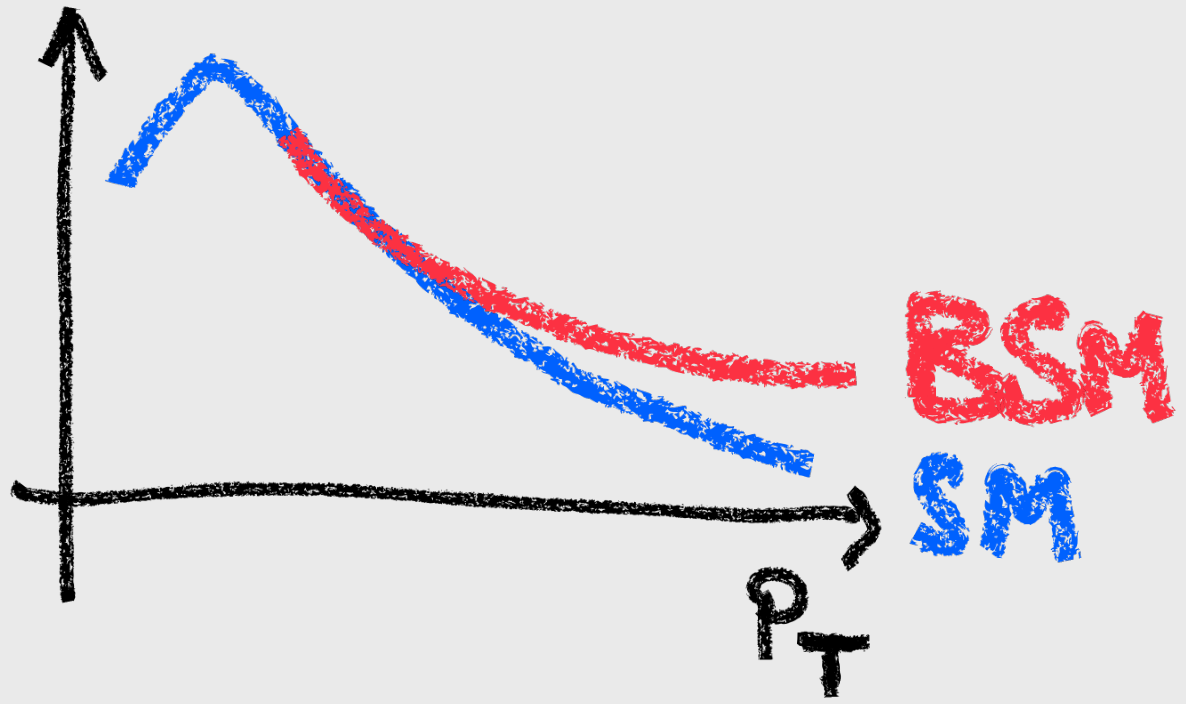
weak sea

plus all the “precision”
that you can steal from
a typical e^+e^- machine

CMS-PAS-SMP-22-010

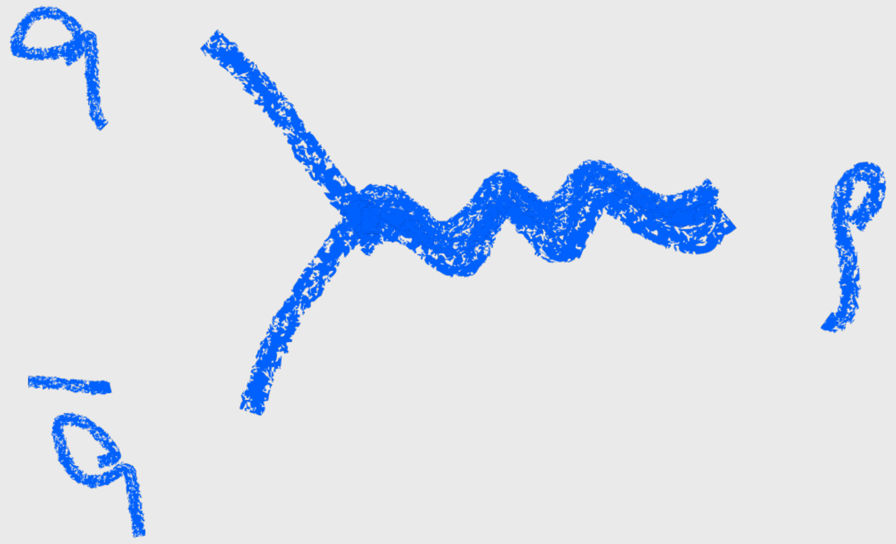
low-p_T LEP-style $A_{FB}^{(l)}$, $\sin^2\theta_W$, …

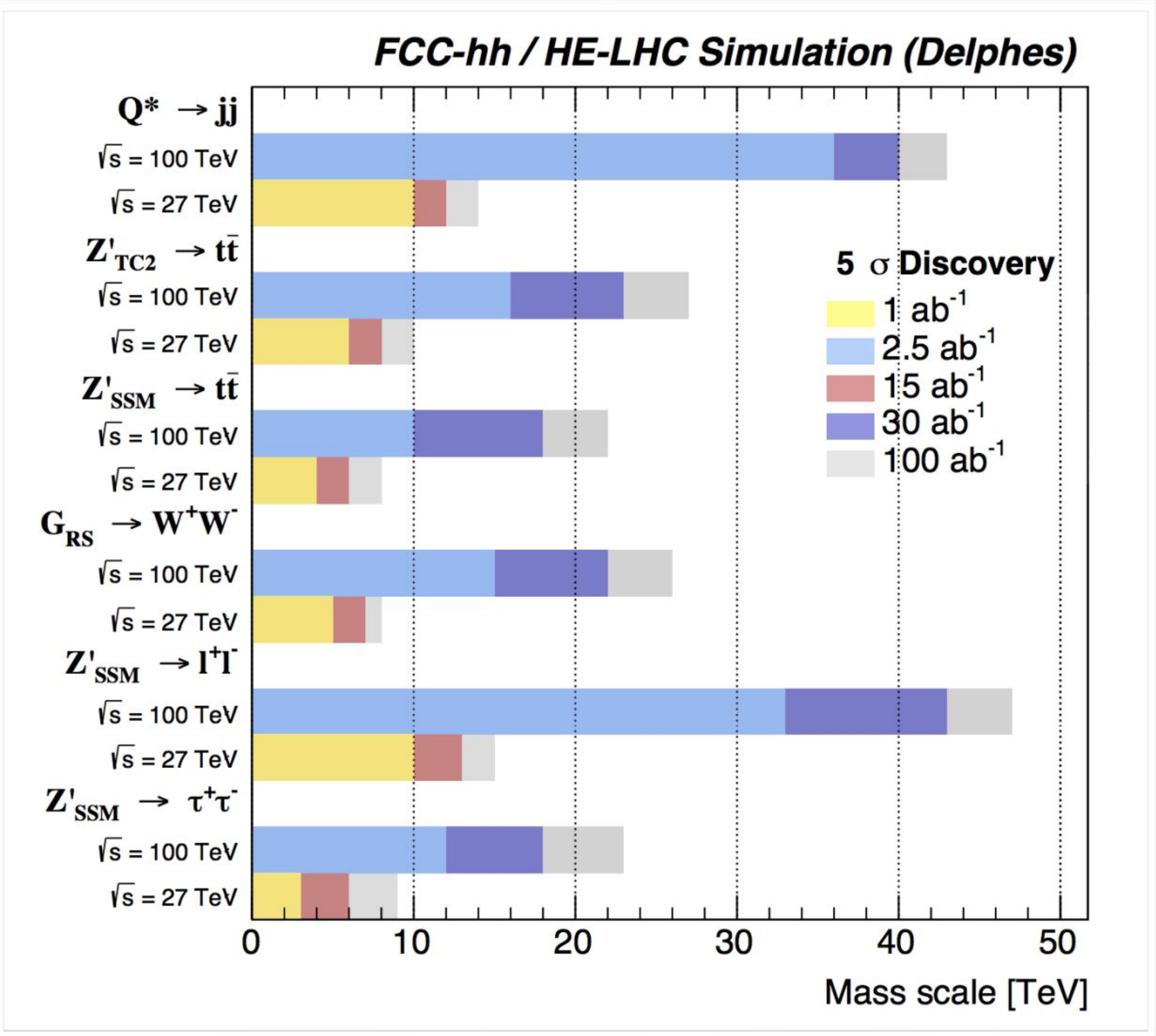
high-p_T EFT-style



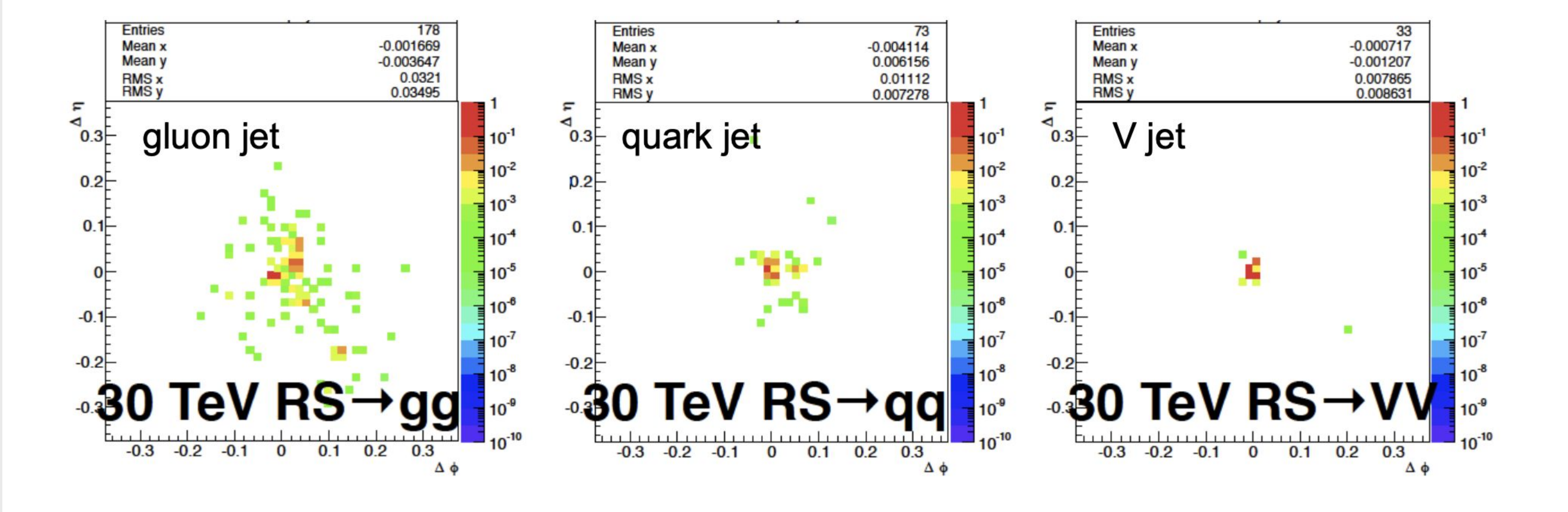
What kind of BSM can we look for at a *pp* machine?

For these kinds of searches we have a clear path ahead

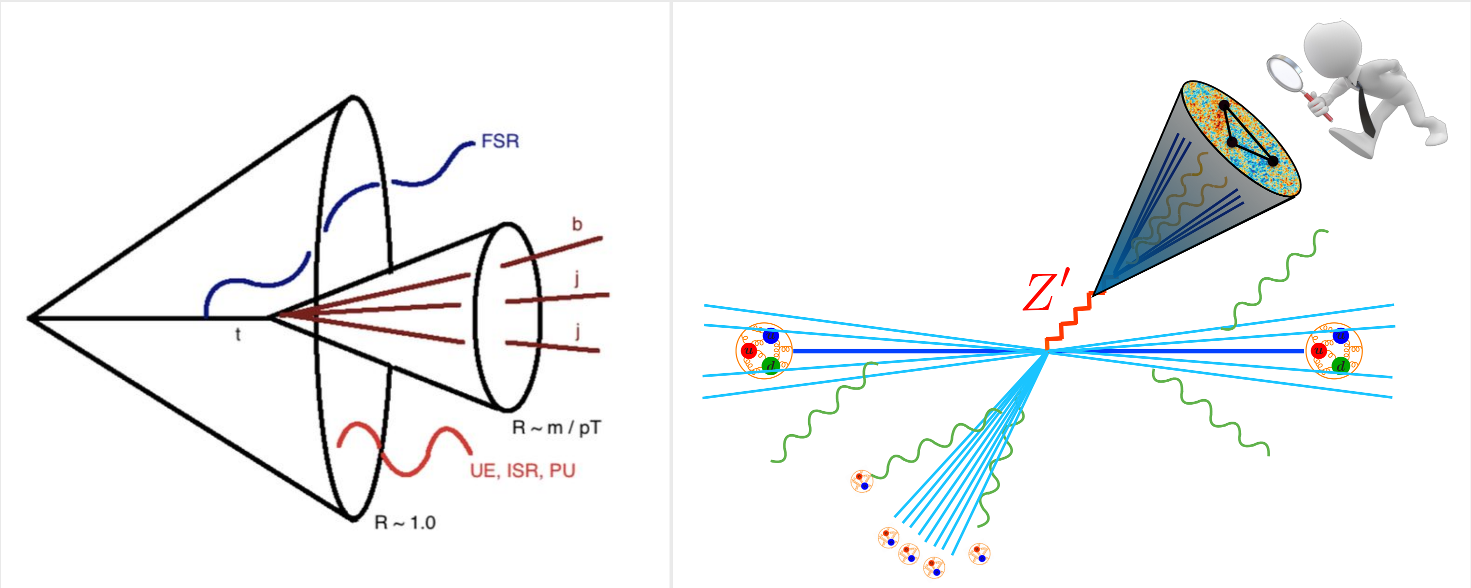




up to non-negligible challenges in dealing with the reconstruction



see M. Selvaggi and I. Moult on Wed.



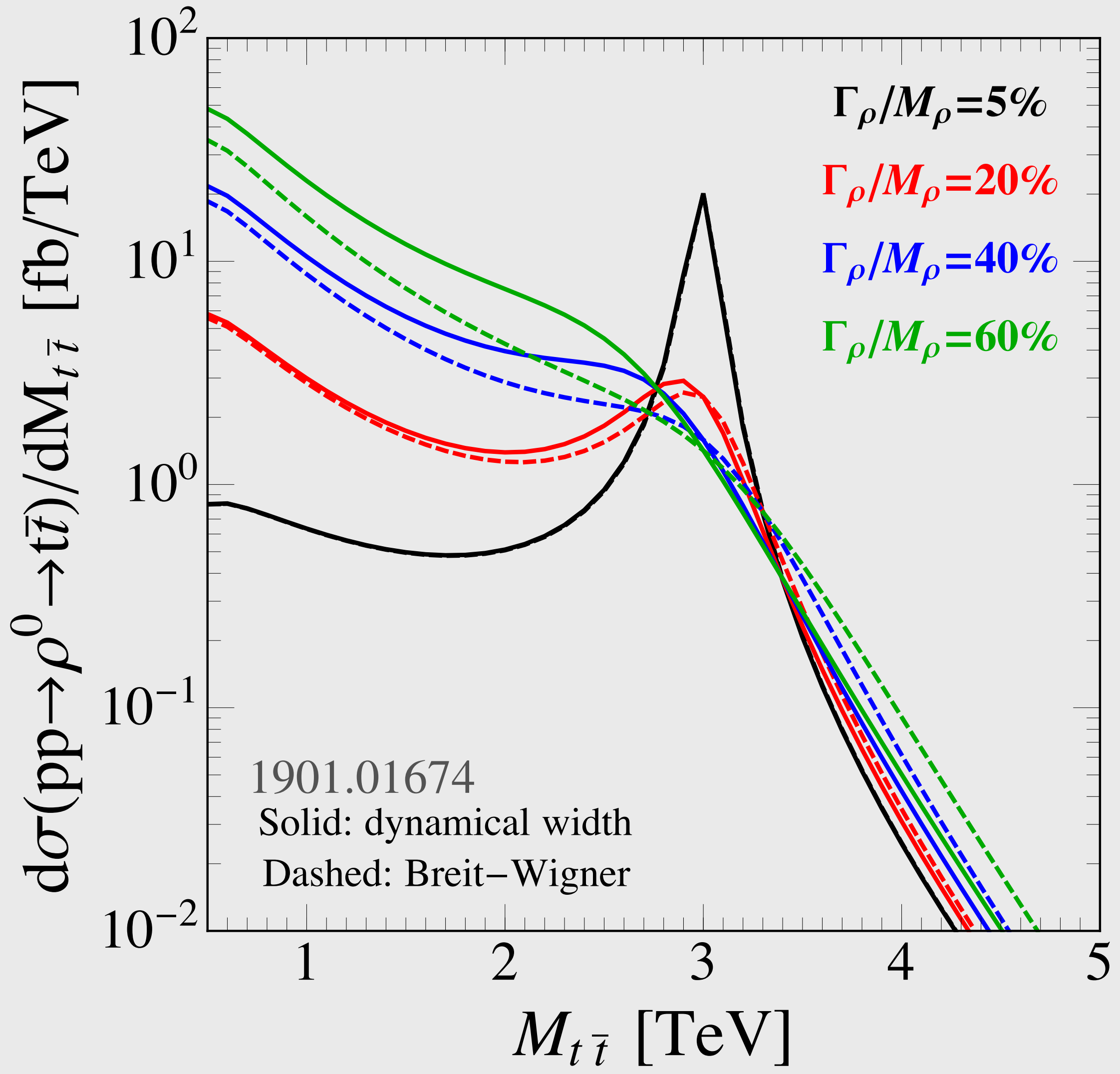
What kind of BSM can we look for at a *pp* machine?

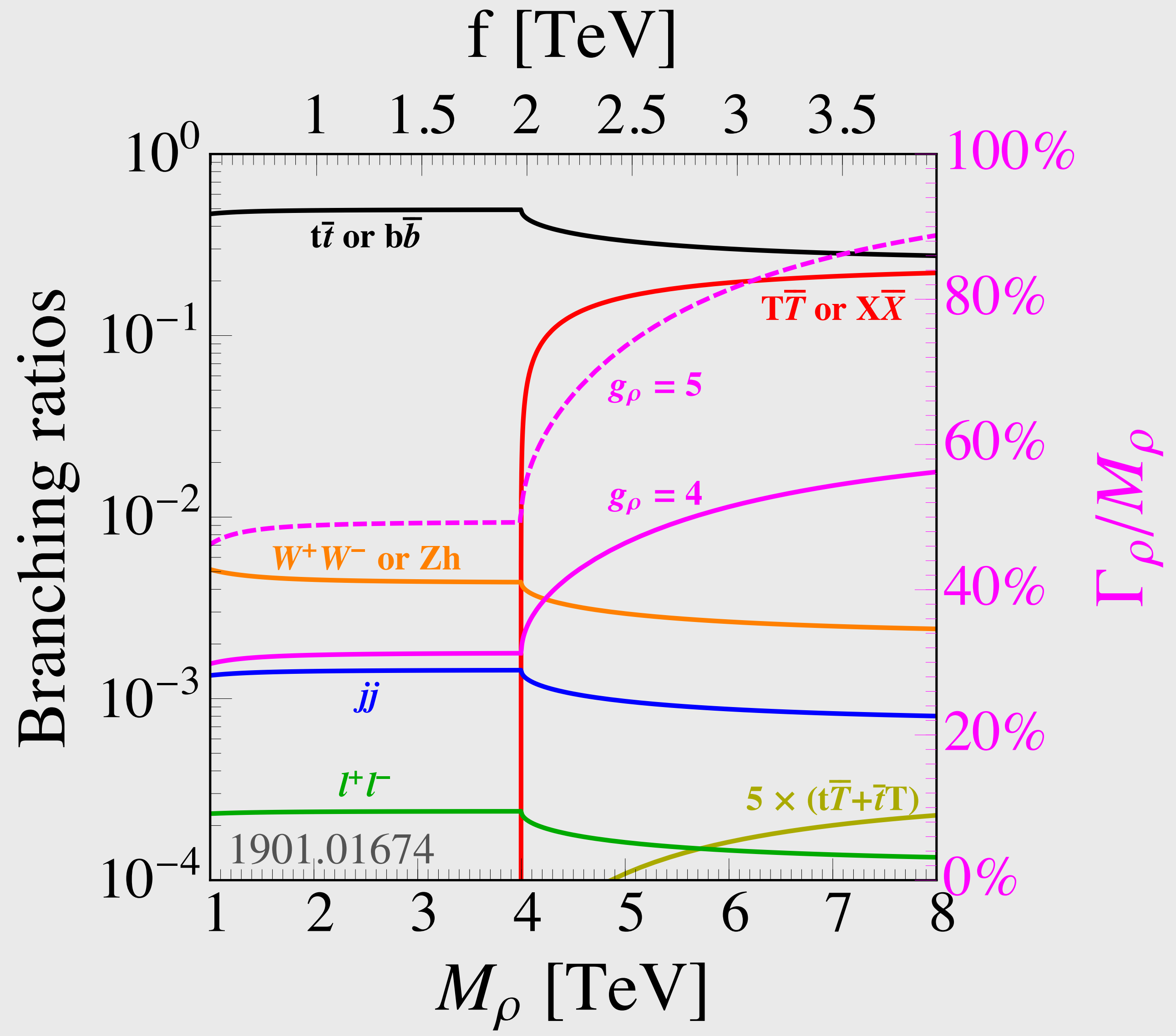
further challenges in dealing with broad or non-resonant signals?

it is far less studied so far.

1706.03068v1 - Alioli, Farina, Pappadopulo, Ruderman - for LHC

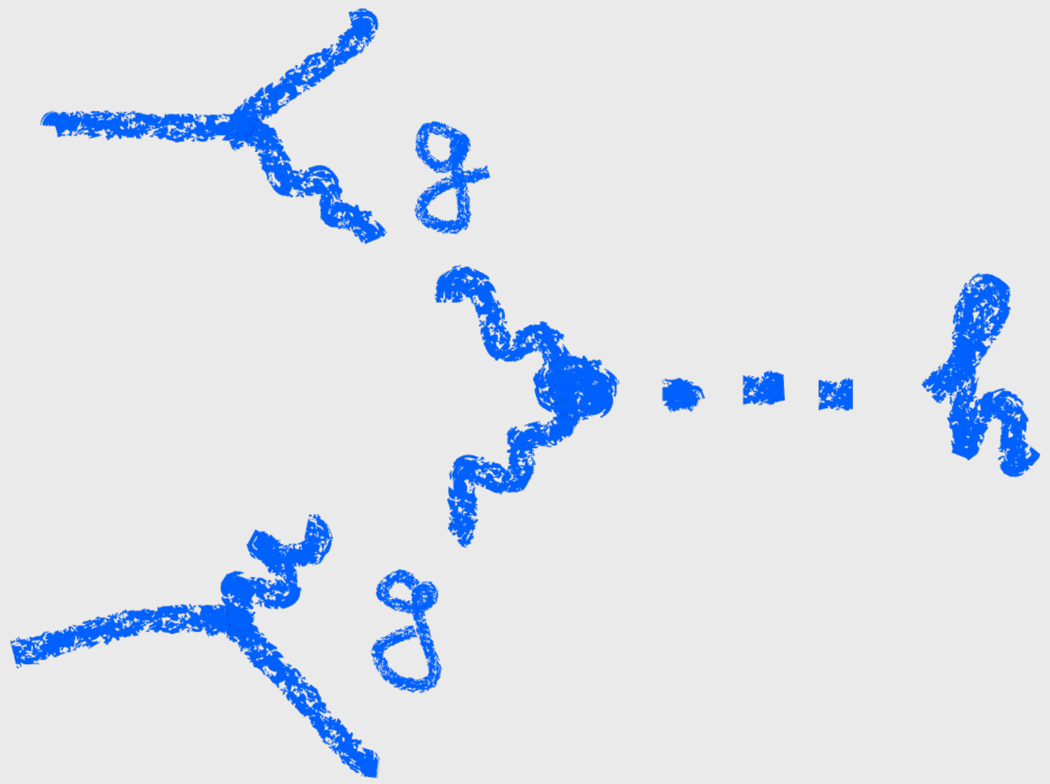
the reach does not necessarily require using mass reconstruction, need to keep an eye on angular resolution as well, but seems less of an issue

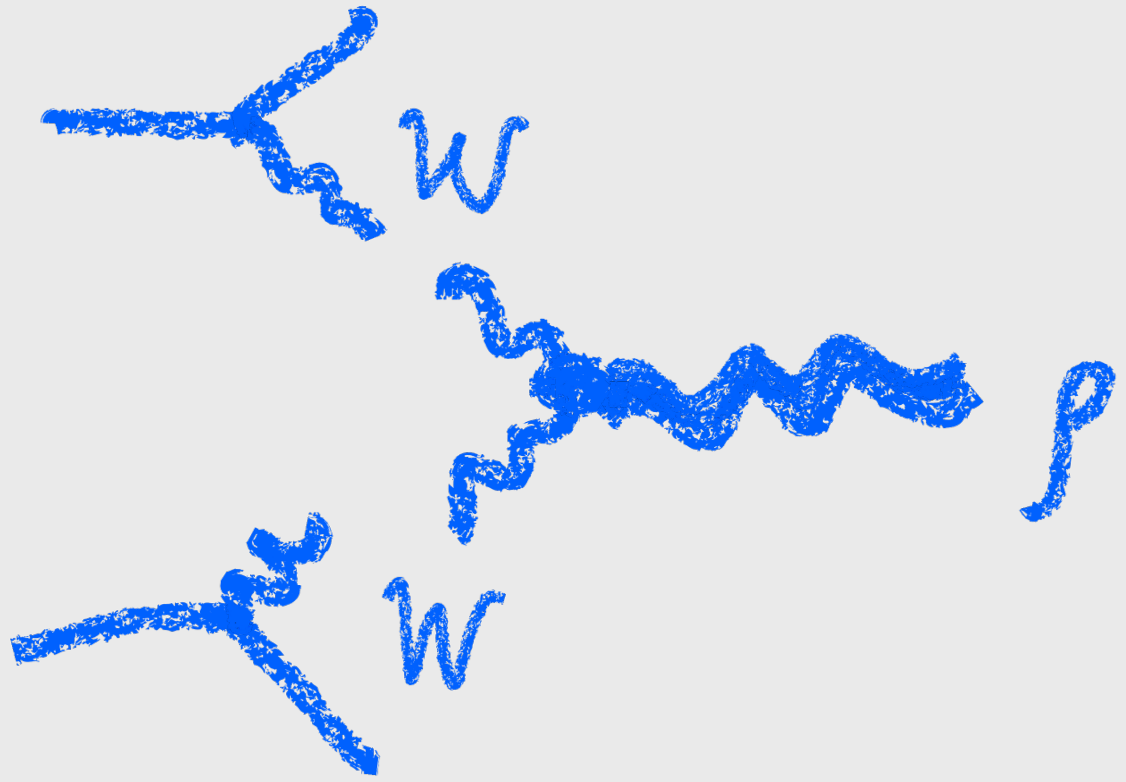




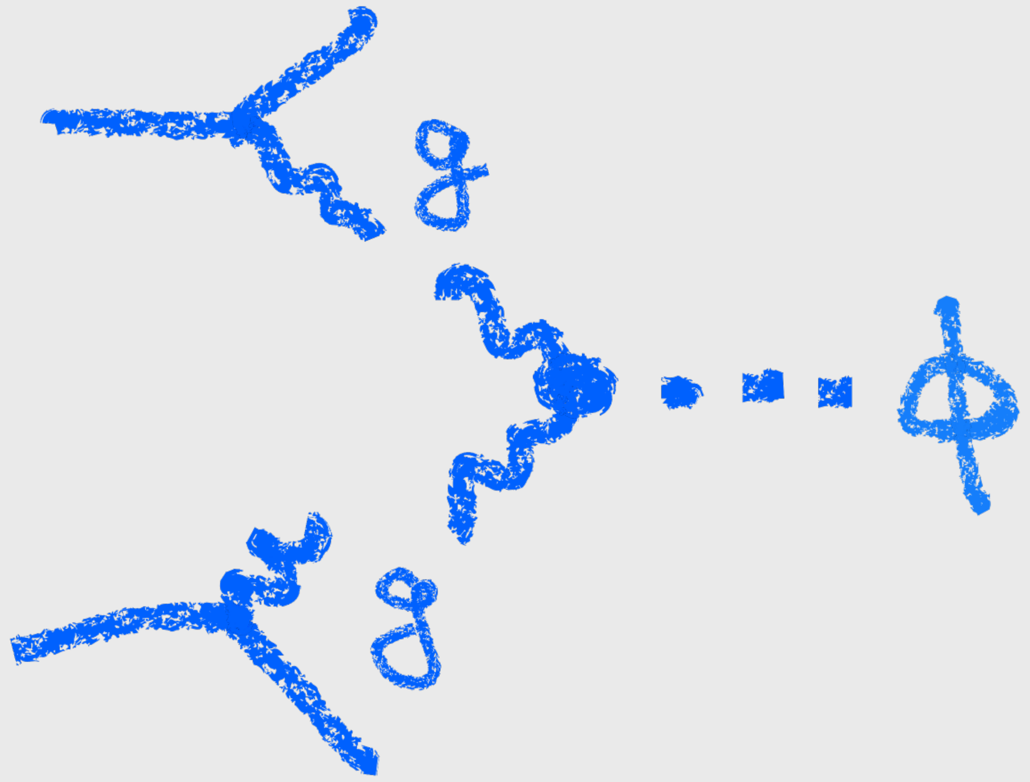
What kind of BSM can we look for at a *pp* machine?

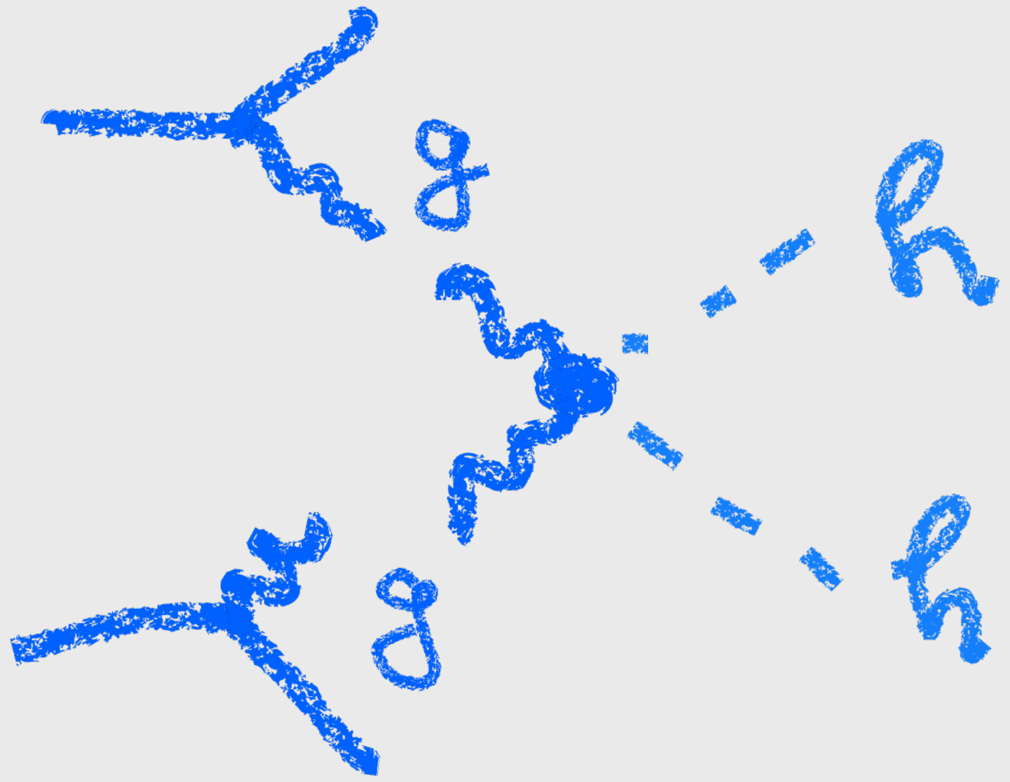
A main driver for the physics program of (HL)-LHC and beyond

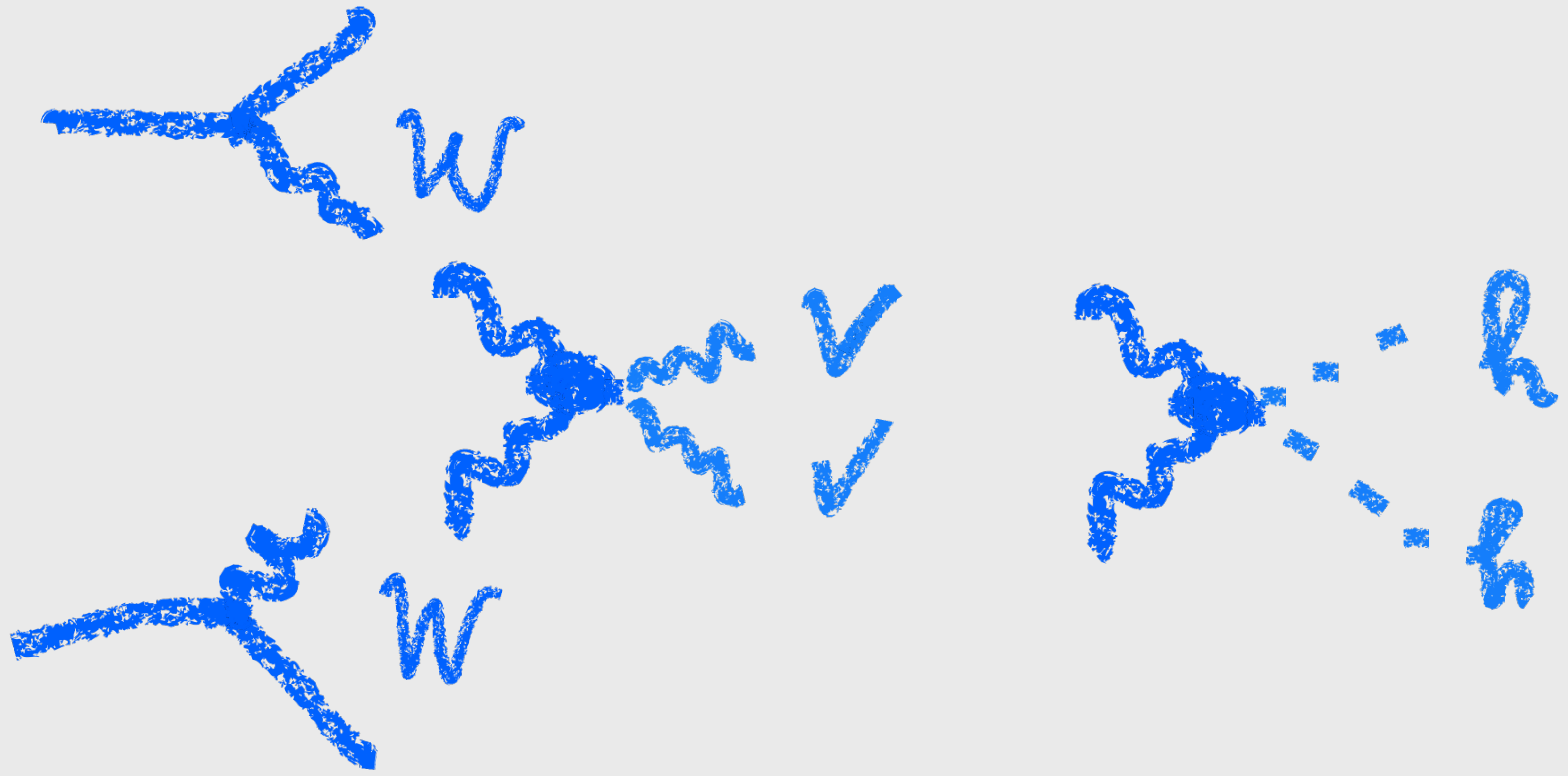




More nuanced questions, e.g. is the Goldstone-Gauge-Higgs sector SO(4) invariant?



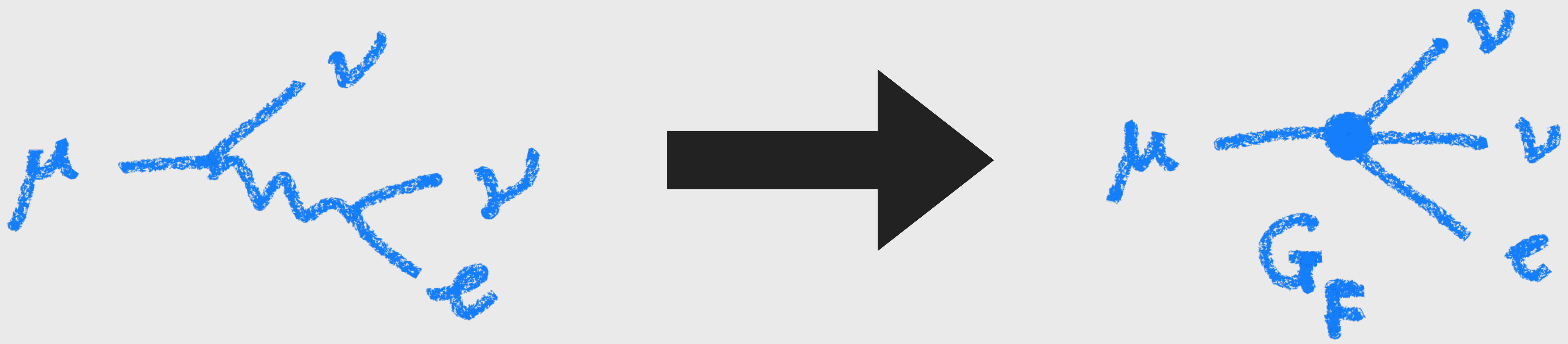




Precision physics at a *pp* machine?

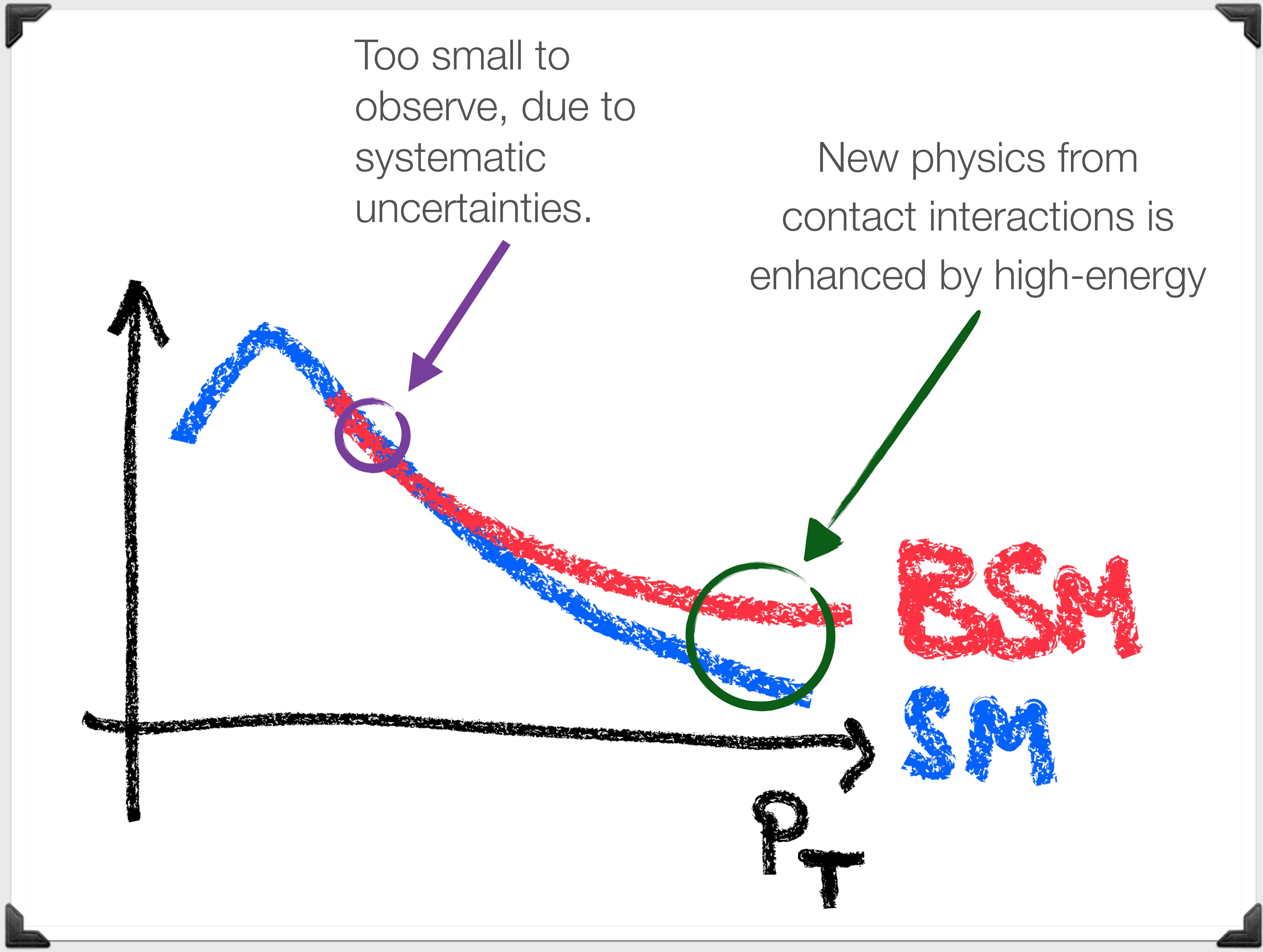
If the LHC has not found any evidence of new physics it is reasonable to assume that new physics is heavy.

Then it can be encapsulated in contact interactions.



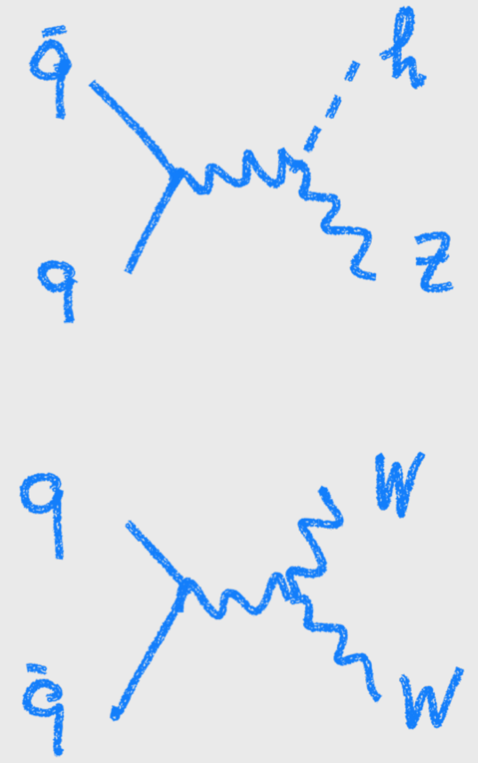
The effect of contact interactions, like the Fermi 4-fermion interaction, grows with energy.

A *pp* machine can exploit this effect!

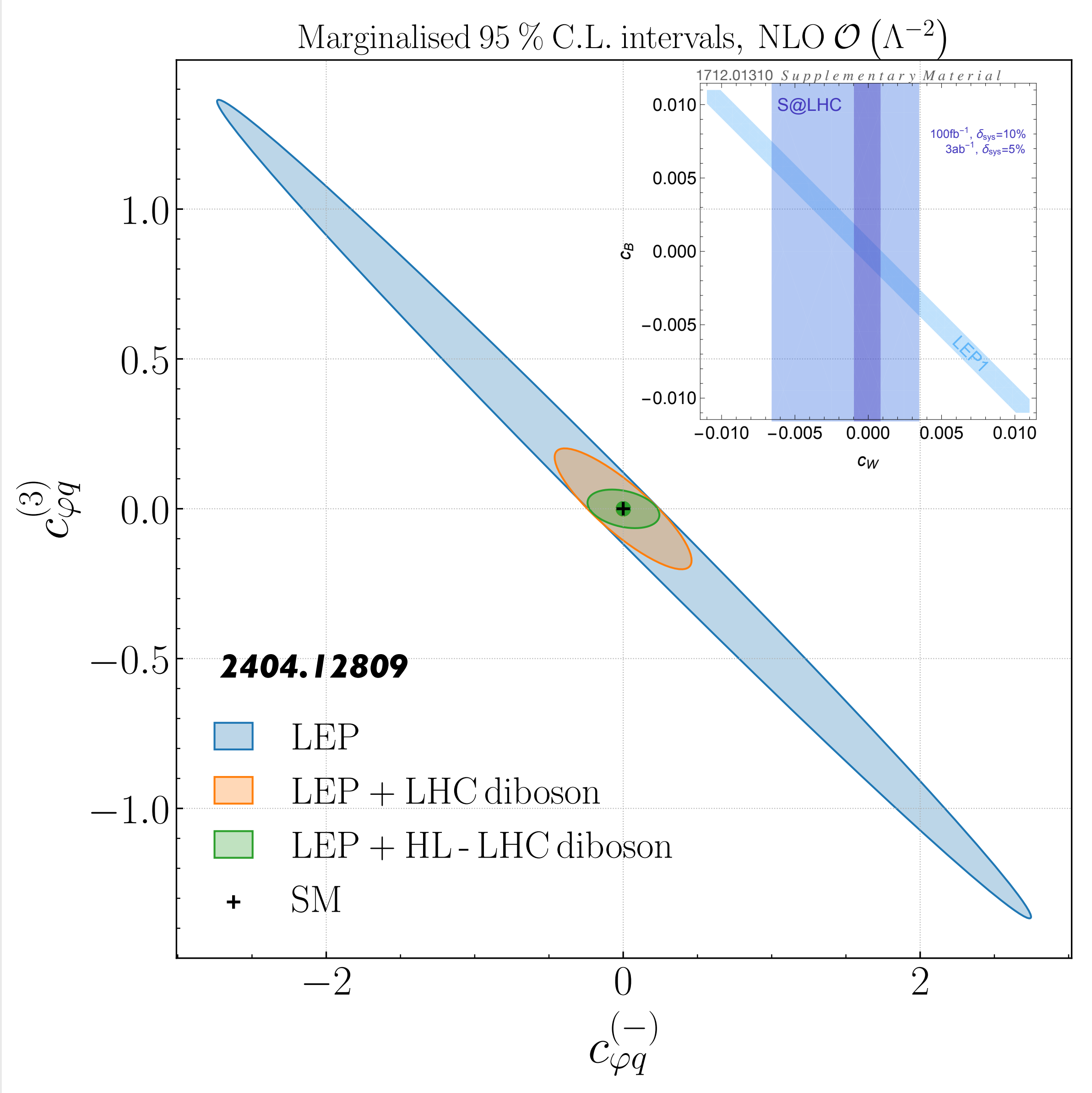


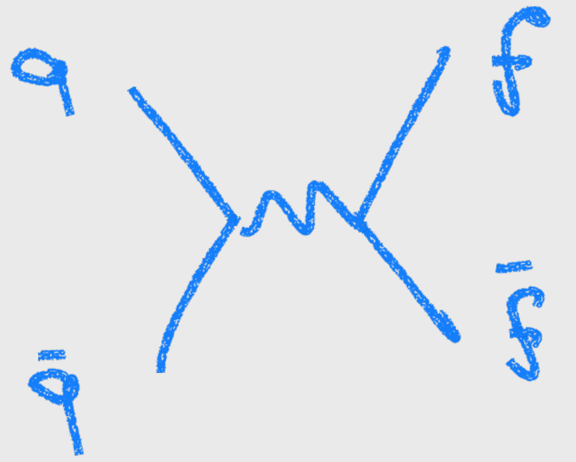
Precision physics at a *pp* machine?

High-p_T Di-boson and Drell-Yan

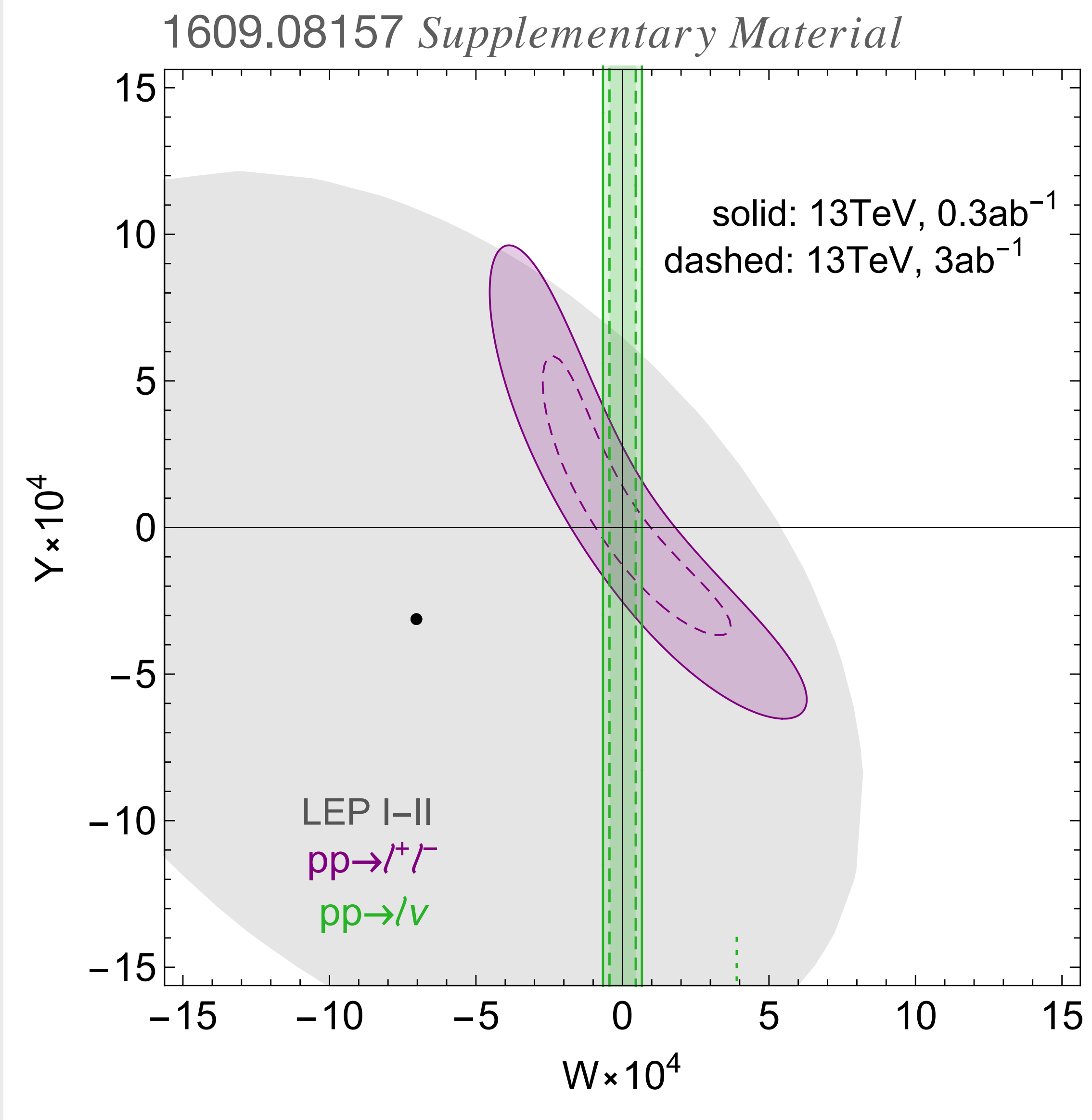


$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$c^{-}_{\varphi q} \equiv C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q}$$

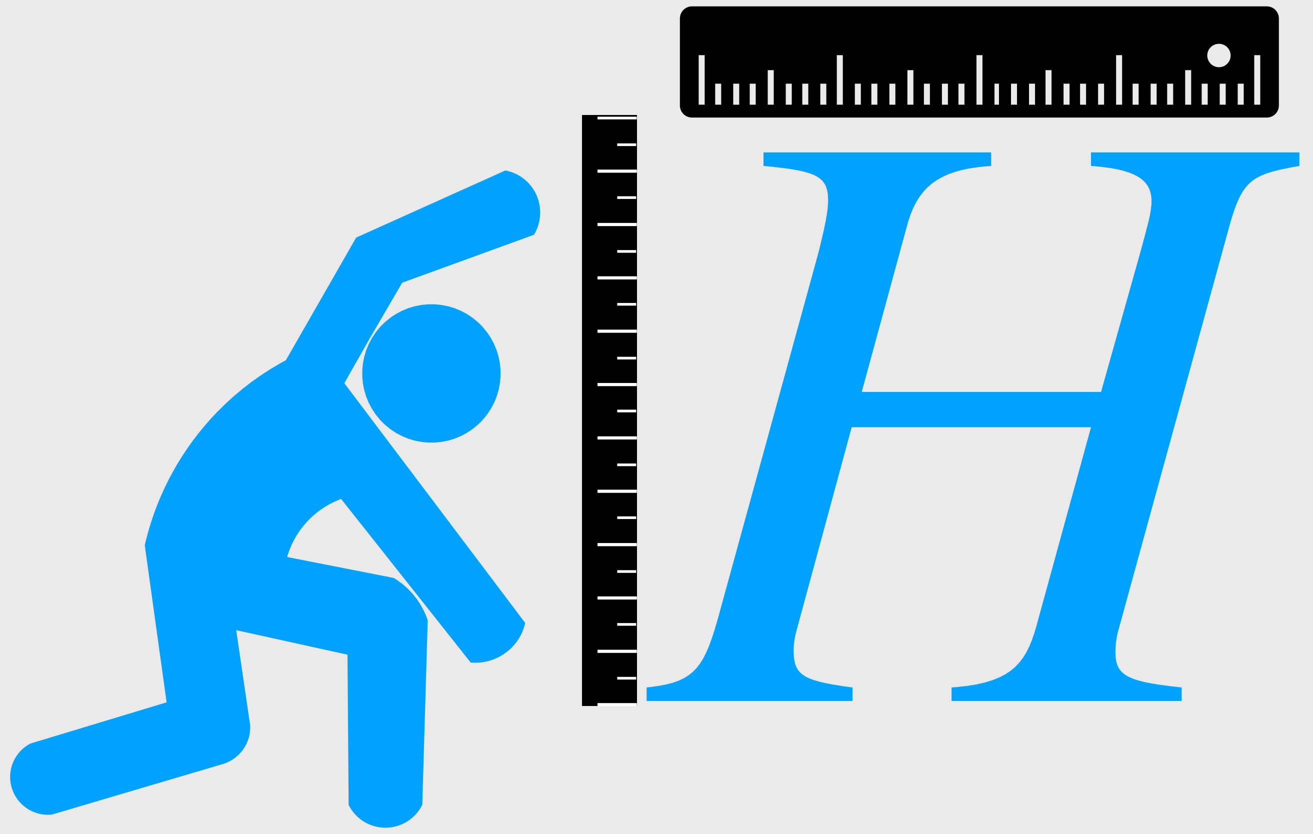




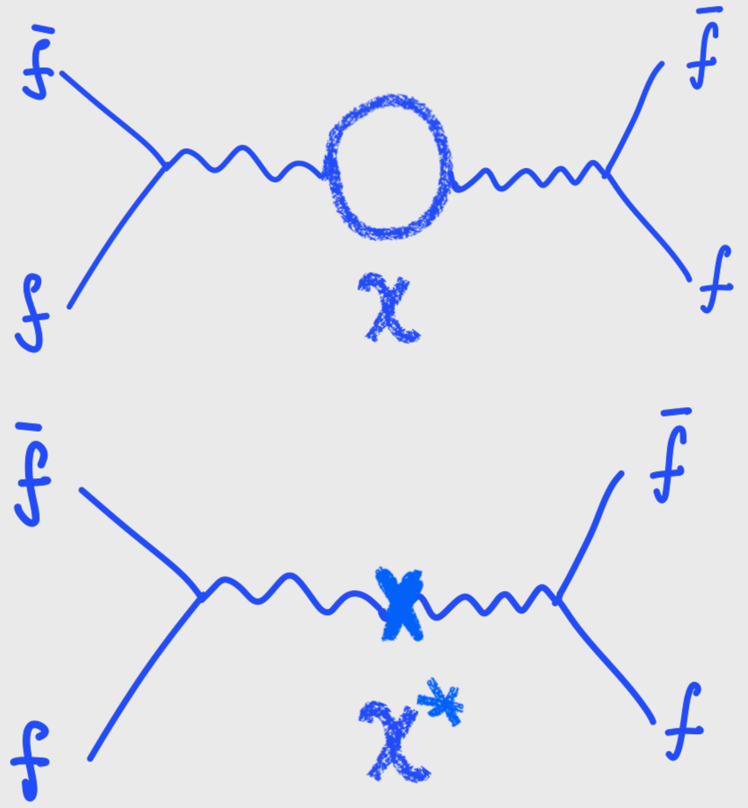
$$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$$
$$-\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$



These two measurements are basically enough to establish up to what distance the **Higgs boson is point-like?**



At the same time also sensitive to any form of **heavy matter charged under the electroweak interactions**



Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

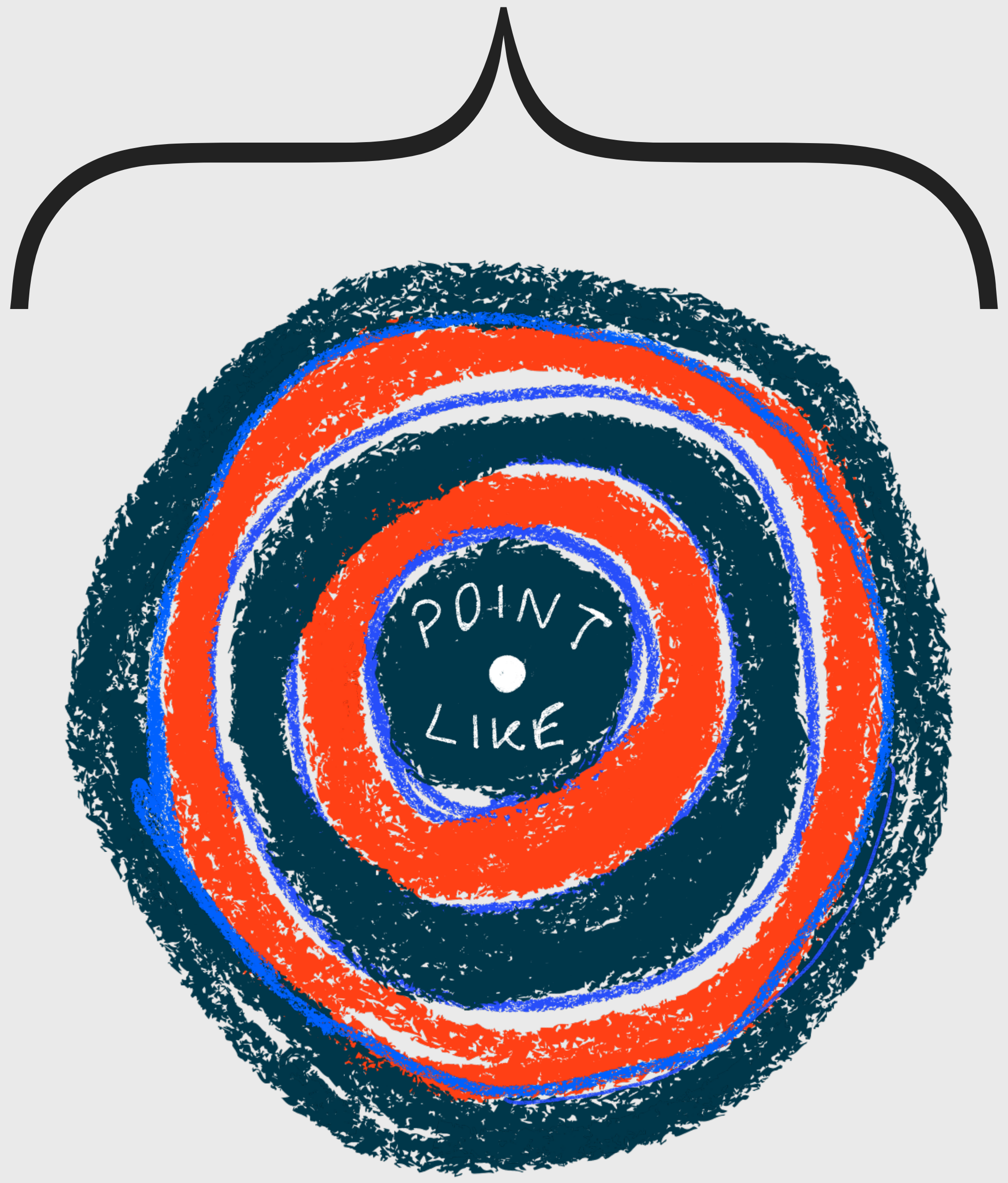
All you need are two parameters

- *Choose a mass scale*
- *Choose a coupling*

$$
\begin{aligned}
\mathcal{L}^{d=6}_{universal} = \; & c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right] \\
& + \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right] \\
& + \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W} \\
& + c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}
\end{aligned}
$$

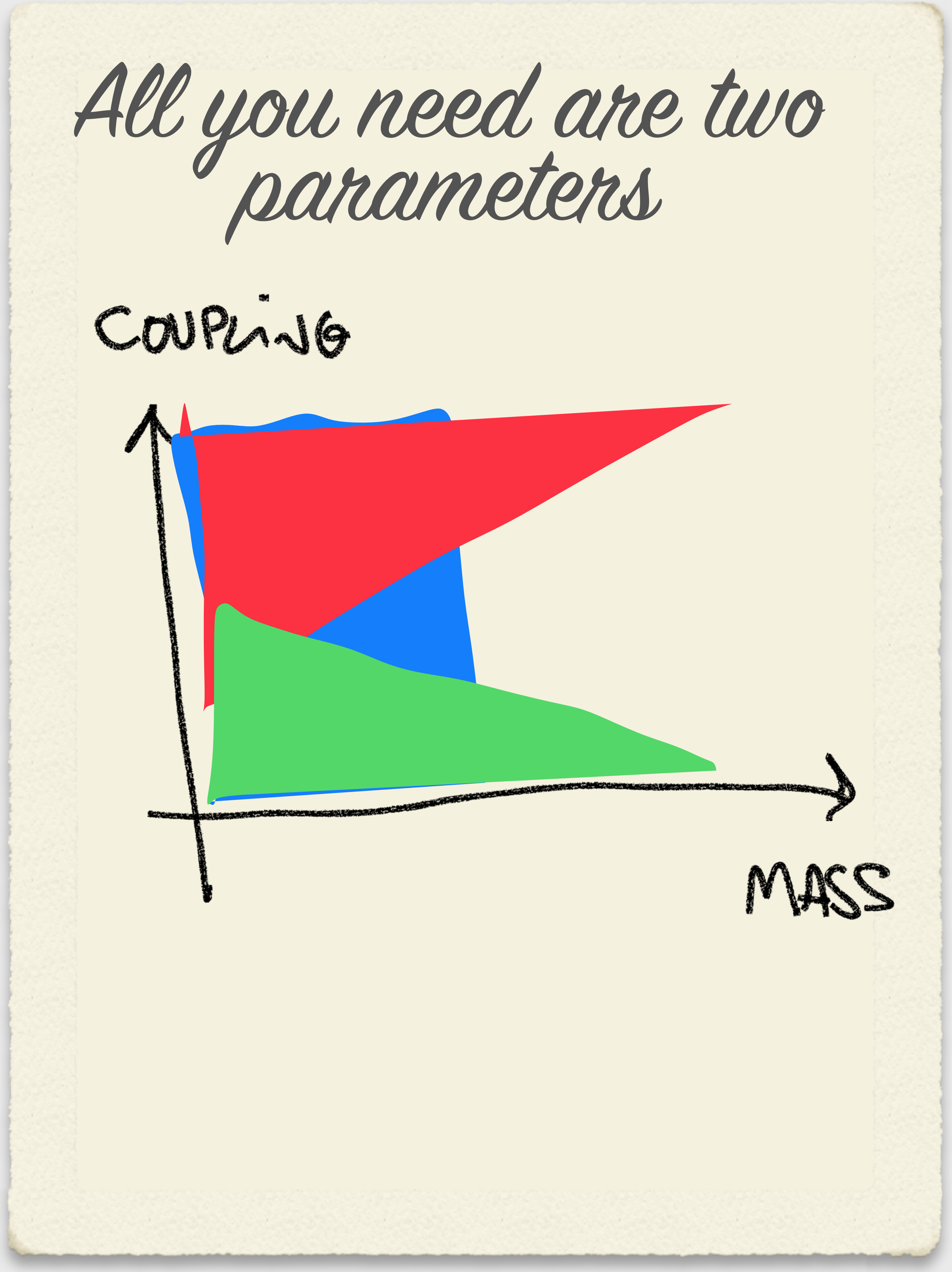
$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$ $\quad 1/(g_\star f) \sim 1/m_\star$ $\quad 1/f \sim g_\star/m_\star$

$\ell_{Higgs} \sim 1/m_\star$



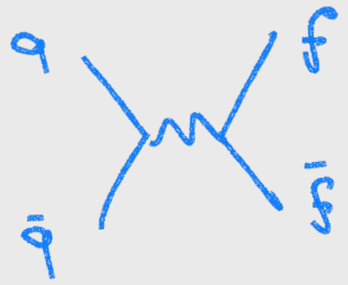
Effects of the size of the Higgs boson

h ~ π | STRONGLY INTERACTING LIGHT HIGGS



$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

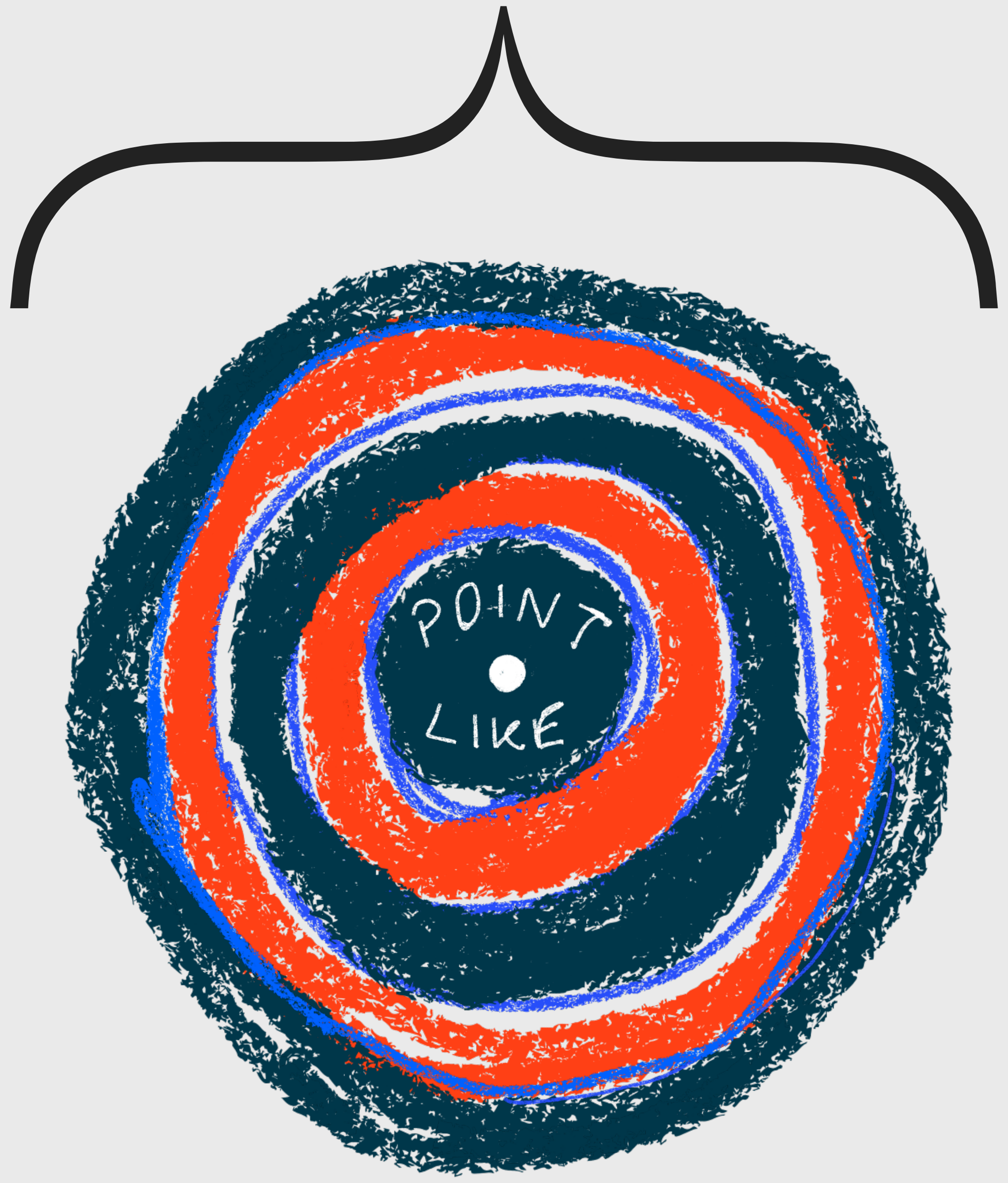
$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$



$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

$$\ell_{Higgs} \sim 1/m_\star$$

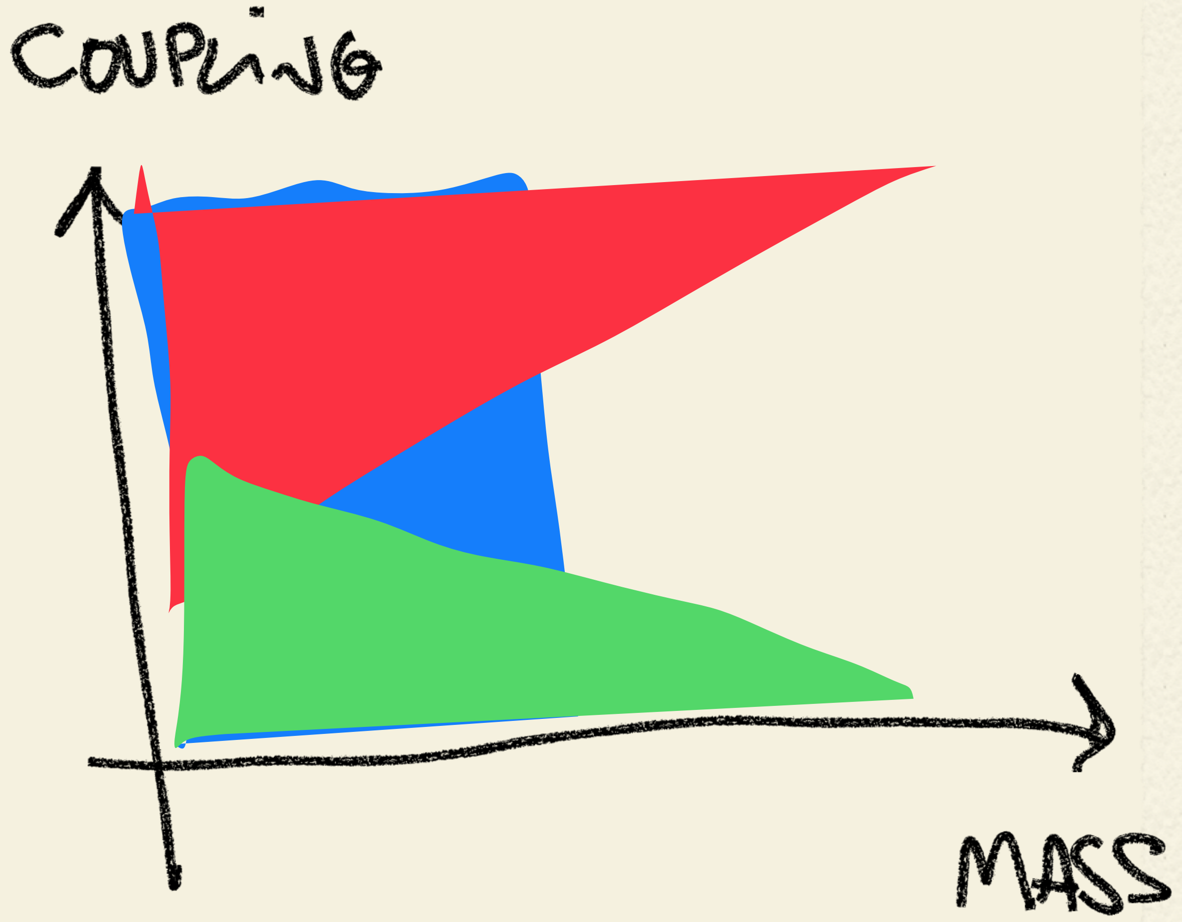


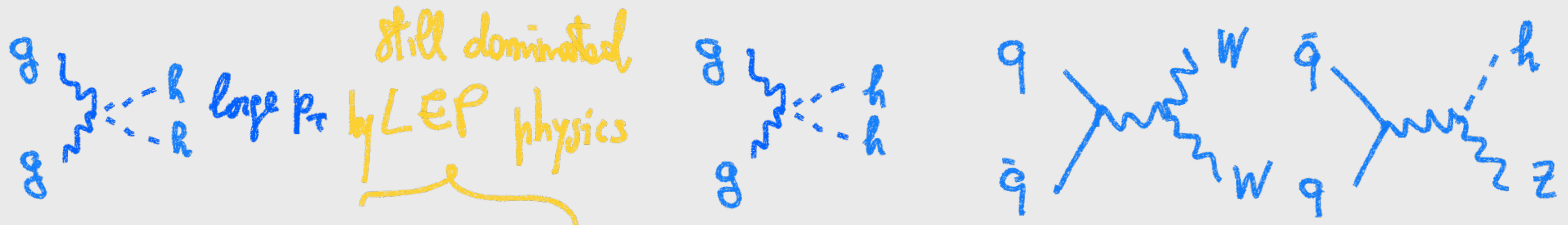
$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$ | $1/(g_\star f) \sim 1/m_\star$ | $1/f \sim g_\star/m_\star$

Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

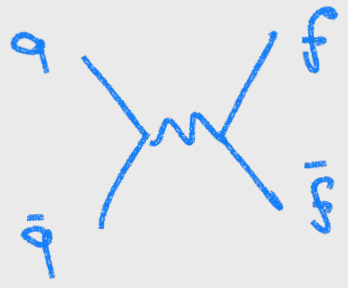
All you need are two parameters





$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$



$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

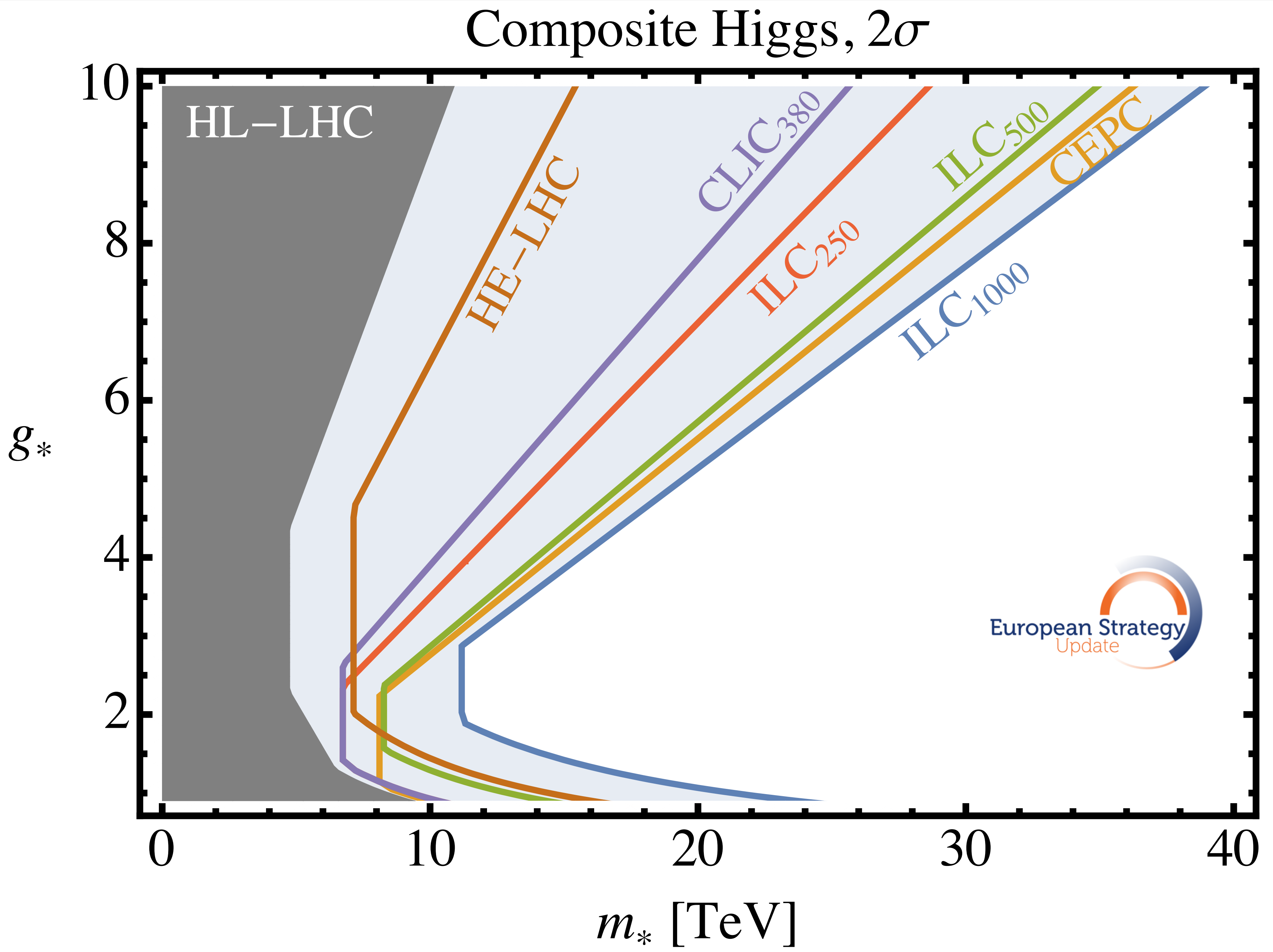
$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

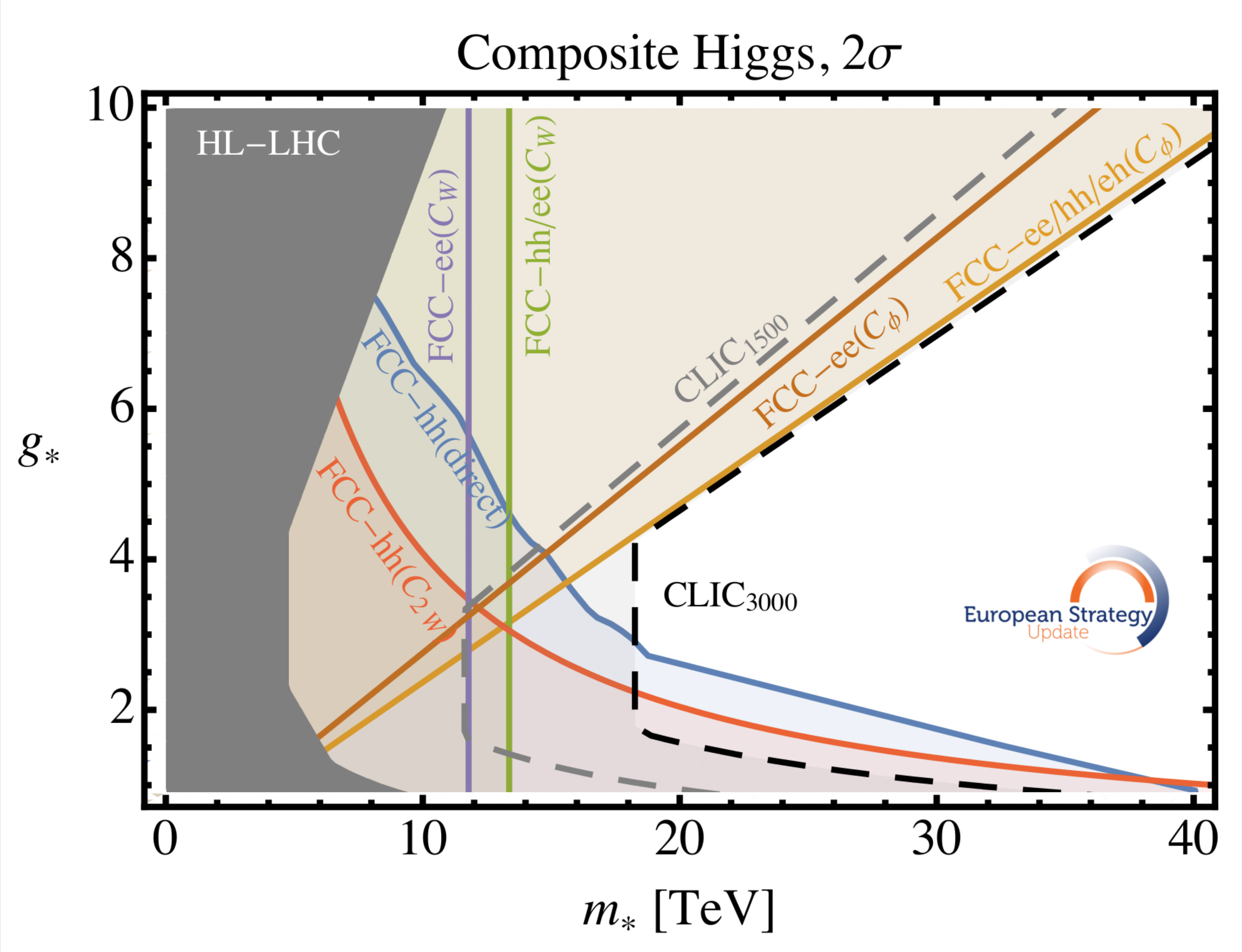
$$+ c_{tD}\frac{g_*^2}{m_*^2}\mathcal{O}_{tD}$$

$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$ $1/(g_\star f) \sim 1/m_\star$ $1/f \sim g_\star/m_\star$

$$\ell_{Higgs} \sim 1/m_\star$$

Higgs compositeness





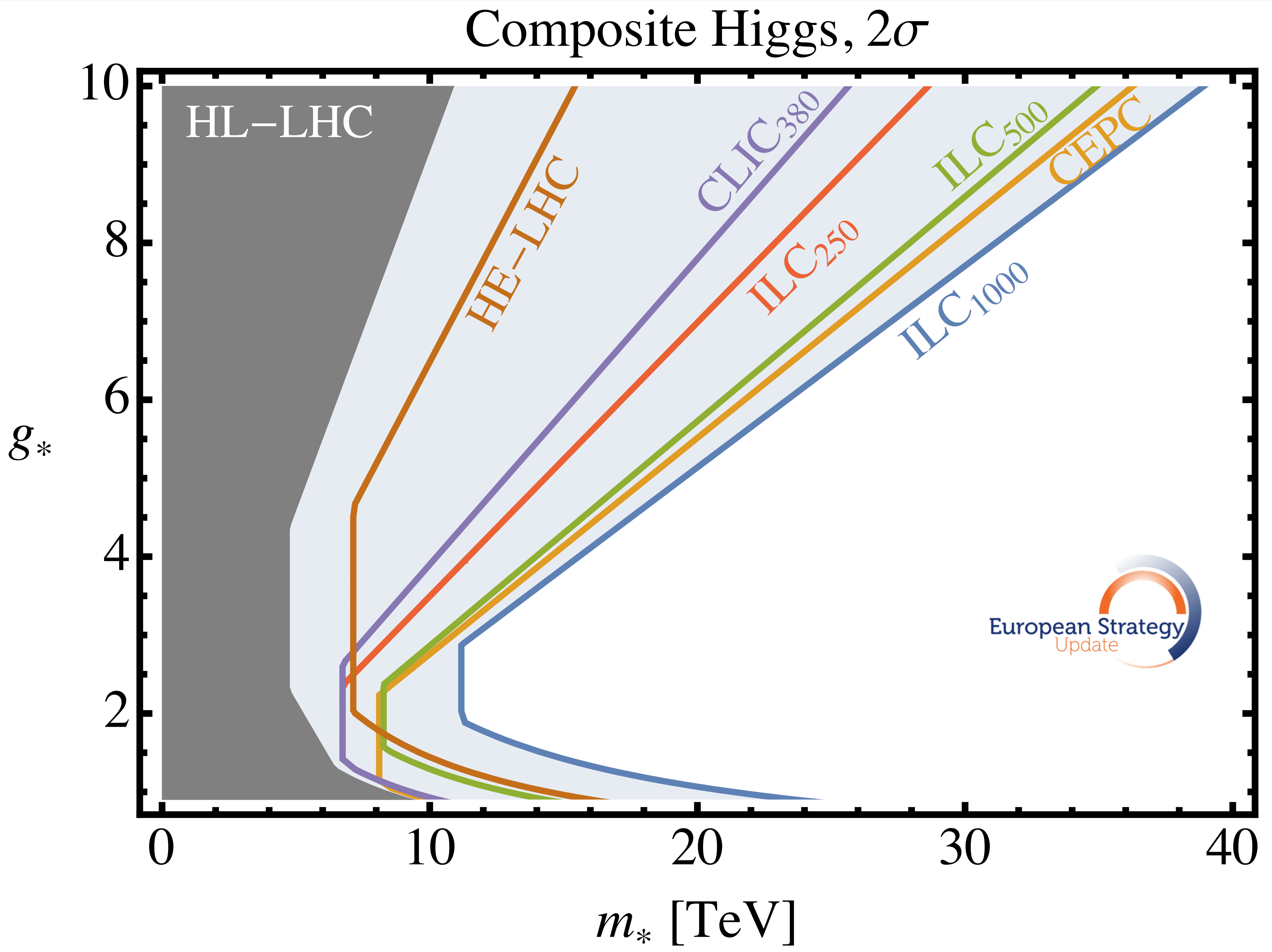
compositeness at few TeV @ HL-LHC

Higgs mildly less composite than QCD pion

compositeness at few 10 TeV

Higgs significantly less composite than QCD pion

Higgs compositeness



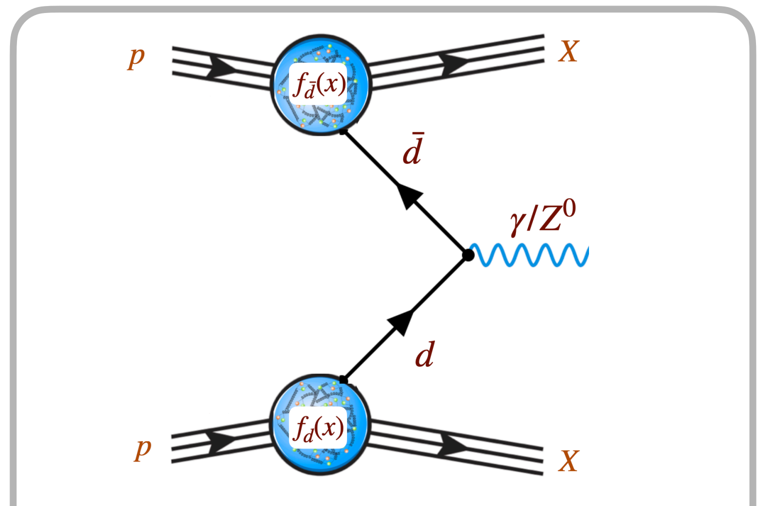
compositeness at few TeV @ HL-LHC

Higgs mildly less composite than QCD pion

Higgs significantly less composite than QCD pion

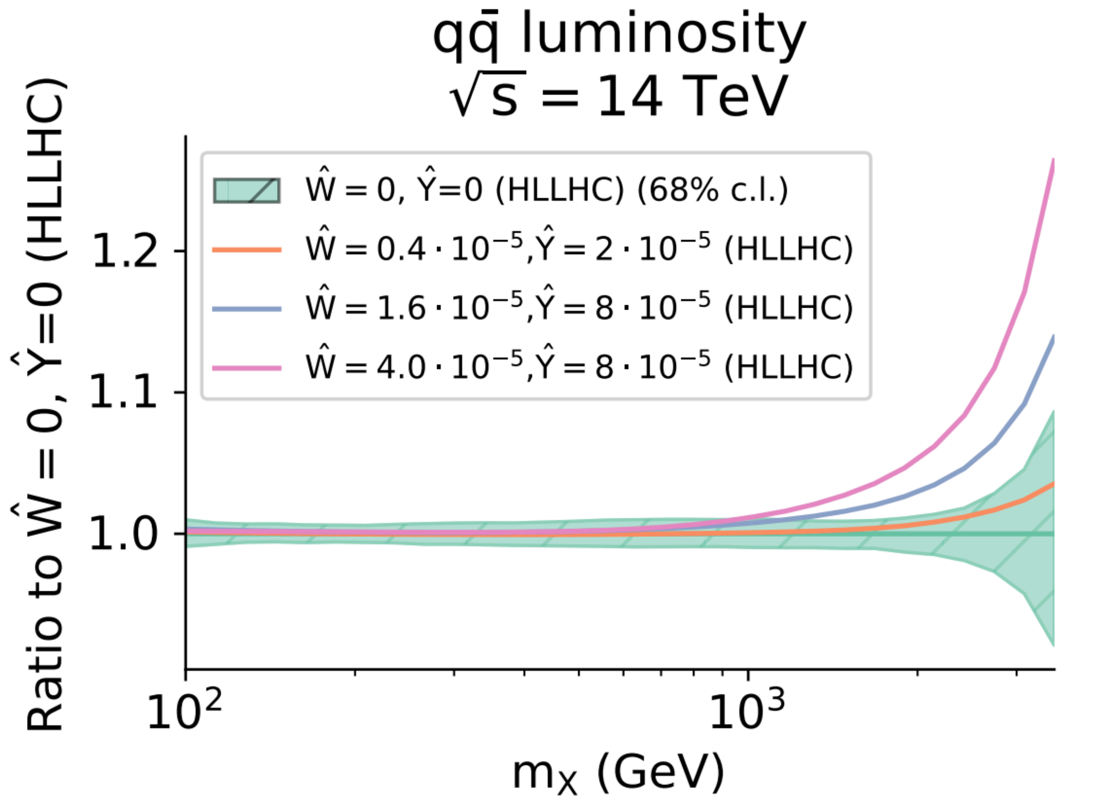
Precision physics at a *pp* machine?

SMEFT PDFs from high-mass Drell-Yan

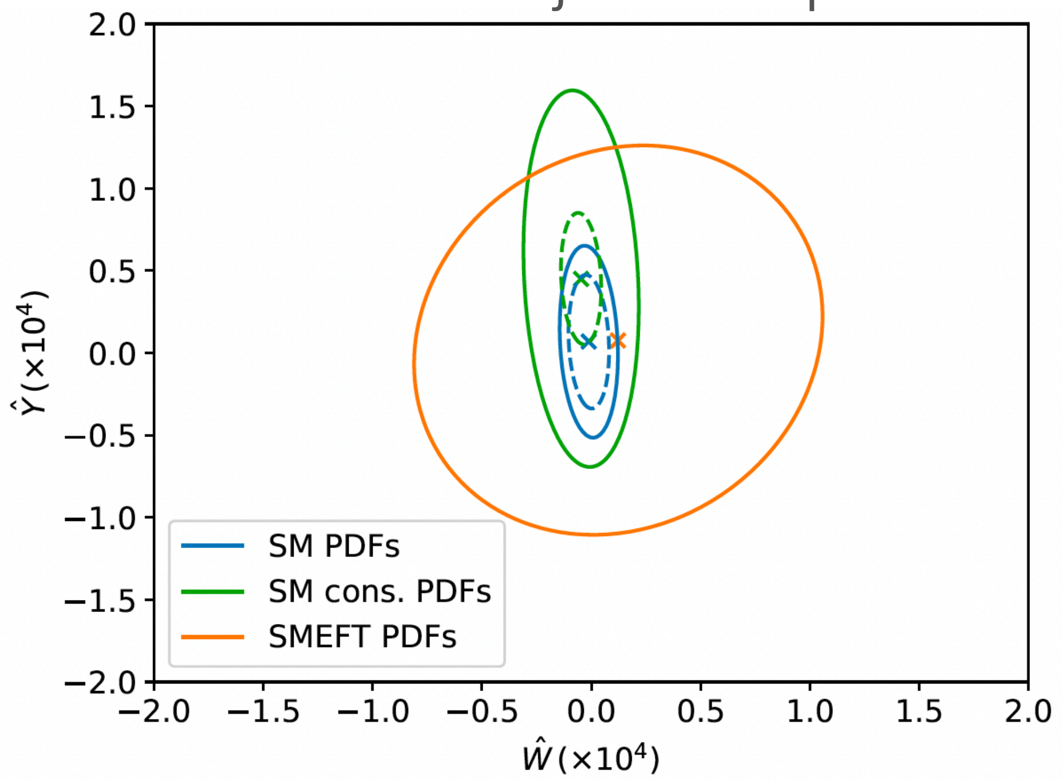


High-mass Drell-Yan: *A. Greljo, S. Iranipour, Z. Kassabov, M. Madigan, J. Moore, JR, M. Ubiali, C. Voisey, JHEP 2021*

- Published Run II DY data: EFT vs PDF interplay **negligible**
- HL-LHC projections: strong constraints on large-*x* antiquark PDFs, may be **reabsorbed into SMEFT PDFs**
- Bounds based on SM-PDFs **overly optimistic** as compared to those obtained from SMEFT-PDFs
- Emphasises importance of **SMEFT-PDF interplay** at the HL-LHC



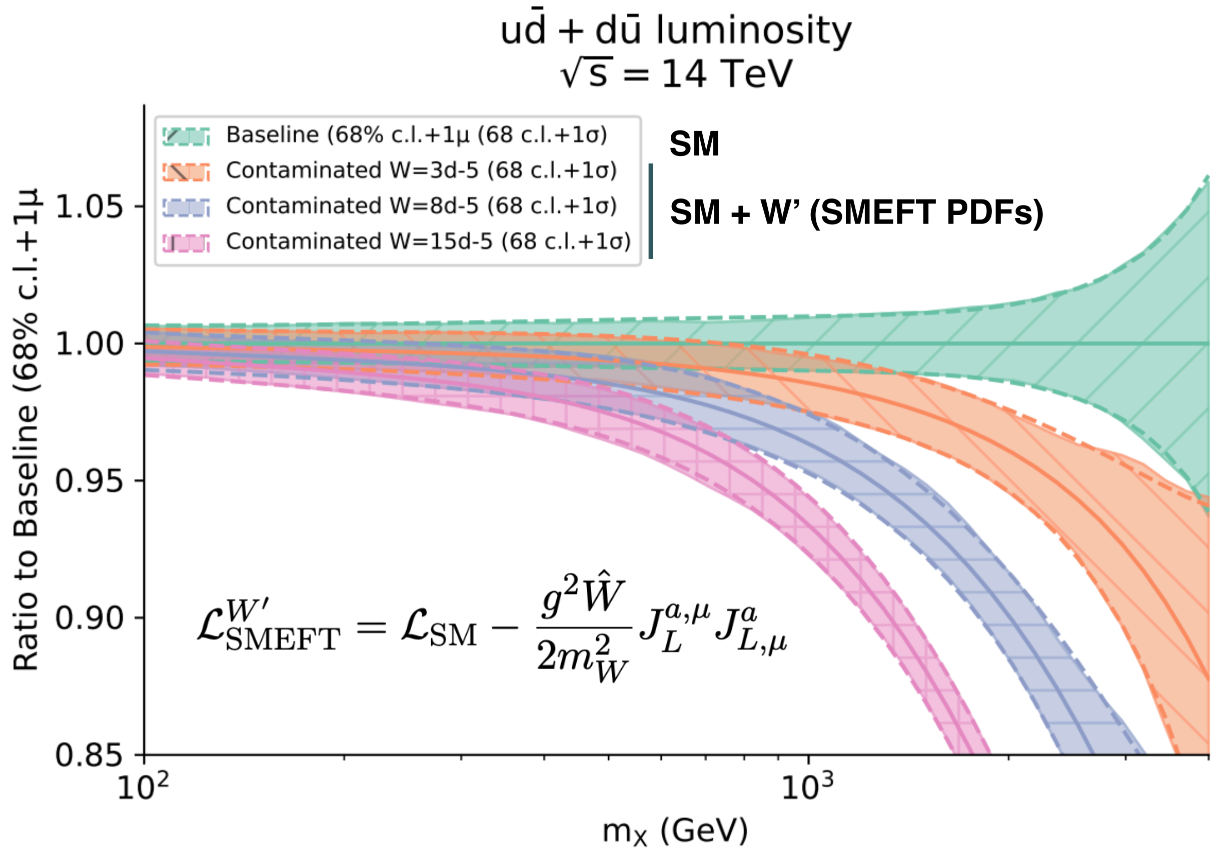
Rojo@LHCp 2024

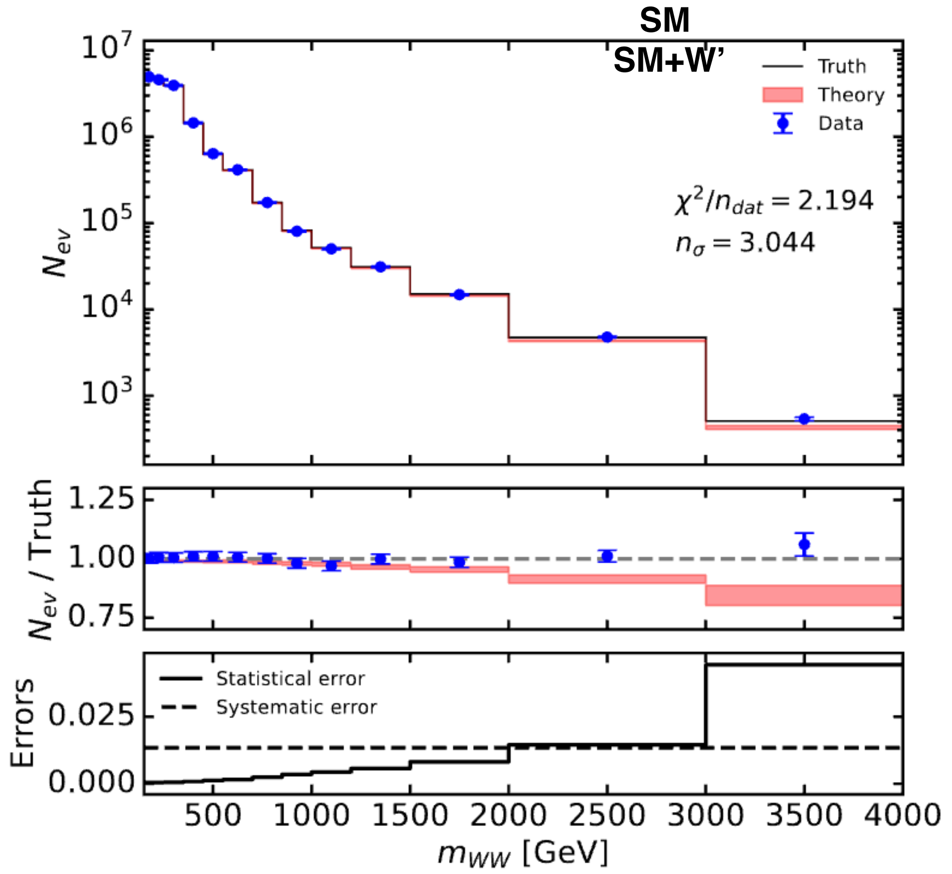


https://indico.cern.ch/event/1253590/contributions/5814396

Lifting the PDF/BSM Degeneracy

- Assume a BSM scenario with an extra W' gauge boson with **$M_{W'}$ = 13.8 TeV**
- Generate **HL-LHC pseudo-data** (NC & CC Drell-Yan) for this model and include in global PDF fit
- **Data-theory agreement unchanged,** but the $q\bar{q}$ luminosity **shifts far beyond PDF uncertainties**.
- Why? Because anti-quark PDFs at large-*x* poorly constrained, **"fitting away" BSM signals**
- Miss BSM signals in SMEFT analysis & spurious effects in ``SM" processes (e.g. diboson)





Hammou, Madigan, Mangano, Mantani, Morales, Ubiali, arXiv:2307.10370

- Need accurate **low-energy measurements** constraining **large-*x* PDFs** to robustly disentangle QCD from BSM effects and break this degeneracy
- Including **DIS neutrino measurements from the LHC (**FASER, SND@LHC, FPF) removes this PDF/BSM degeneracy, fixing the large-*x* PDFs independently from high-p_T data
- Essential input to realise the **full BSM search potential of the HL-LHC**

Precision physics at a *pp* machine?

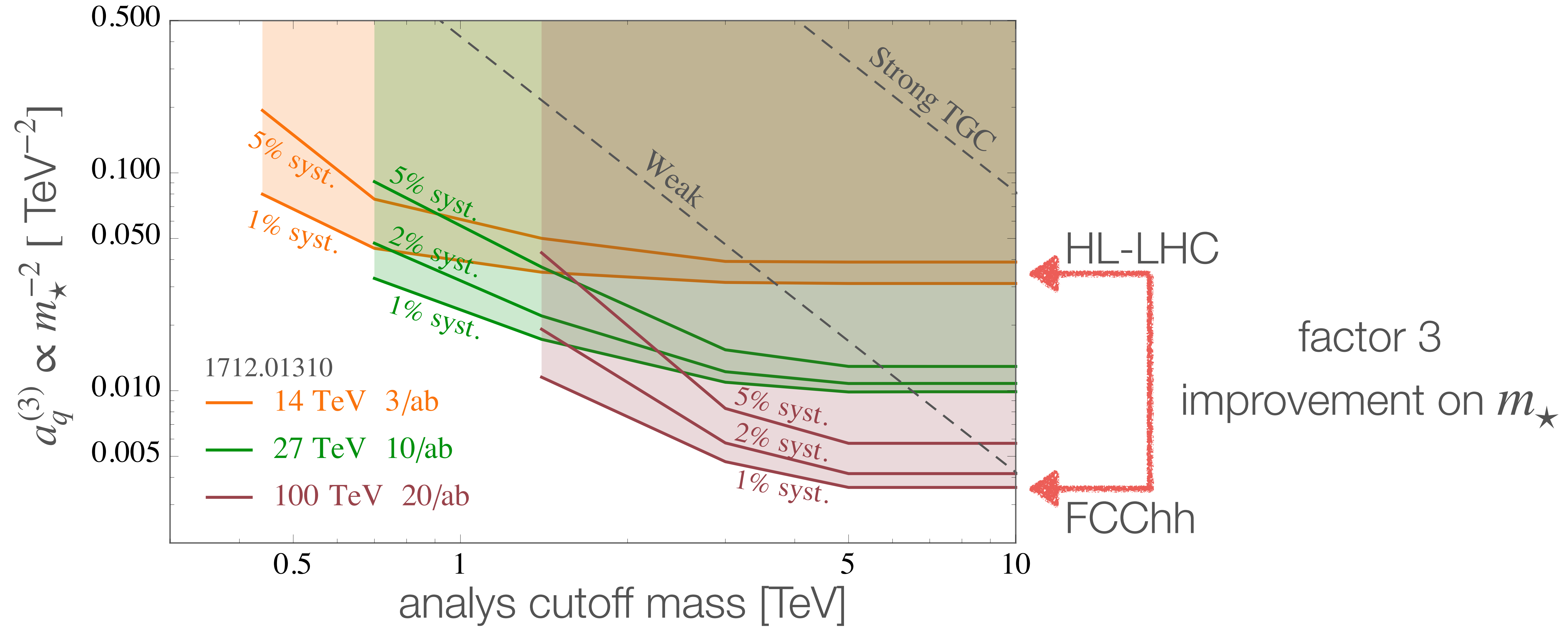
SMEFT PDFs from high-mass Drell-Yan

Published Run II DY data: EFT vs PDF interplay **negligible**

Lifting the PDF/BSM Degeneracy

Assume a BSM scenario with an extra W' gauge boson with $\mathbf{M_{W'}}$ **= 13.8 TeV**

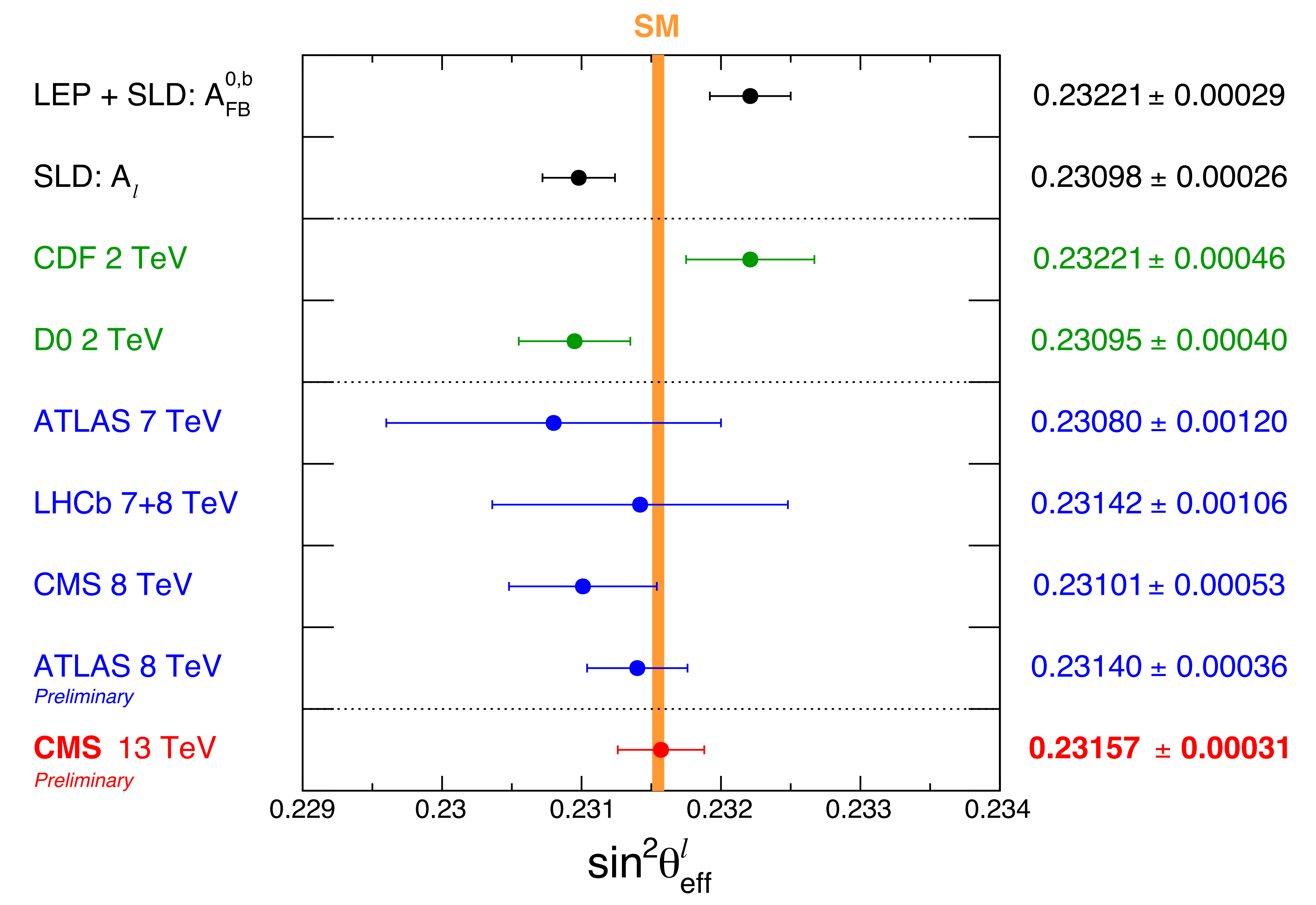
- These wrinkles from contaminations can be ironed out with more data in PDF fits.
- In general the strategy seems very robust, as it requires "some" control over systematics, but completely within feasibility

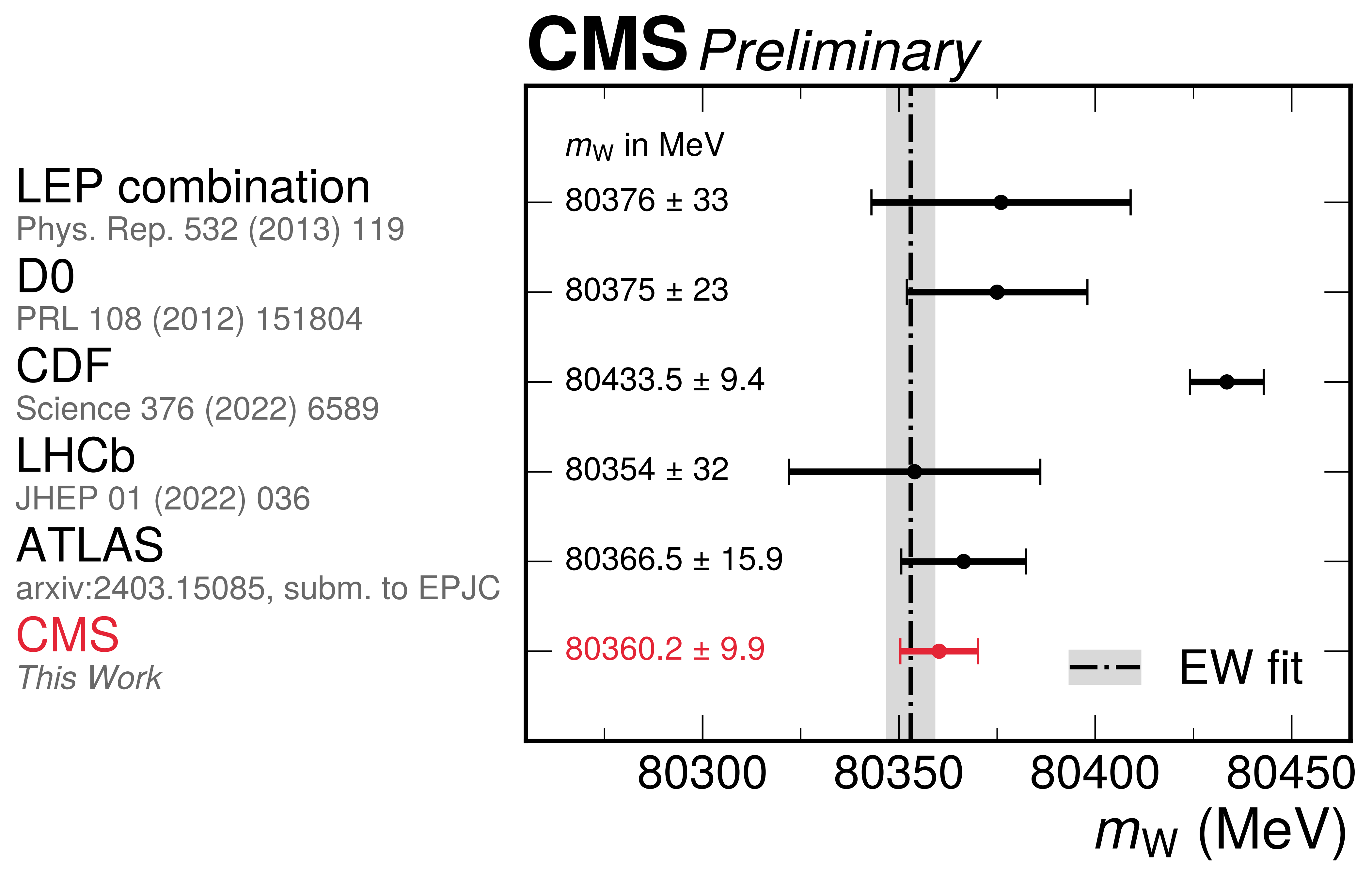


Precision obtained by leveraging high-p_T to see the magnified effect of small new physics couplings can tolerate relatively large systematics

Low-p_T precision physics at a *pp* machine?

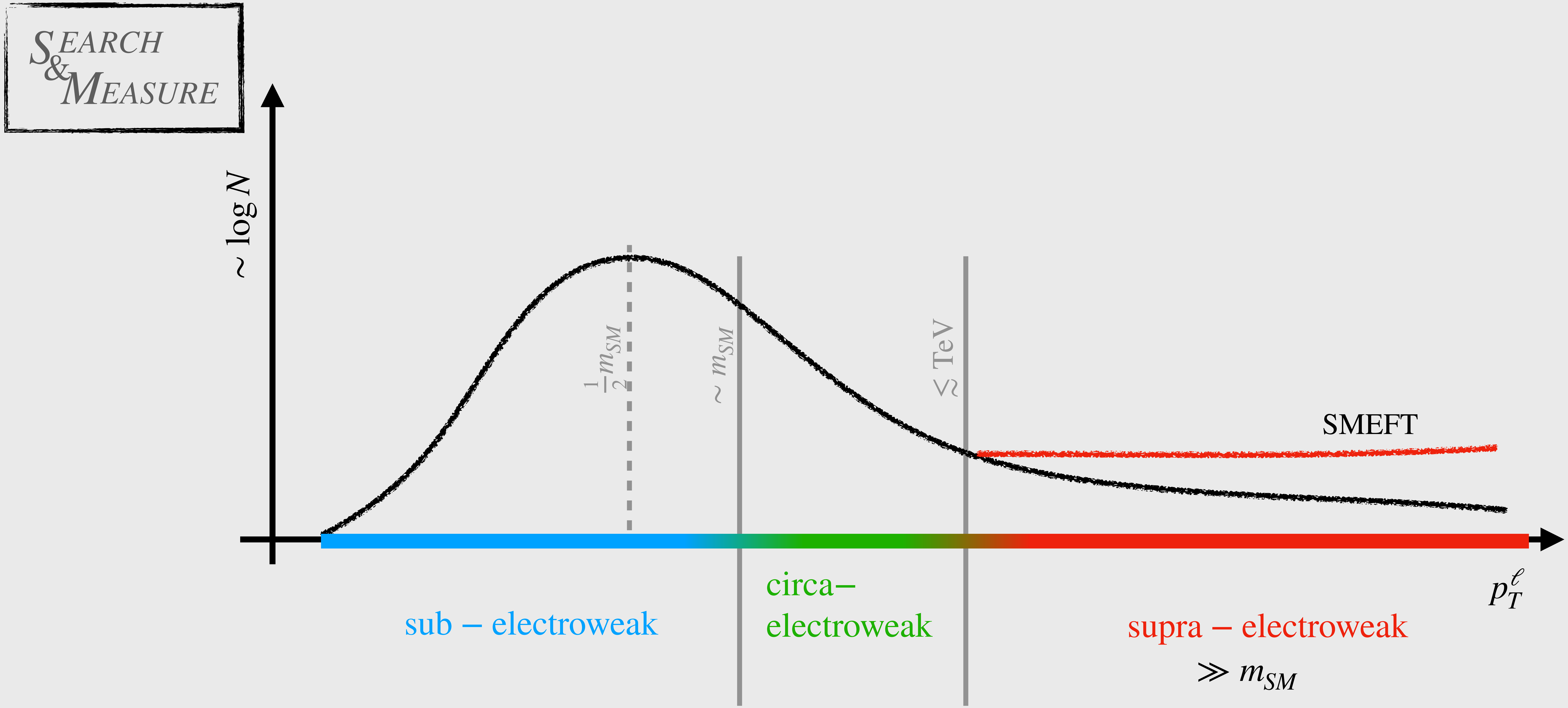
LHC has demonstrated that a *pp* machine can reach precision
This hinges on a spectacular control of **systematic uncertainties**.



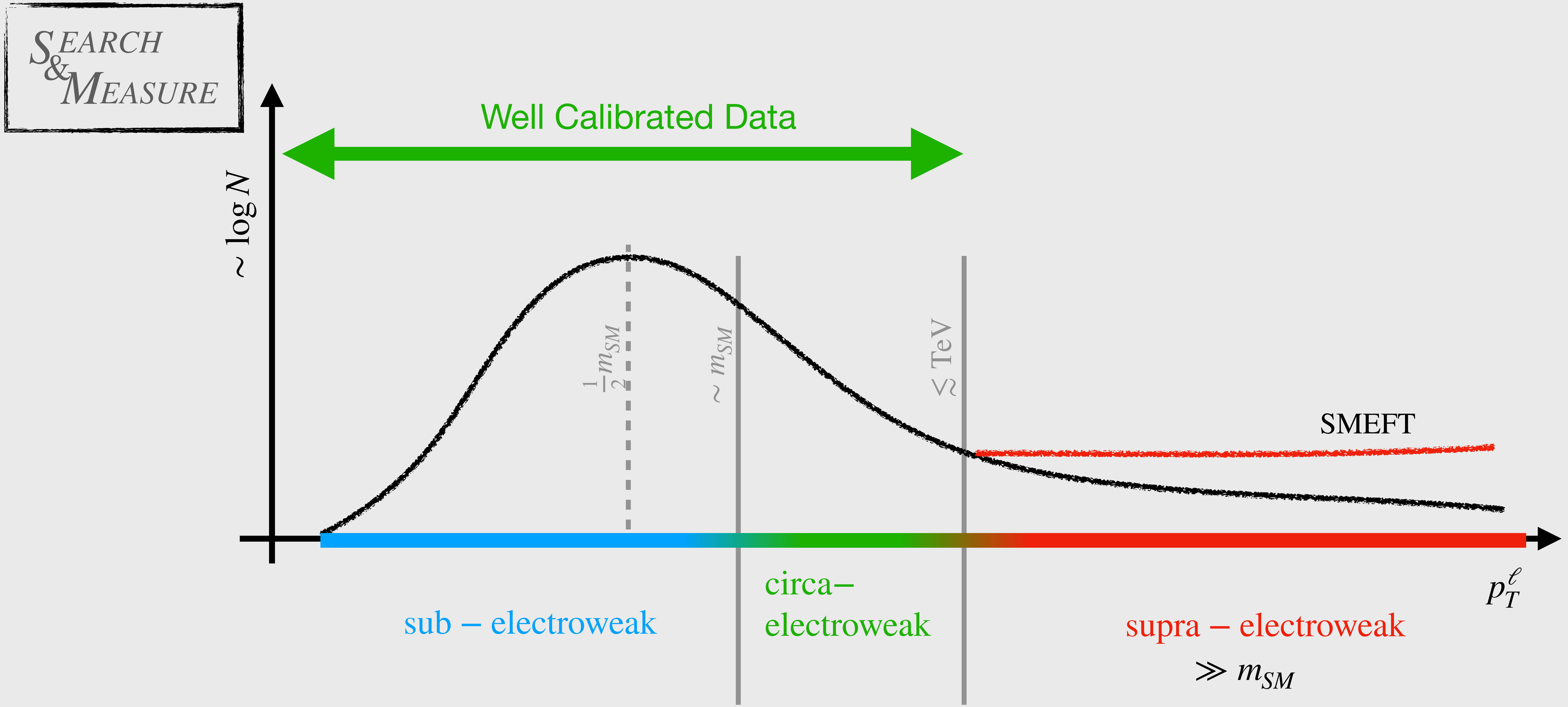


Such control over systematics is **far from guaranteed** for a future *pp* machine. Today is too early to say if we can tackle BSM scenarios via low-p_T precision measurements. A cleaner $\ell^+\ell^-$ machine would make things easier.

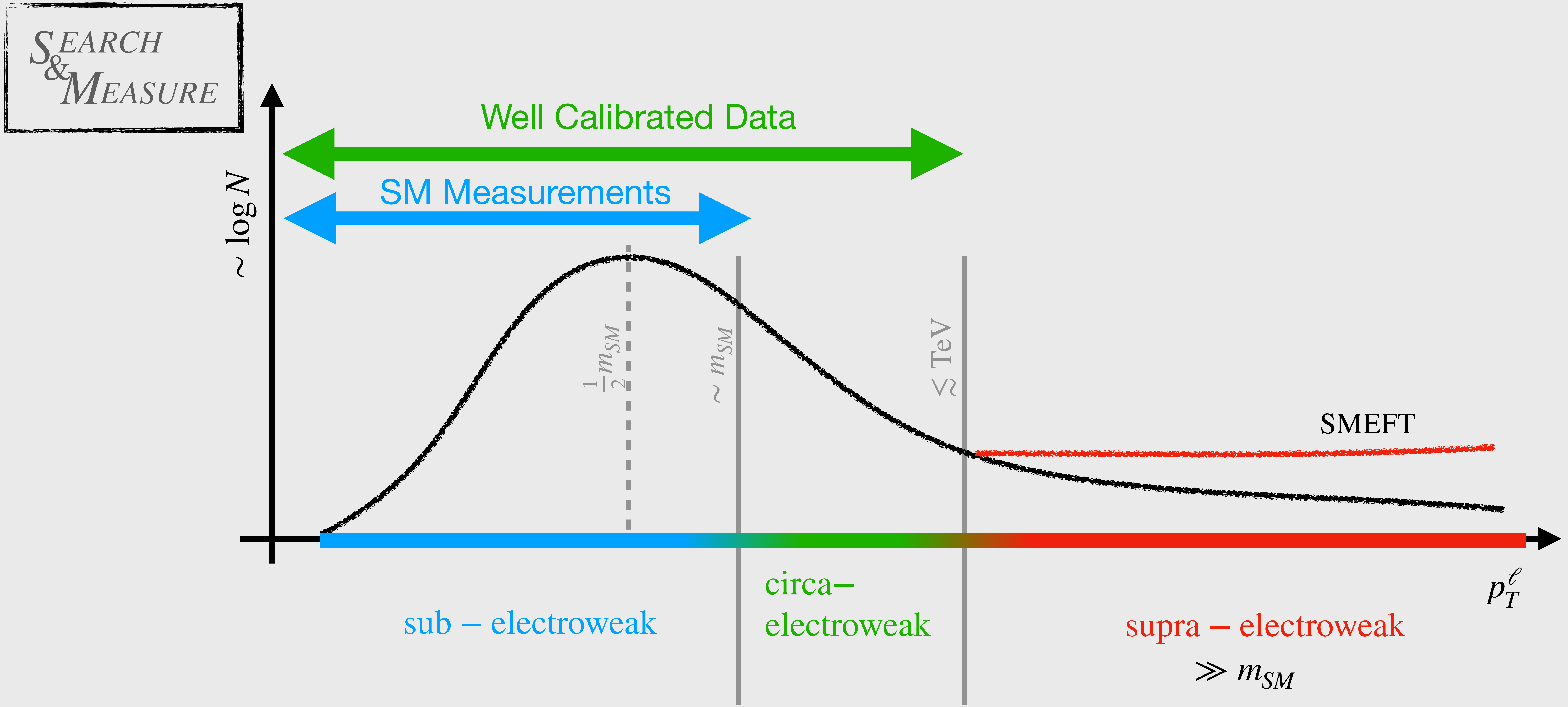
Search and Measure (SM) at a *pp* machine?



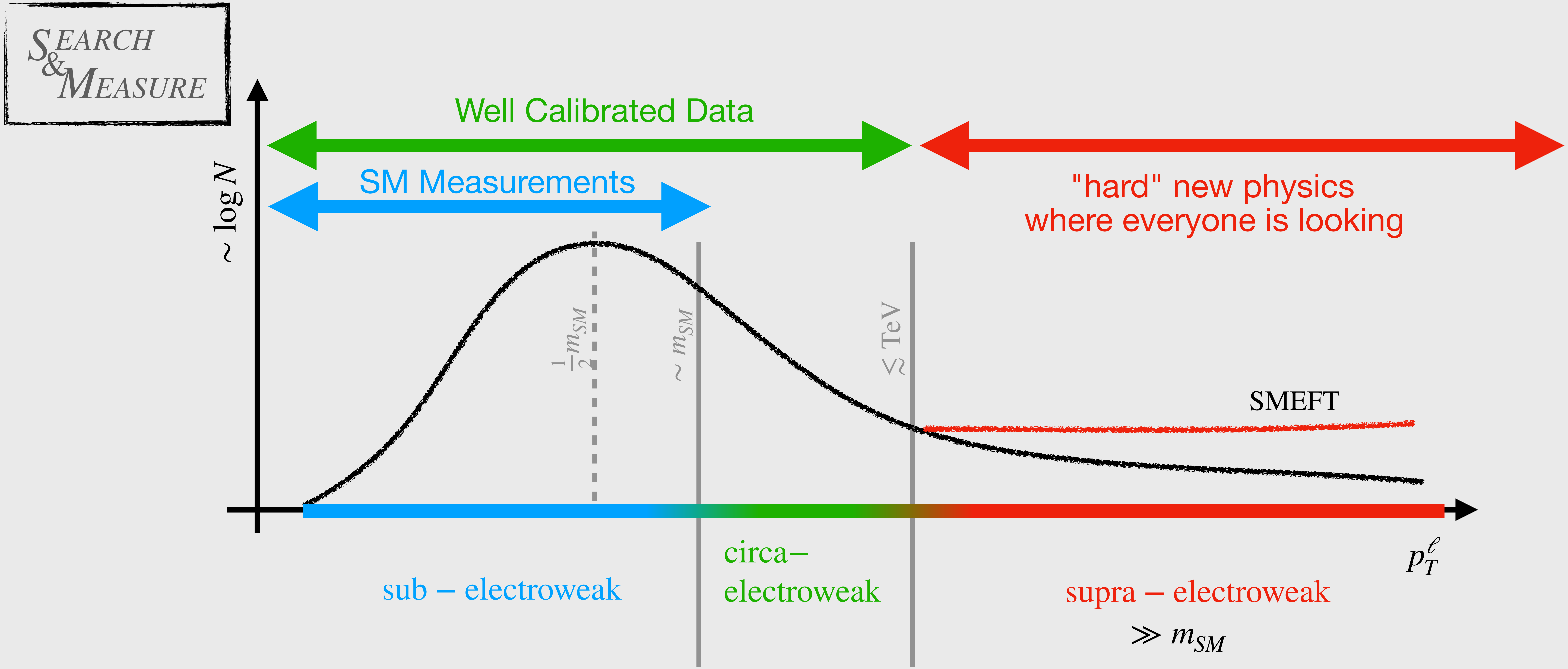
Search and Measure (SM) at a *pp* machine?



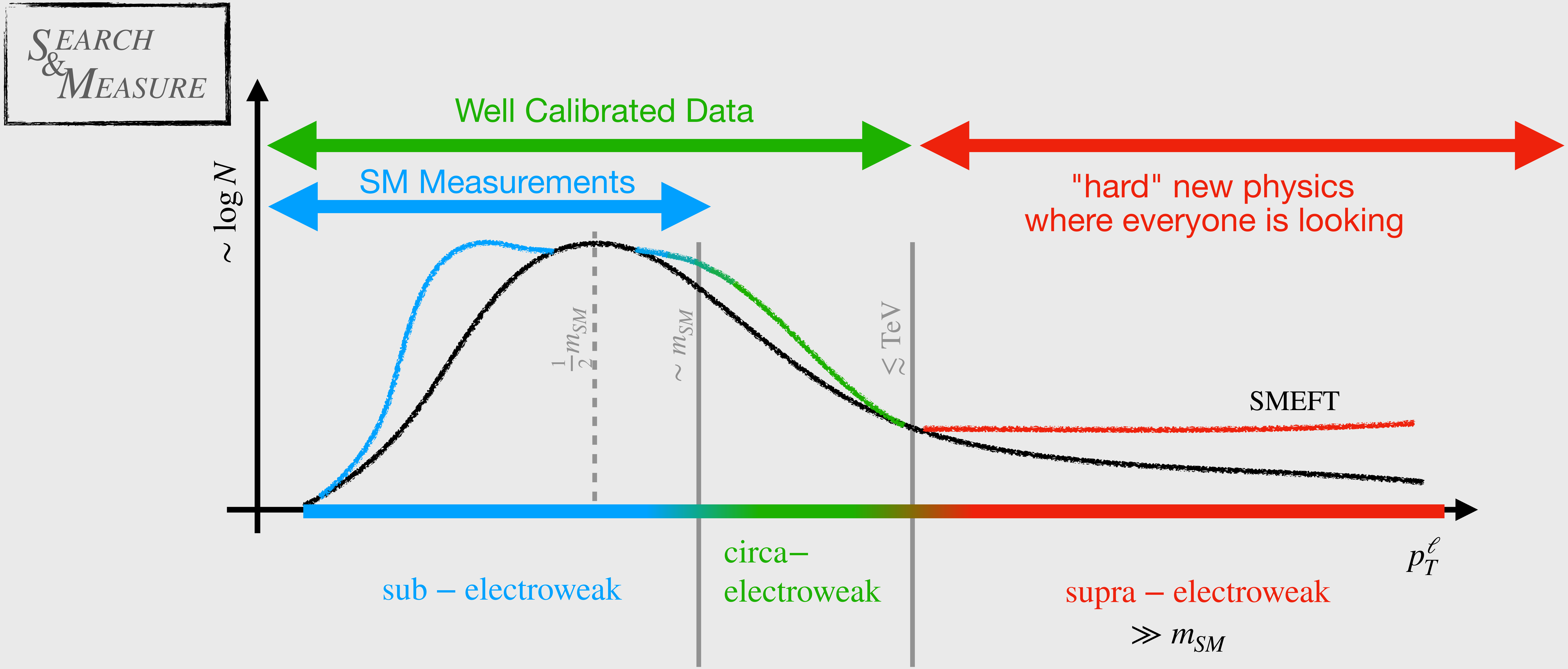
Search and Measure (SM) at a *pp* machine?



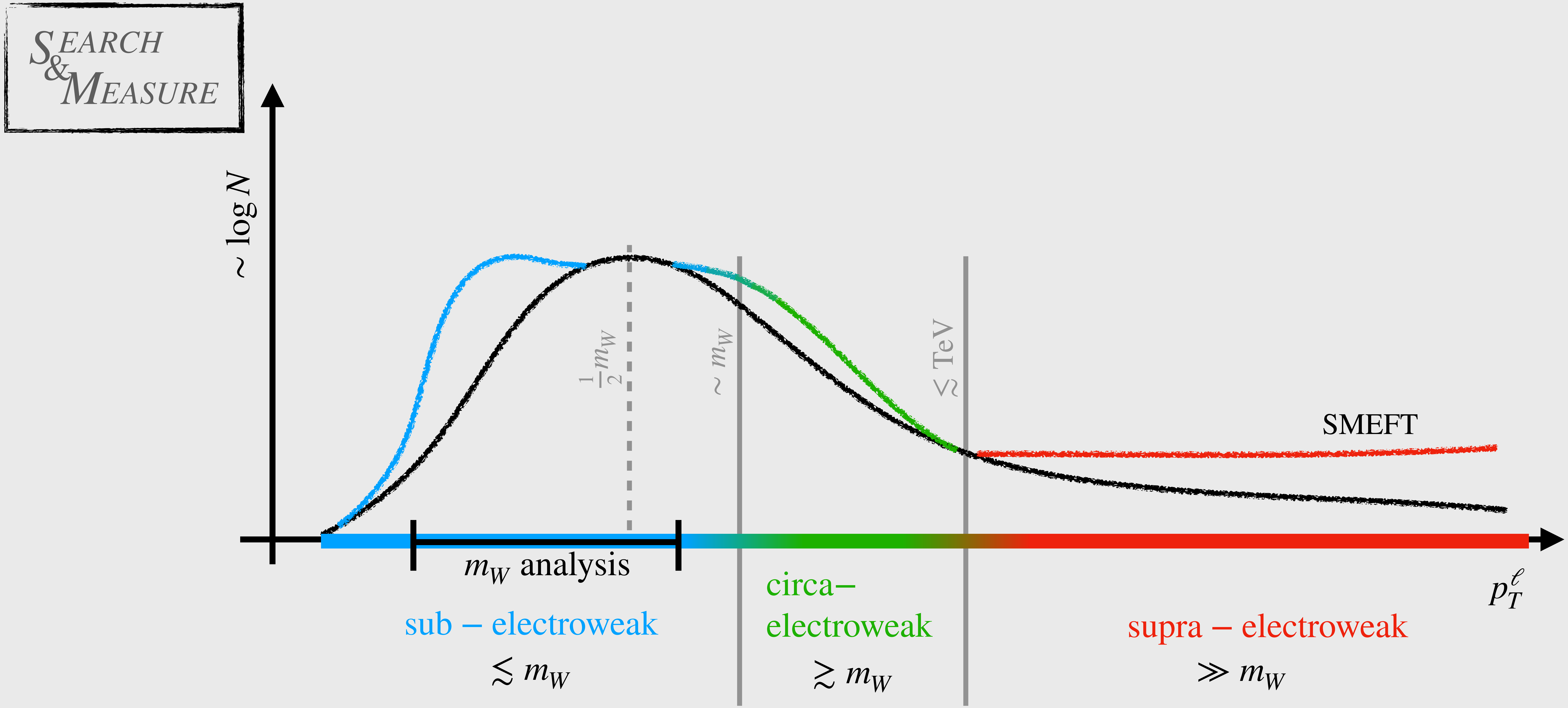
Search and Measure (SM) at a *pp* machine?



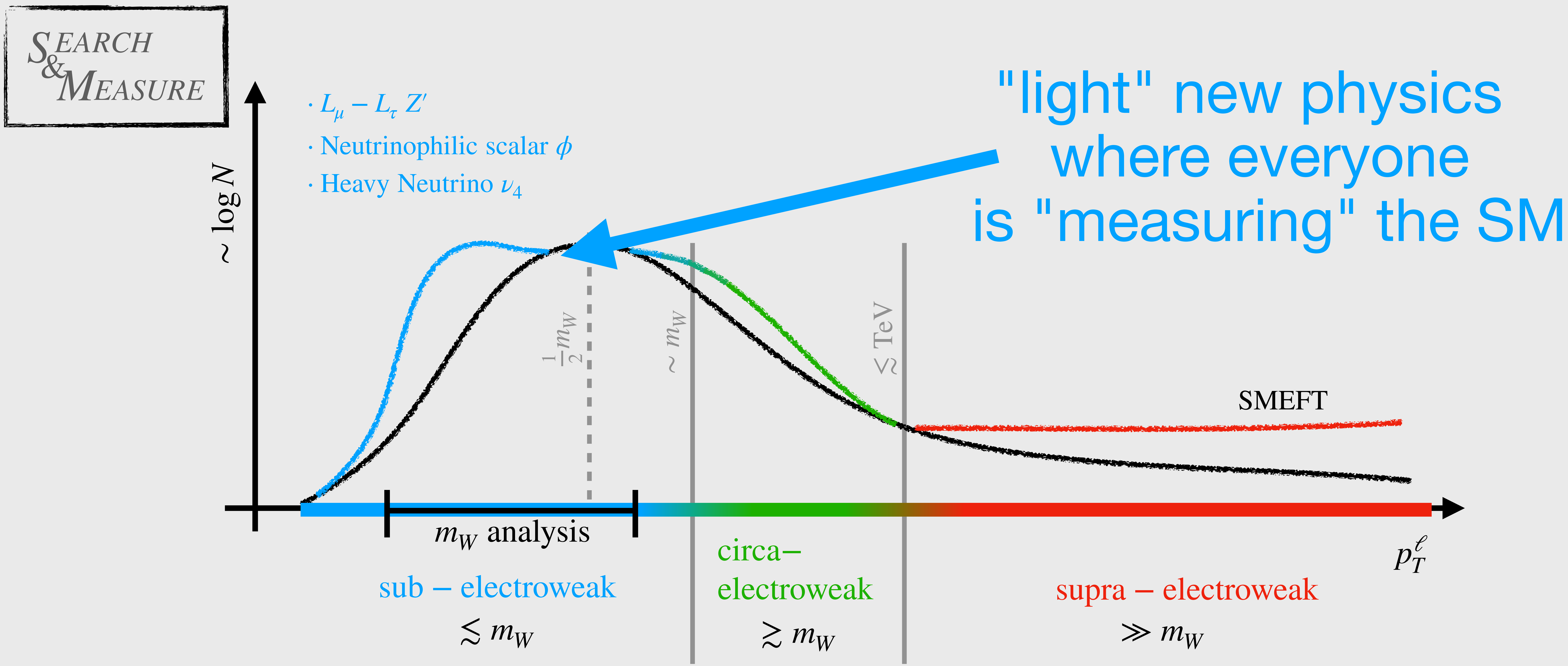
Search and Measure (SM) at a *pp* machine?



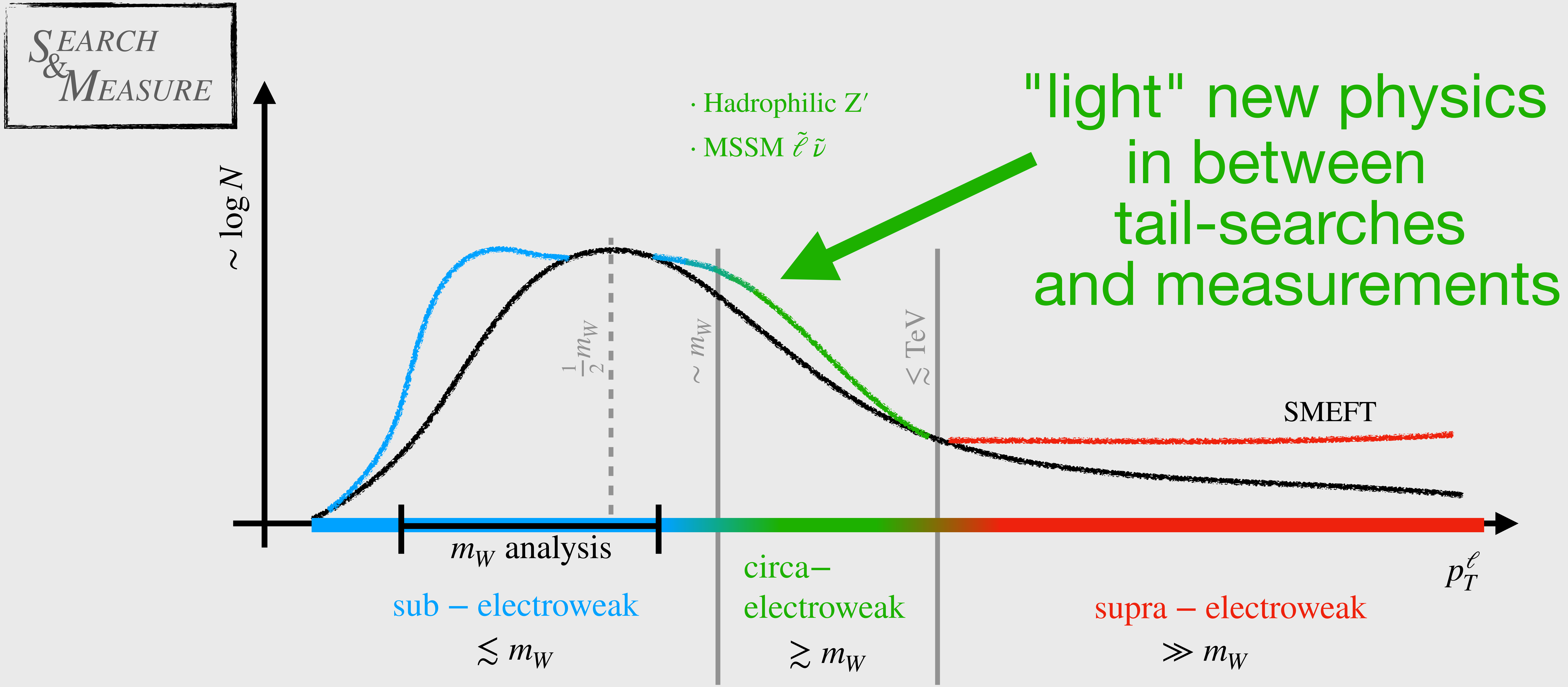
Search and Measure (SM) at a *pp* machine?



Search and Measure (SM) at a *pp* machine?

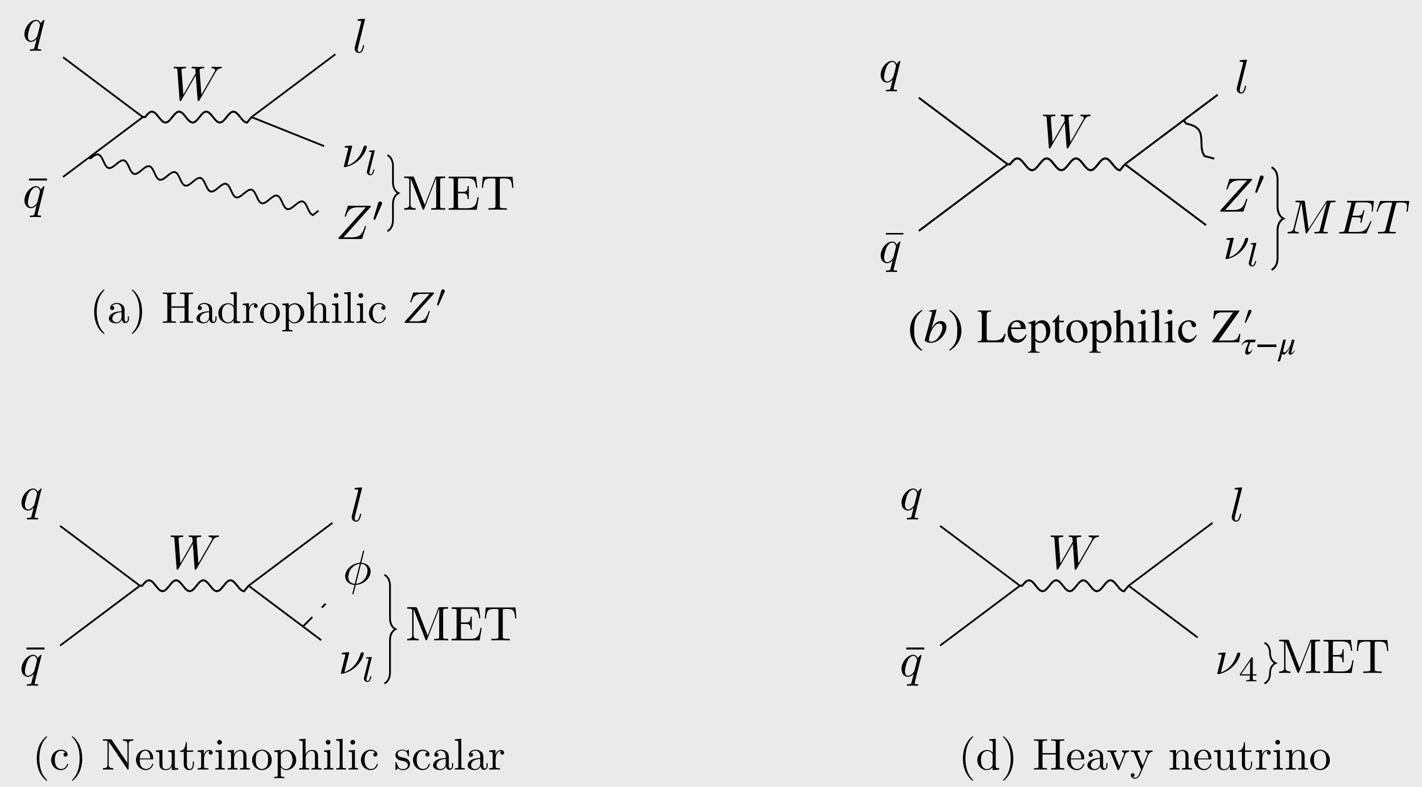


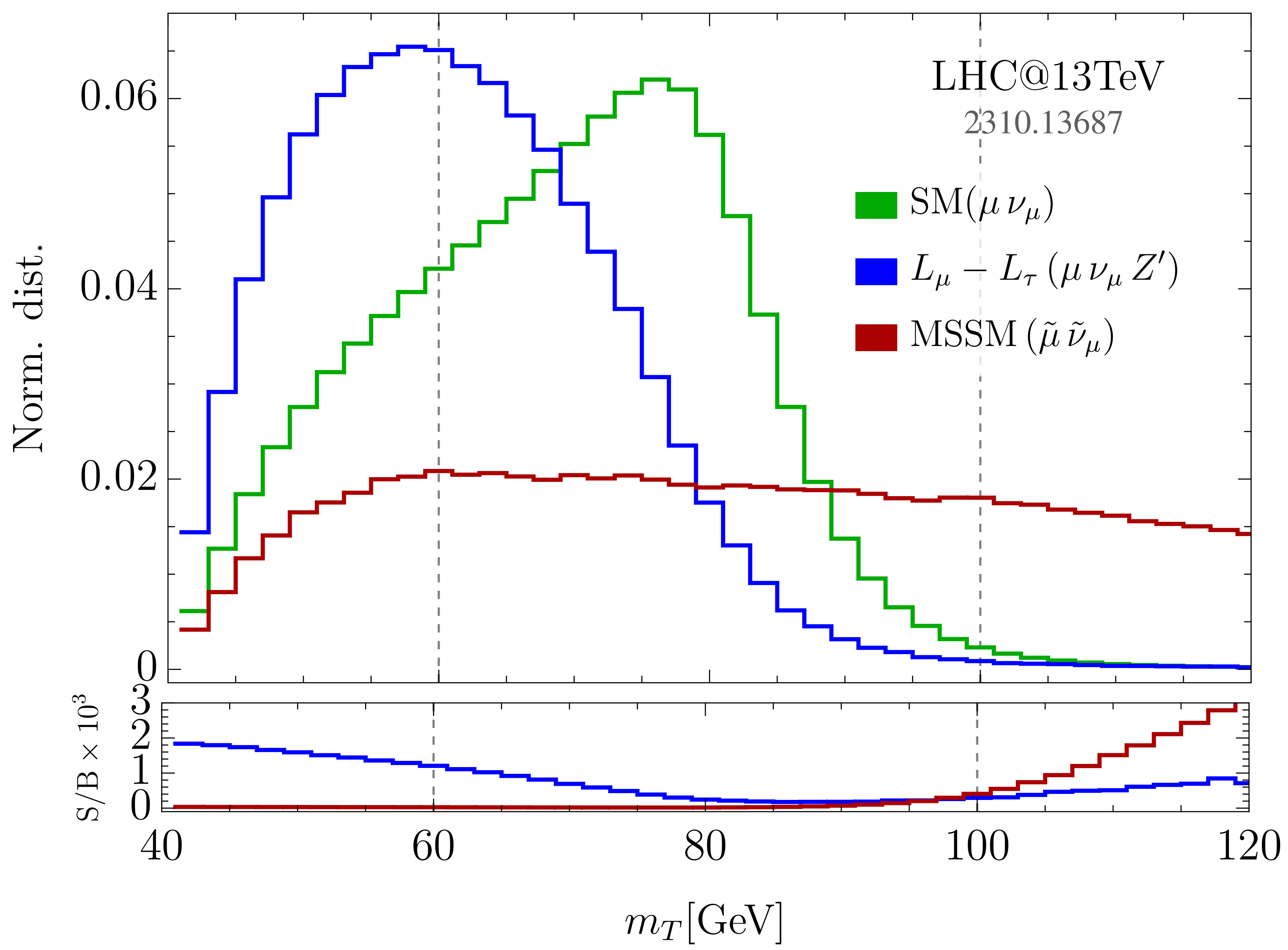
Search and Measure (SM) at a *pp* machine?

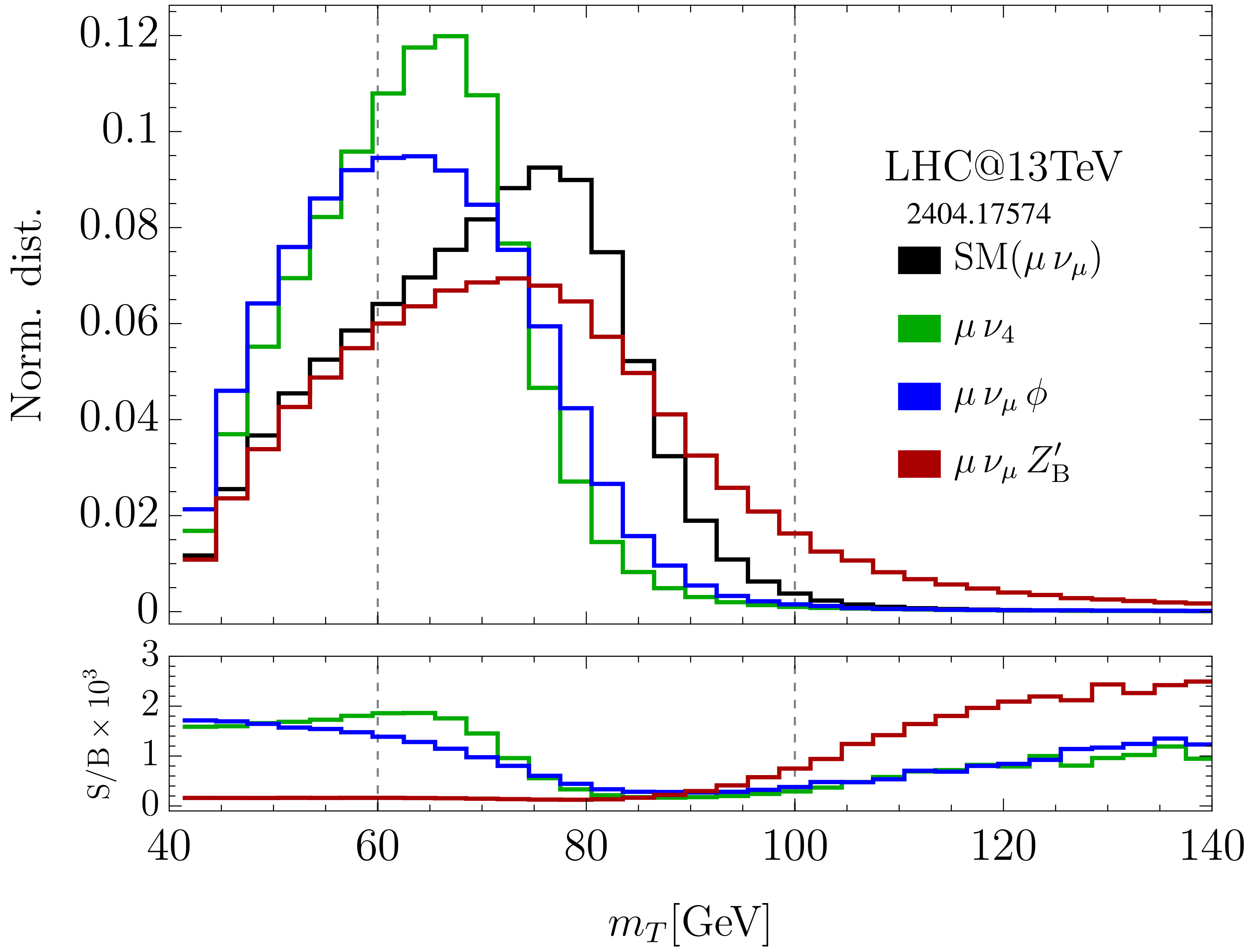


Search and Measure (SM) at a *pp* machine?

SEARCH & MEASURE in ℓ + mET



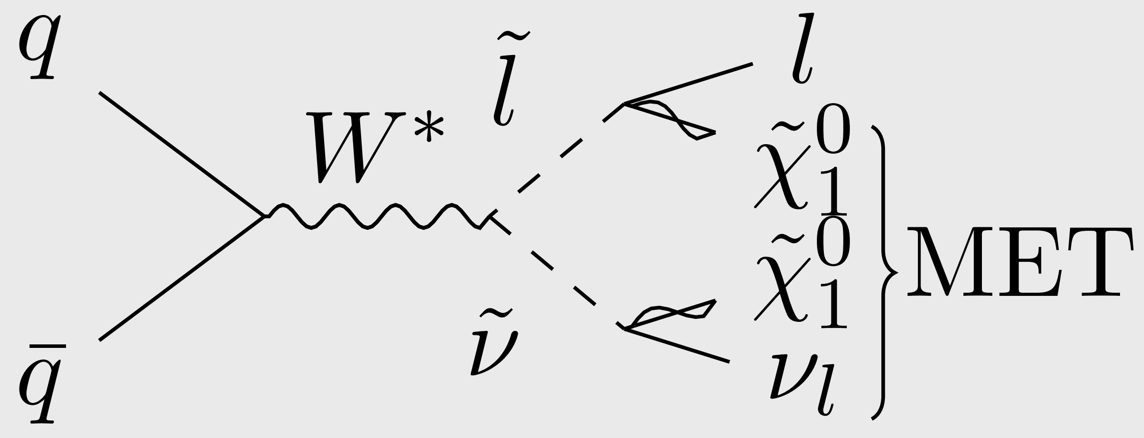


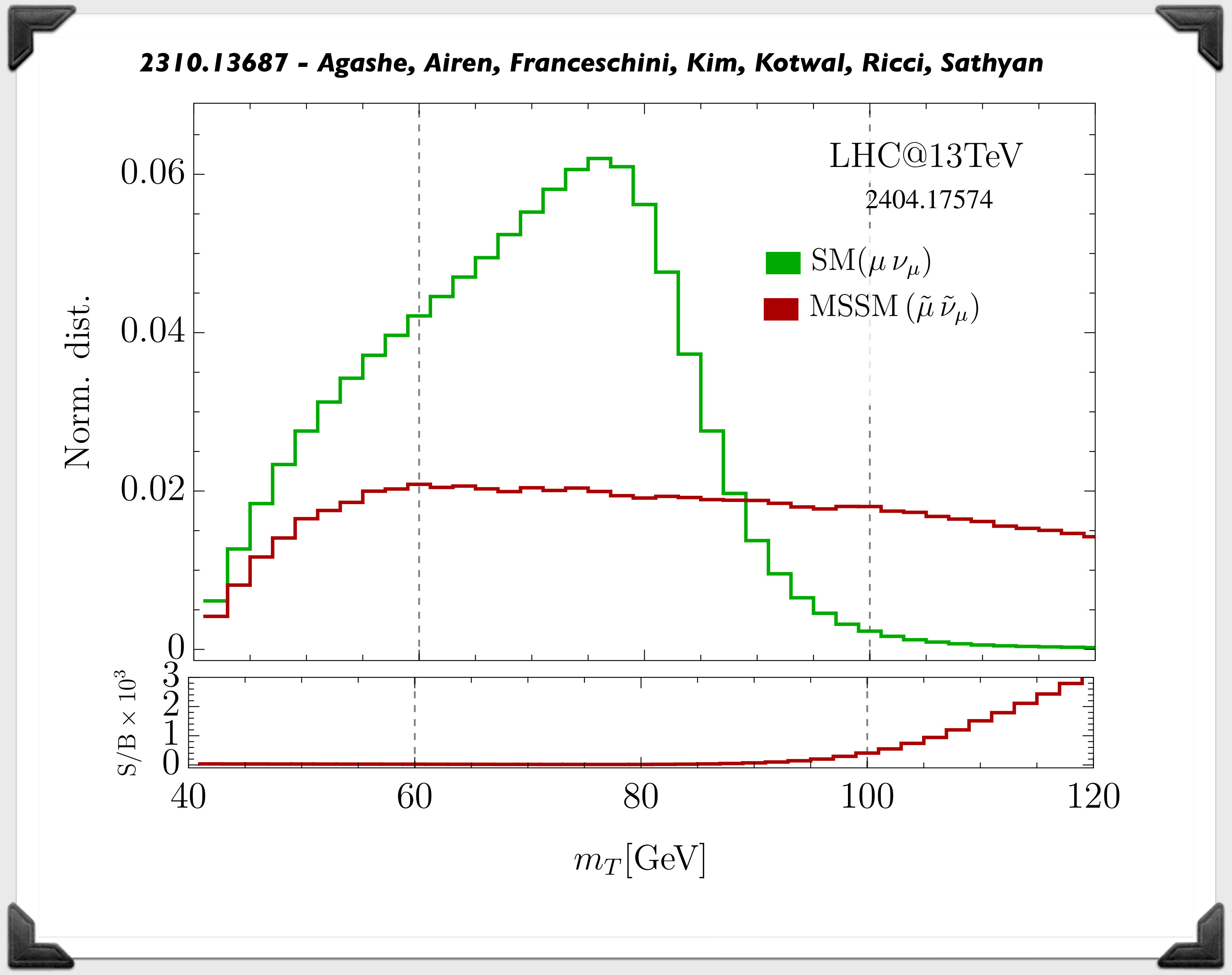


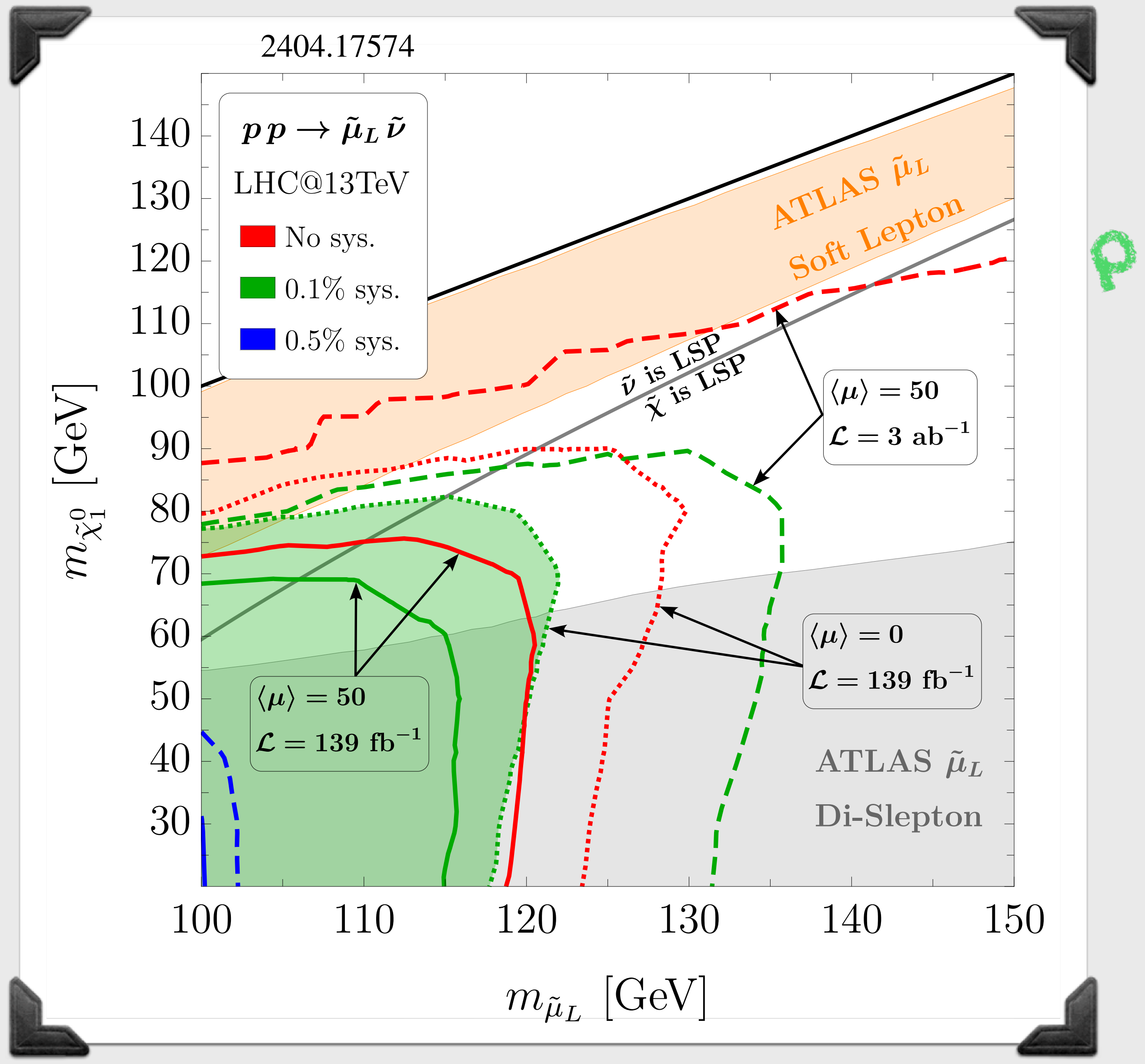
Search and Measure (SM) at a *pp* machine?

SEARCH & MEASURE

in ℓ + mET

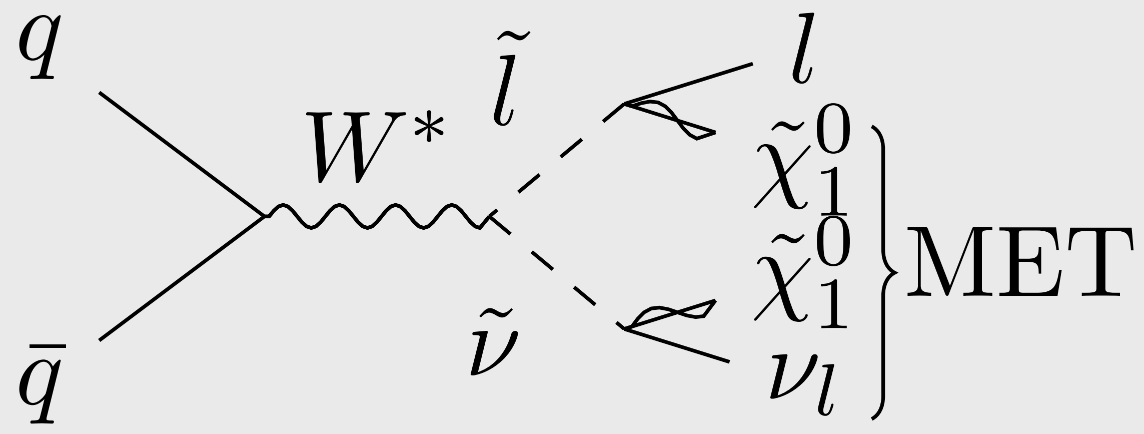


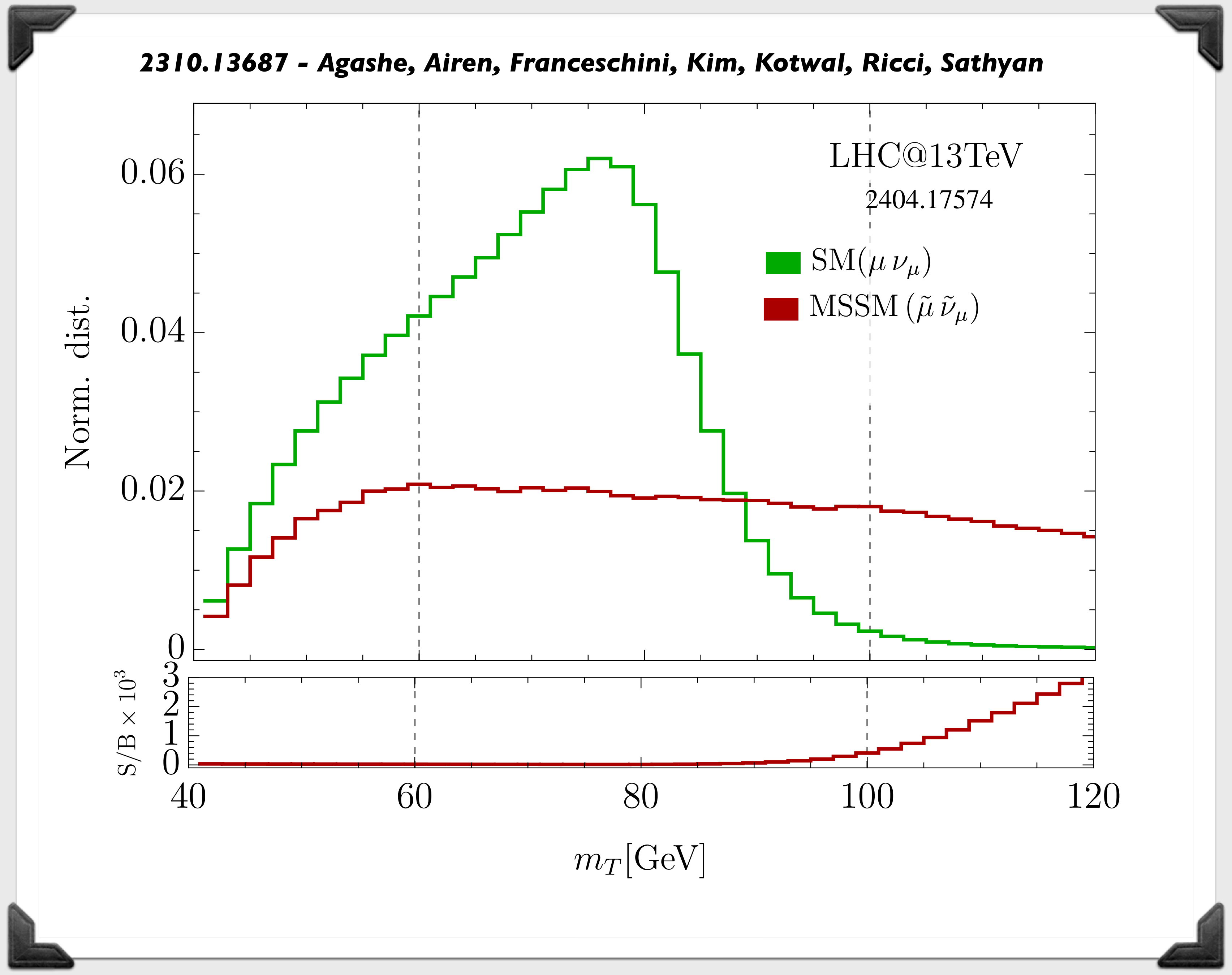


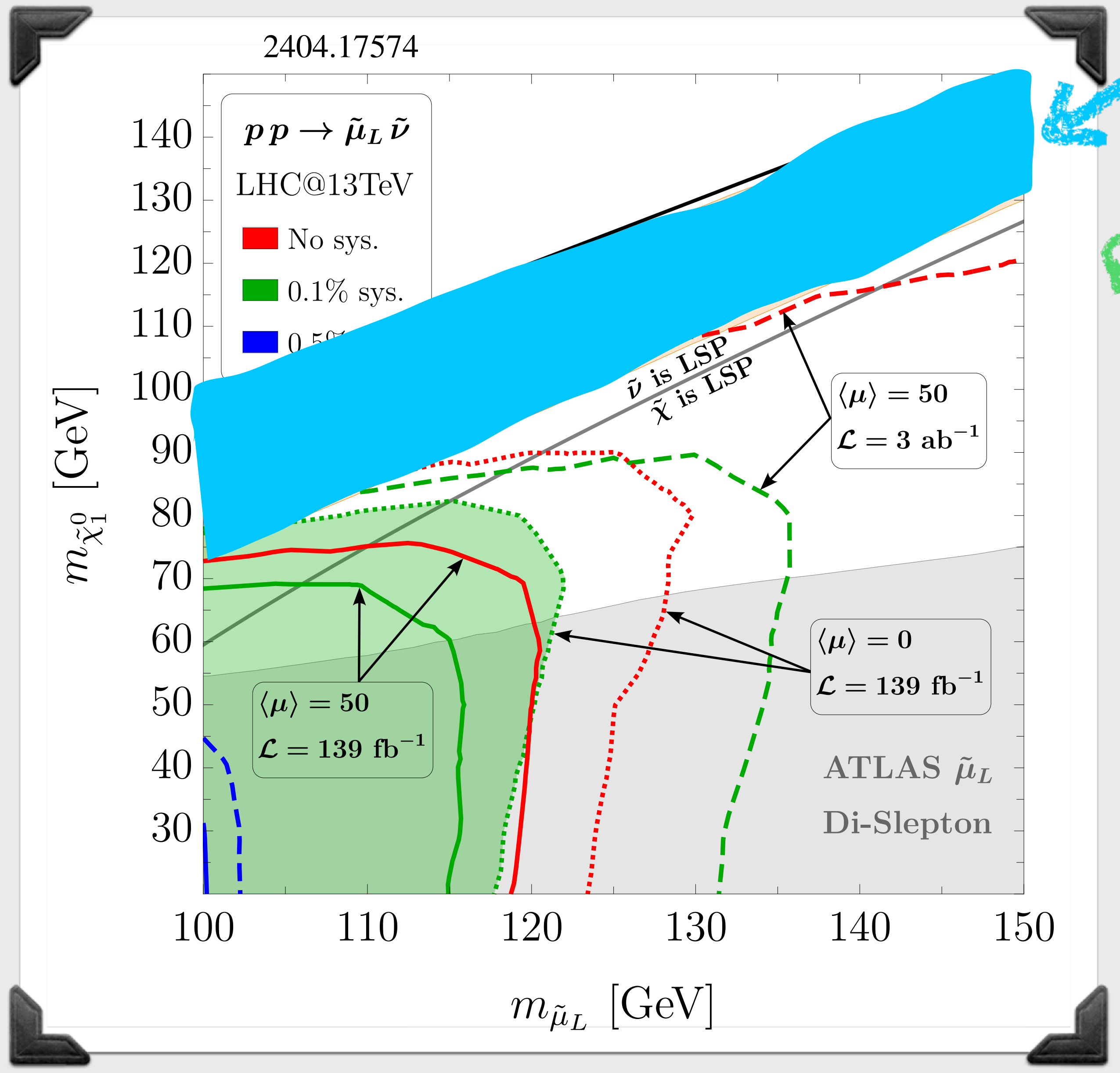


Search and Measure (SM) at a *pp* machine?

SEARCH & MEASURE in ℓ + mET





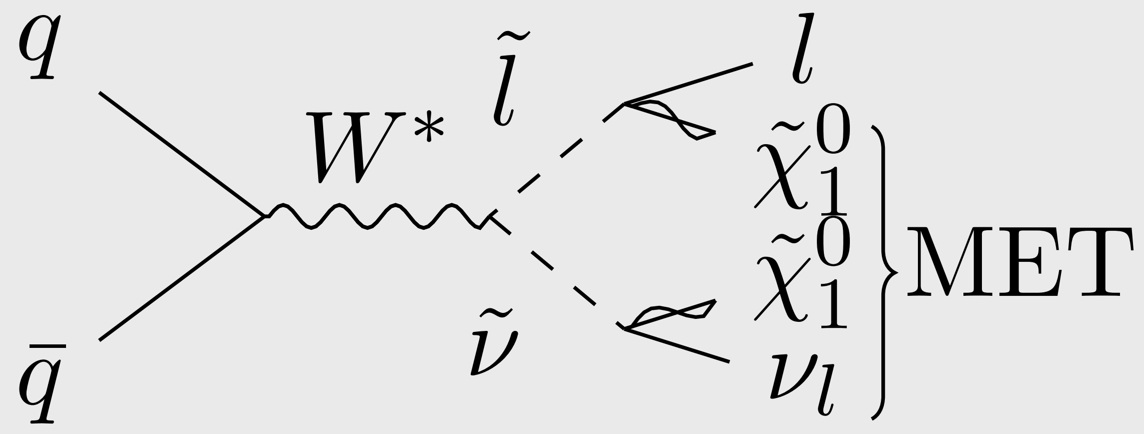


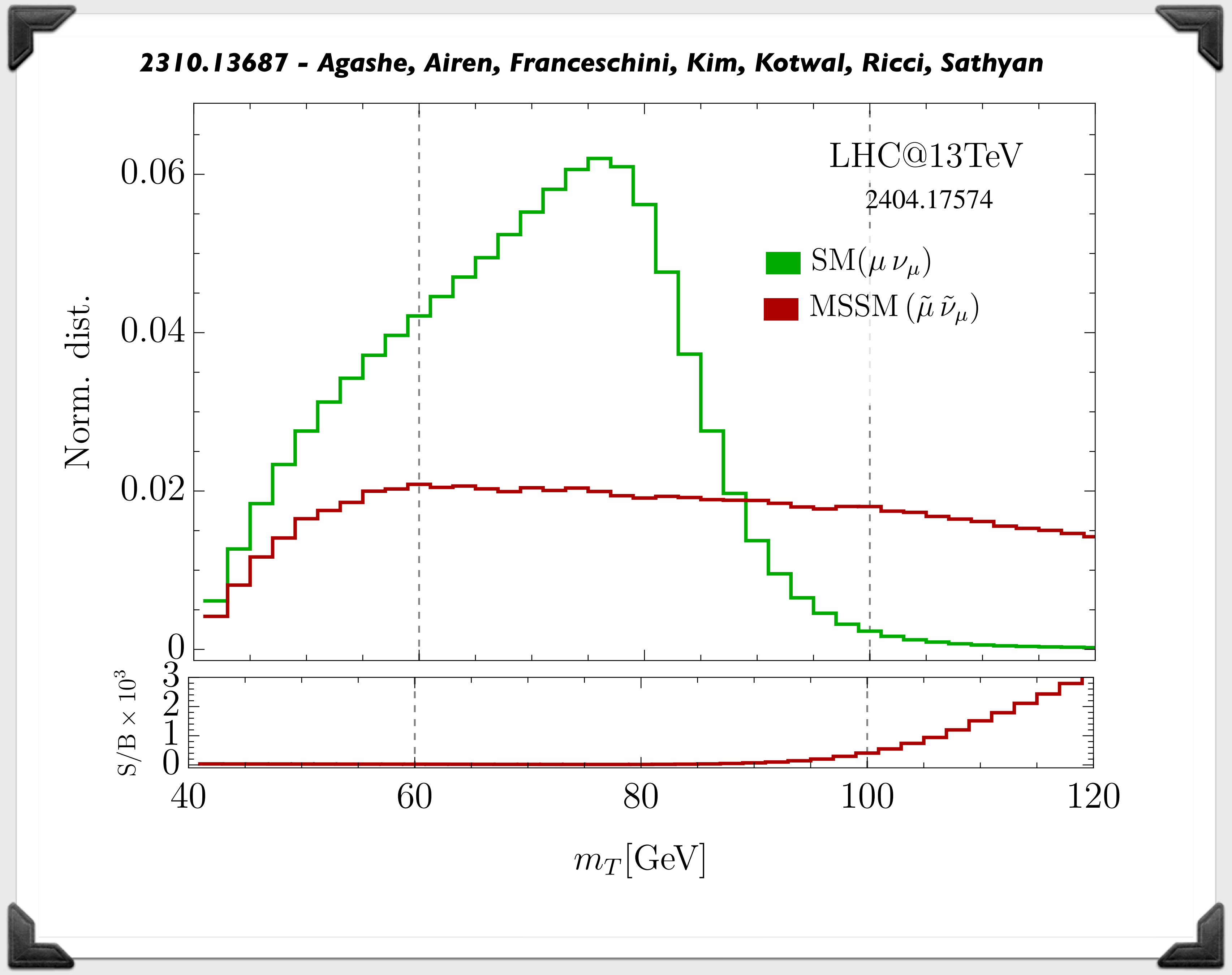
PRESENT BOUND Soft ℓ

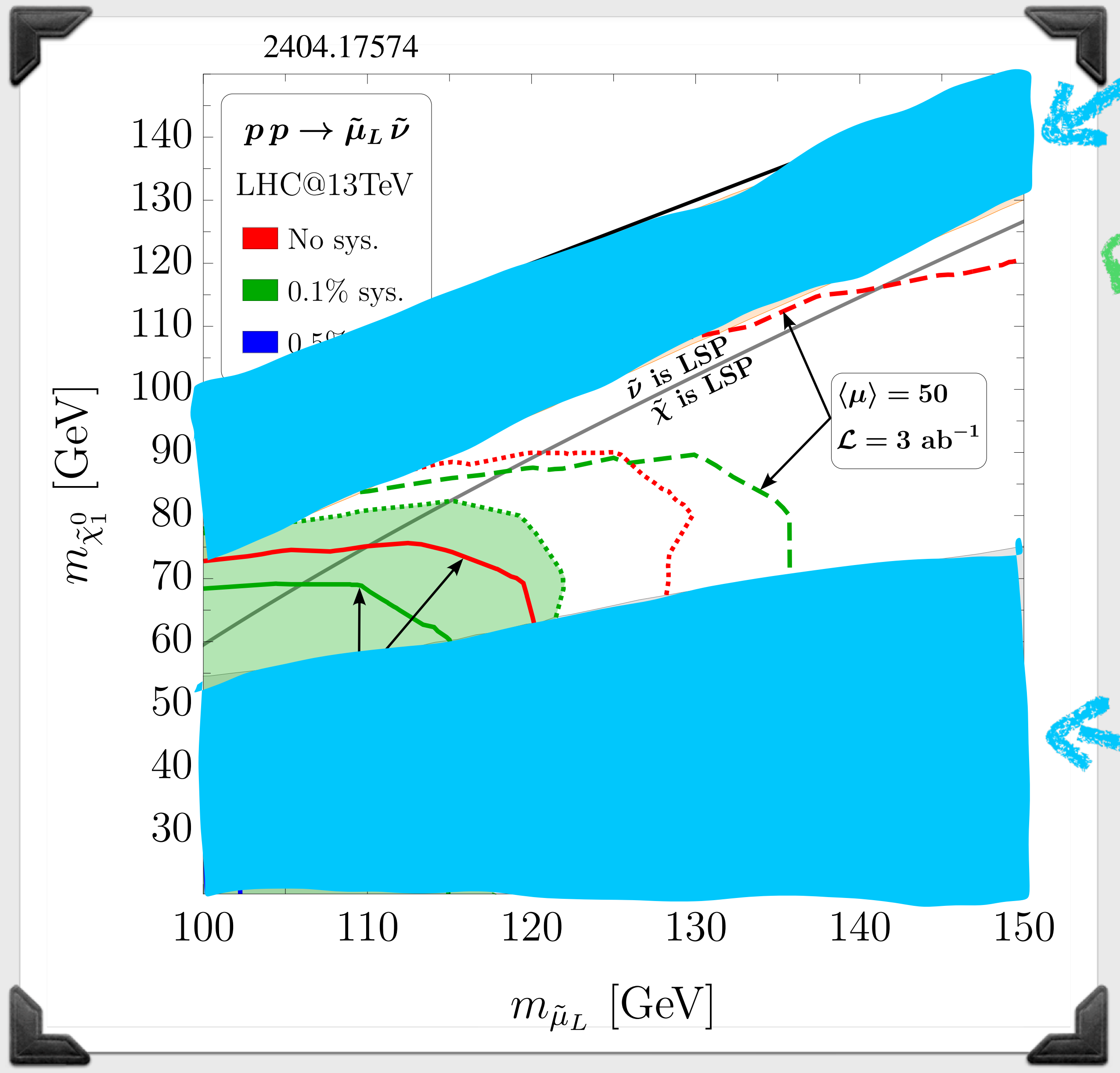
Search and Measure (SM) at a *pp* machine?

SEARCH & MEASURE

in ℓ + mET





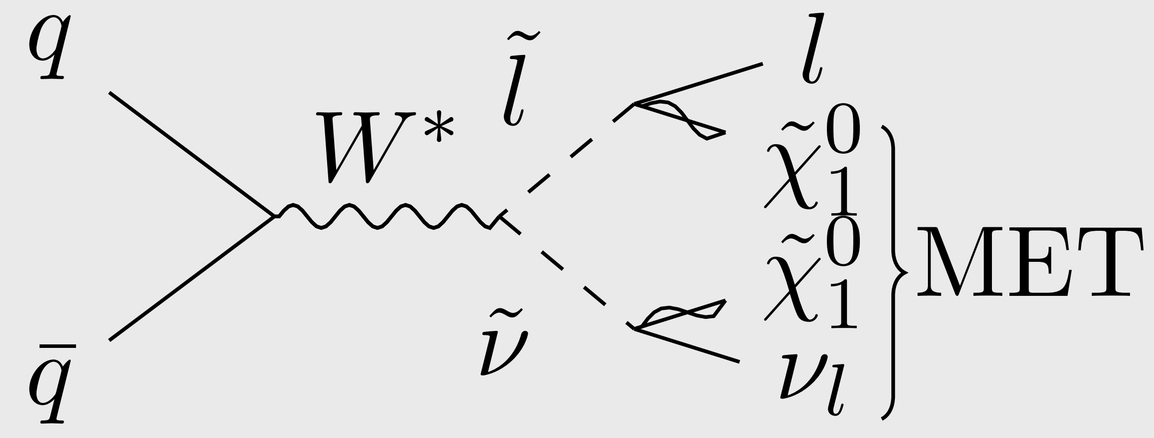


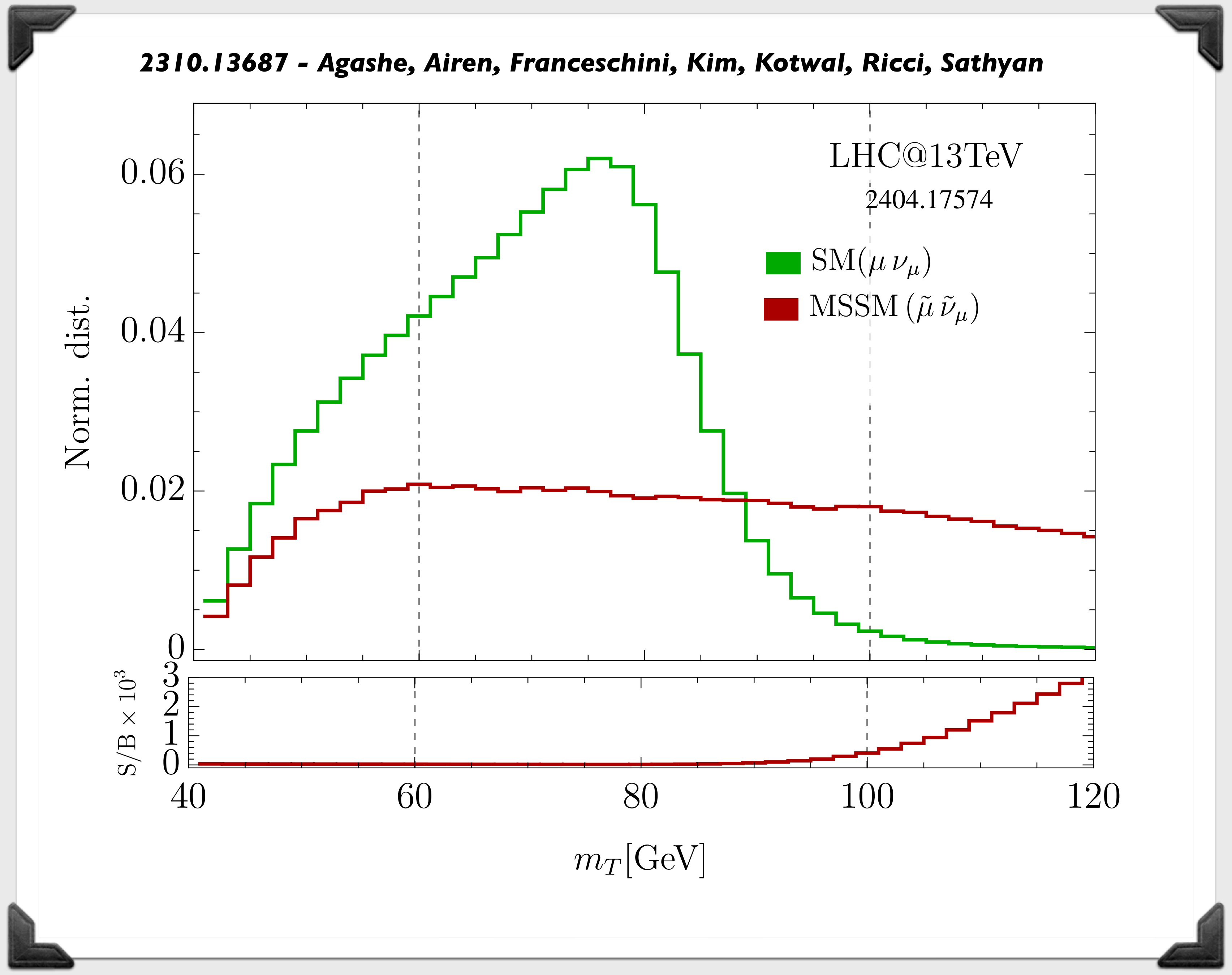
PRESENT BOUND soft ℓ

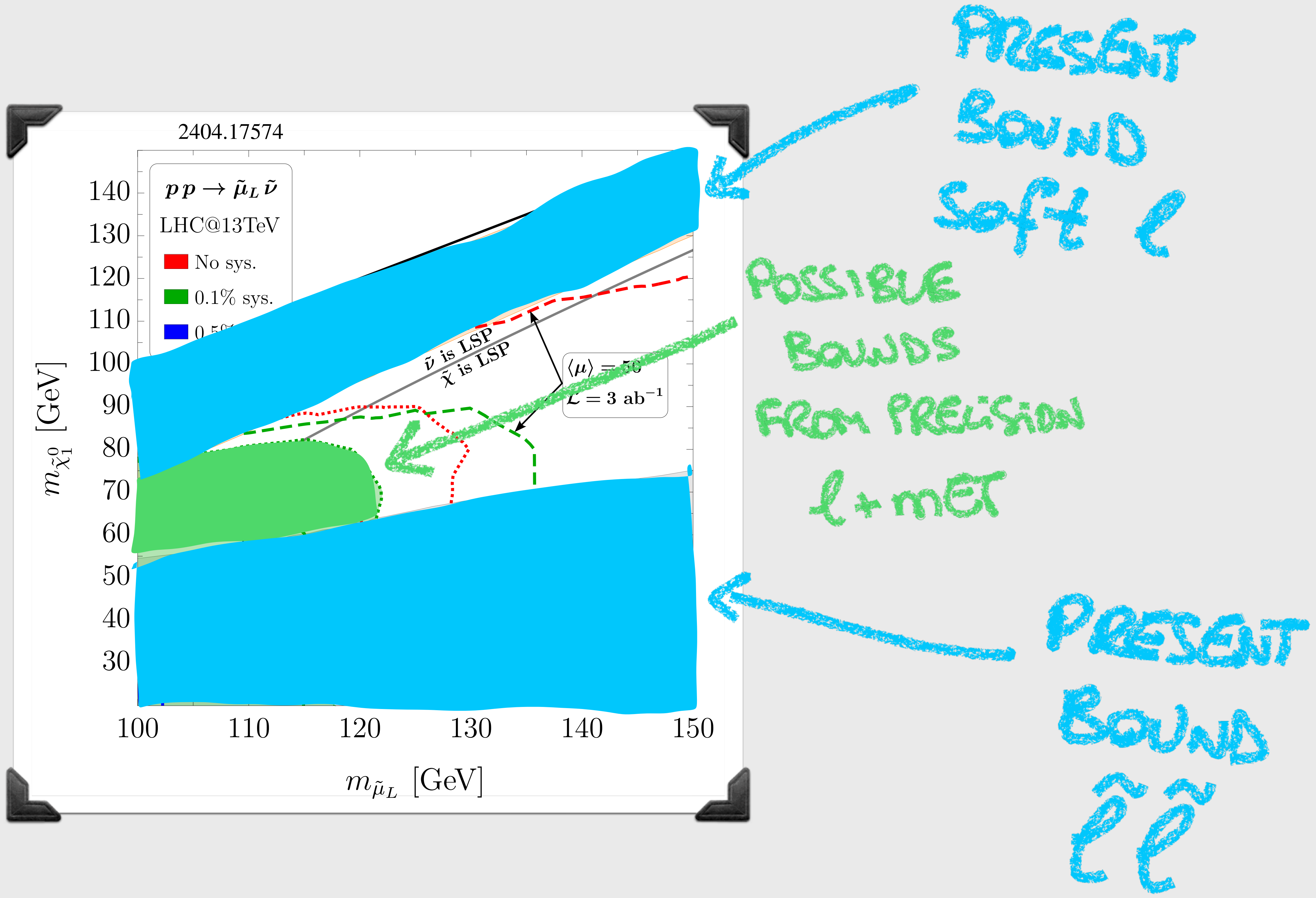
PRESENT BOUND $\tilde{\ell}\tilde{\ell}$

Search and Measure (SM) at a *pp* machine?

SEARCH & MEASURE in ℓ + mET

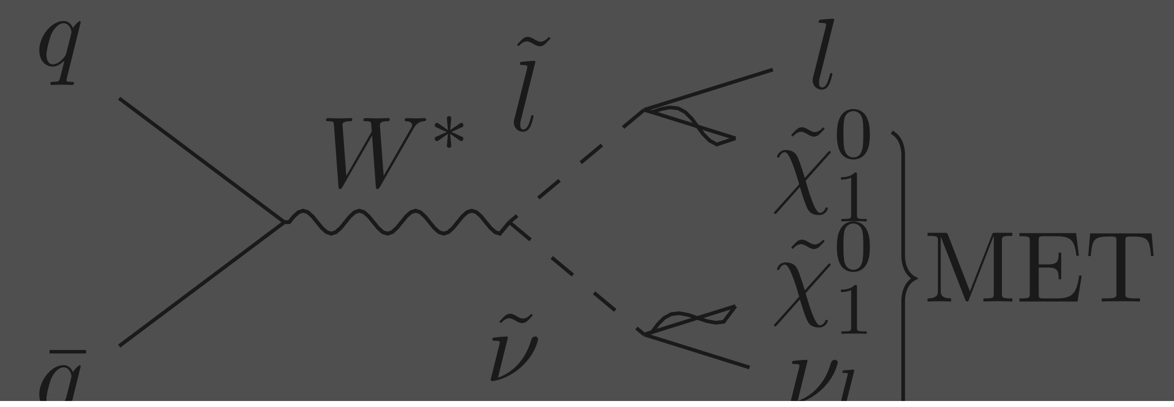






Search and Measure (SM) at a *pp* machine?

SEARCH & MEASURE



- A *pp* machine has its Achille's heel in the electroweak searches. You have to expect gaps in the coverage for models that predict new non-colored states

- "precision" can come in rescue, but can a future *pp* machine deliver such "precision" program as the (HL-)LHC?

40 60 80 100 120

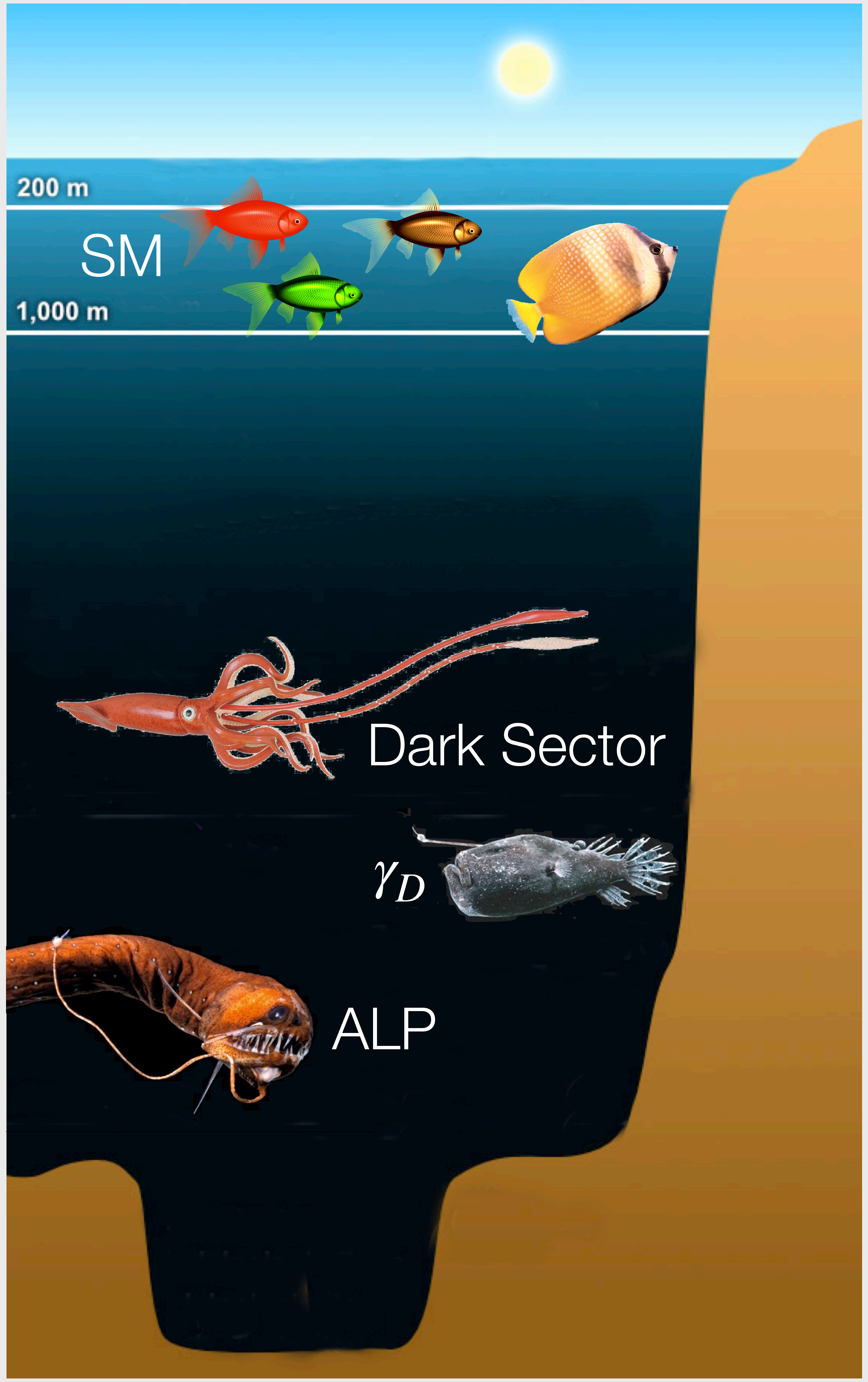
m_T[GeV]

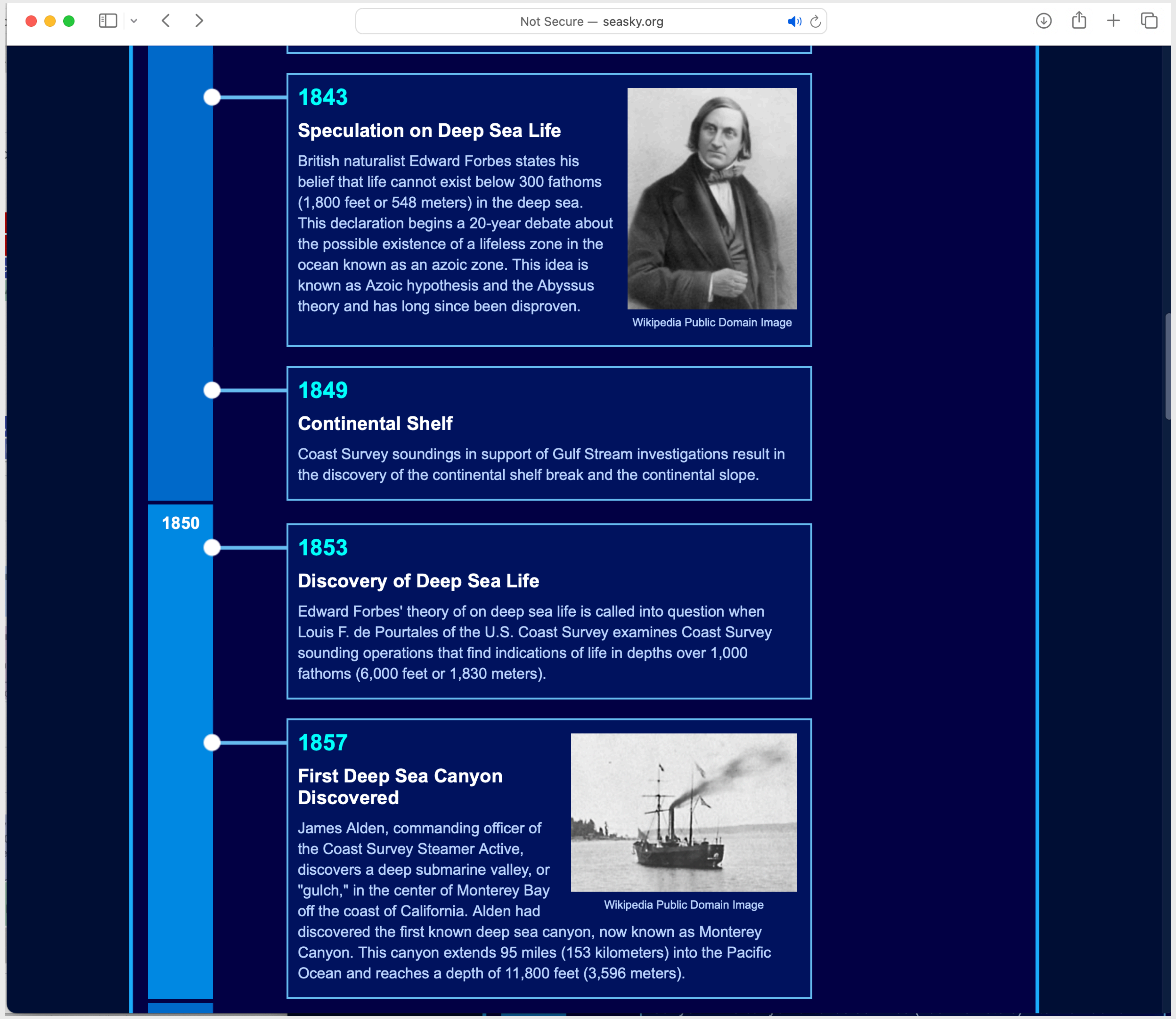
$m_{\tilde{\mu}_L}$ [GeV]

Exotica? Why?

First of all because we know that strange things happen in Nature

You have to look for them, not assume they do not exists (Forbes 1843)




Not Secure — seasky.org

1850

1843

Speculation on Deep Sea Life

British naturalist Edward Forbes states his belief that life cannot exist below 300 fathoms (1,800 feet or 548 meters) in the deep sea. This declaration begins a 20-year debate about the possible existence of a lifeless zone in the ocean known as an azoic zone. This idea is known as Azoic hypothesis and the Abyssus theory and has long since been disproven.

Wikipedia Public Domain Image

1849

Continental Shelf

Coast Survey soundings in support of Gulf Stream investigations result in the discovery of the continental shelf break and the continental slope.

1853

Discovery of Deep Sea Life

Edward Forbes' theory of on deep sea life is called into question when Louis F. de Pourtales of the U.S. Coast Survey examines Coast Survey sounding operations that find indications of life in depths over 1,000 fathoms (6,000 feet or 1,830 meters).

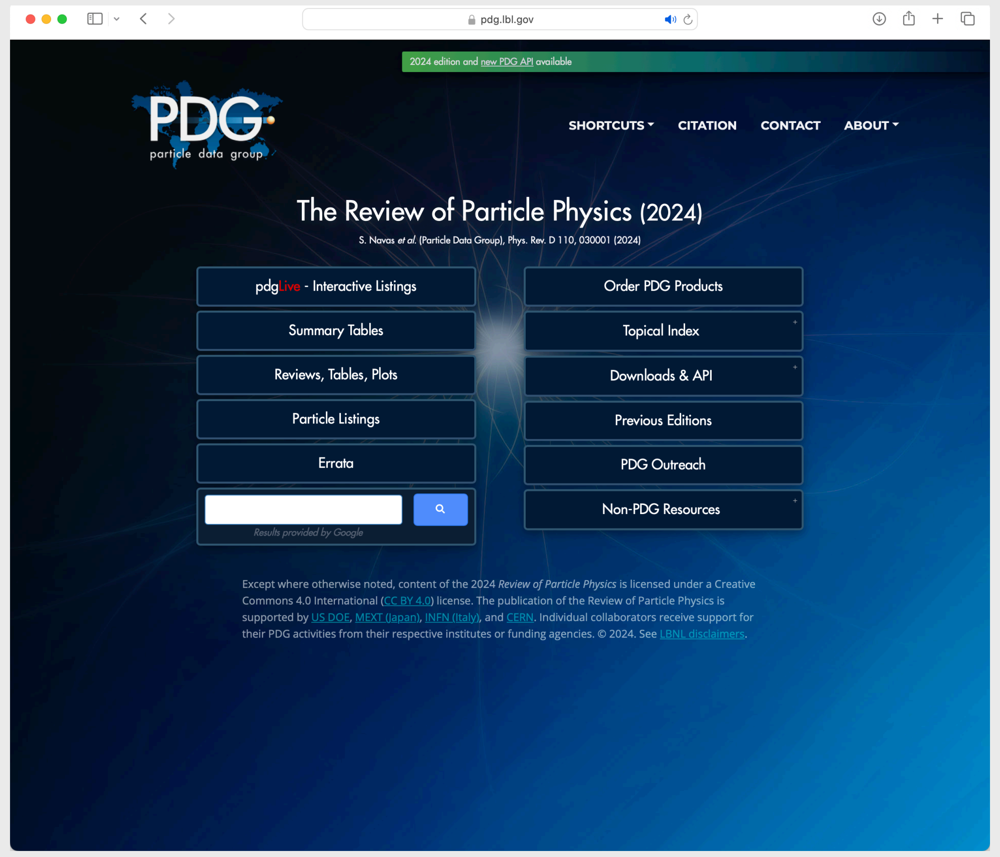
1857

First Deep Sea Canyon Discovered

James Alden, commanding officer of the Coast Survey Steamer Active, discovers a deep submarine valley, or "gulch," in the center of Monterey Bay off the coast of California. Alden had discovered the first known deep sea canyon, now known as Monterey Canyon. This canyon extends 95 miles (153 kilometers) into the Pacific Ocean and reaches a depth of 11,800 feet (3,596 meters).

Wikipedia Public Domain Image

Exotica? Why? Long lived particles!



"Ordinary" Long Lived Particles

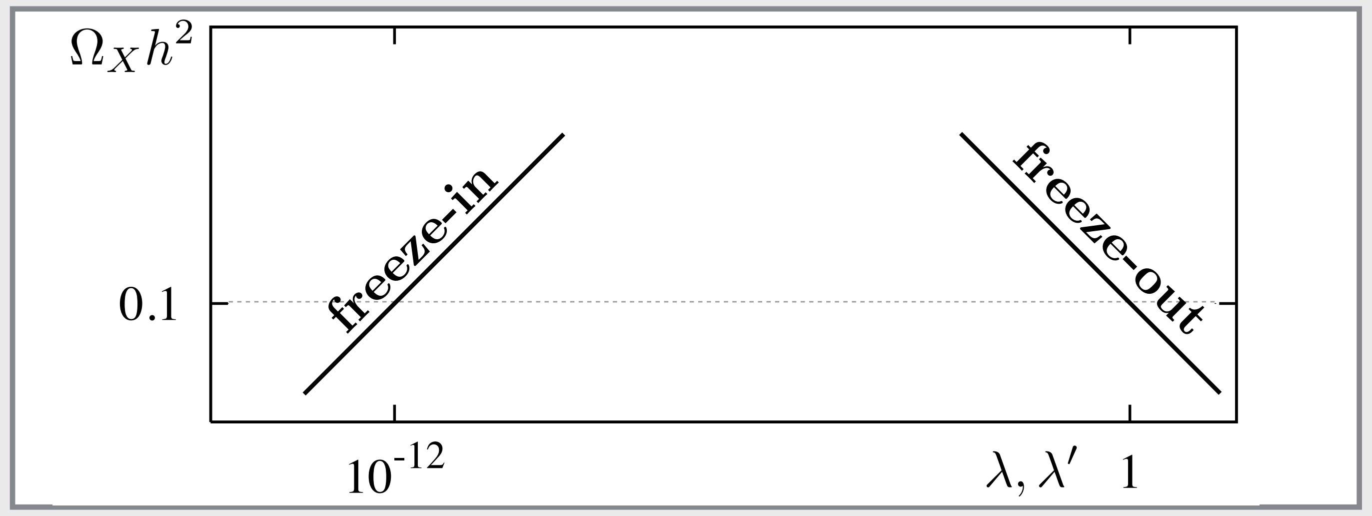
n	2.655×10^{14} mm
n−bar	2.655×10^{14} mm
Λ	78.91 mm
Λ−bar	78.91 mm
Σ+	24.04 mm
Σ−	24.04 mm
Σ−	44.4 mm
Σ+	44.4 mm
Ξ0	86.9 mm
Ξ0−bar	86.9 mm
Ξ−	49.2 mm
Ξ+	49.2 mm
Omega−	24.6 mm
Omega+	24.6 mm
Λ_c	0.060 mm
Λ_c−bar	0.060 mm
Ξ_c^+	0.133 mm
Ξ_c^−	0.133 mm
Ξ_c^0	0.033 mm
Ξ_c^0−bar	0.033 mm
Omega_c	0.021 mm
Omega_c−bar	0.021 mm
Λ_b	0.369 mm
Λ_b−bar	0.369 mm

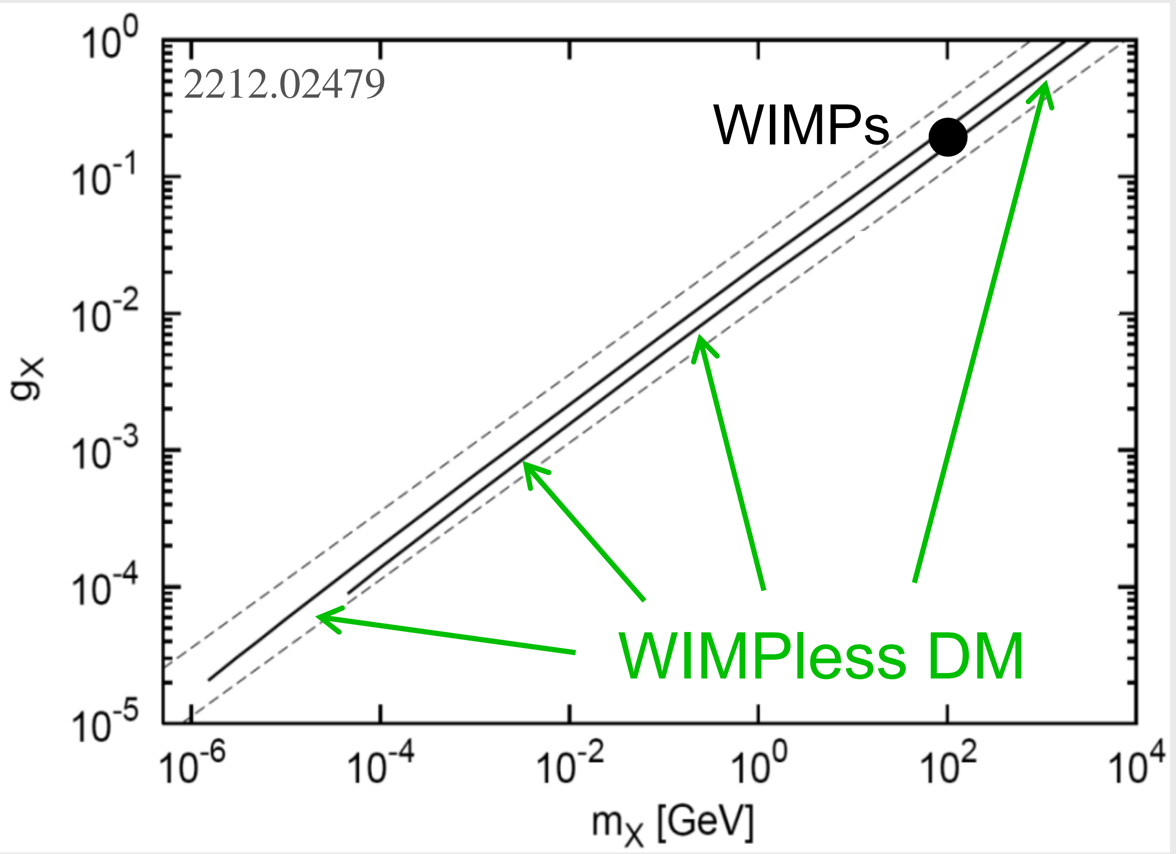
Wolfram Particle Data

Long lifetime can be associated to

- either some symmetry breaking effect (nearly degenerate particles)
- or very weak couplings.

Both are generic ingredients of BSM models. For instance an ultra-weak coupling could be behind the “freeze-in” of Dark Matter, or be the sign of the existence of a secluded/hidden sector (do you remember gauge-mediated SUSY-breaking?)





Exotica is not the “non-SUSY”, “non-Higgs”, “non-SM” stuff …

Outlook

- LHC and it experiments provided the first platform to study spontaneous symmetry breaking and **Higgs physics**. Future pp machine promise to do the same. The Higgs boson has a serious chance to show us signs of new physics and we should pursue this direction with full strength.
- There is no guarantee for discoveries with the next generation of colliders, but we should not be worried about that. We will learn plenty of lessons by doing our job … back to regular science exploration!
- The **breadth of the physics** program is very important, especially because we do not know what to expect. In this respect a pp machine is an excellent tool.

Critical points

- The jump in luminosity for the next machine is as critical as the jump in energy. Ideally one wants $\mathscr{L} \sim E^2$, that is $\mathscr{L}_{FCChh} \simeq 50\text{x}\mathscr{L}_{HL-LHC} \simeq 150\text{ab}^{-1}$

M. Mangano on Wed.

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
initial *L*	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27
opt. run time	h	3.8	3.3	6.3	3.8	3.4	4.2	(18-13) ~10

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
ideal $\int L\,dt$ /day	fb^{-1}	7.9	17.1	10.8	7.7	7.7	3,1	(1.9) 0.4
$\int L\,dt$ / year	fb^{-1}	950	2000	1300	920	920	370	240 (55)

- The reach for non-colored states struggles. Precision physics at pp and possible inputs from $\ell^+\ell^-$ machines may come to rescue.

Table 3. 5σ discovery reach for WIMP DM particles at HL-LHC, HE-LHC and FCC-hh [7]. Columns 4 and 5 present the CR extrapolations from HL-LHC to HE-LHC, and from HE-LHC to FCC, respectively. Column 6 gives the extrapolation from HE-LHC to LE-FCC, augmented by a factor 1.3, as discussed in the text.

M(GeV)	HL-LHC	HE-LHC	FCC	HE-LHC (CR)	FCC (CR)	LE-FCC (1.3×CR)
wino	550	1500	4500	1100	3500	2300
higgsino	200	450	1250	420	950	650

M. Mangano on Wed.

Open Questions on the "big picture" on fundamental physics as of 2020s

	?	• what is the dark matter in the Universe?	✓	
		• why QCD does not violate CP?	✓	✓
		• how have baryons originated in the early Universe?	✓	
		• what originates flavor mixing and fermions masses?	✓	
		• what gives mass to neutrinos?	✓	
~~EFT~~		• why gravity and weak interactions are so different?	✓	
~~EFT~~		• what fixes the cosmological constant?	✓	

WEAK INTERACTIONS

STRONG INTERACTIONS

NEED SOME COSMOLOGY INPUTS

The biggest strategic issue in my opinion is that we need to evaluate the importance of these two critical points against:

- **the absence* a forthcoming energy/mass threshold in the above open questions**
- **the ubiquity of weak interactions as central aspect of the above open questions**

Thank you!

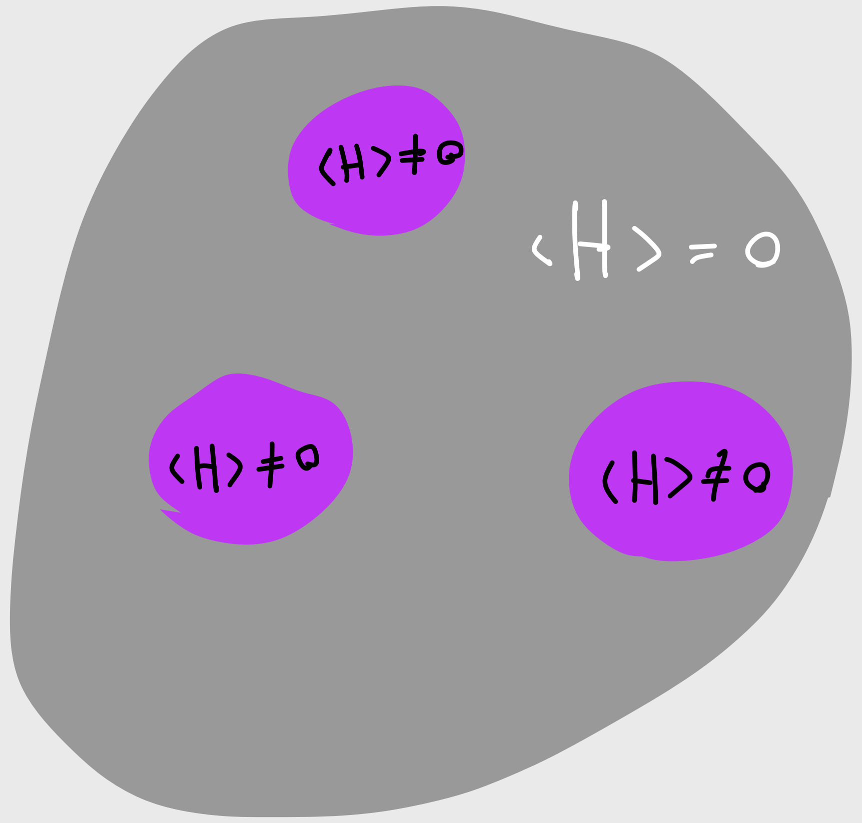
Thank you!

Thank you!

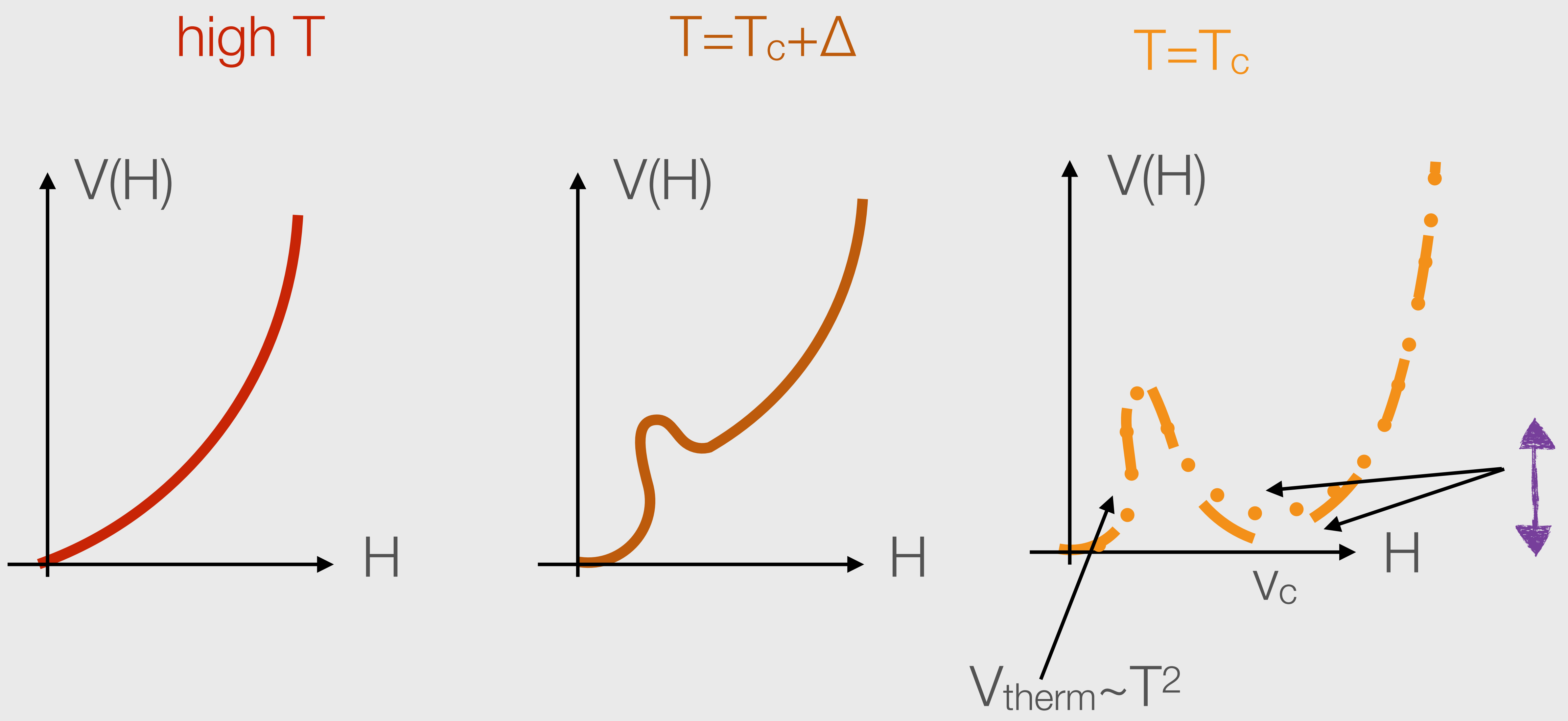
flashing concrete results for

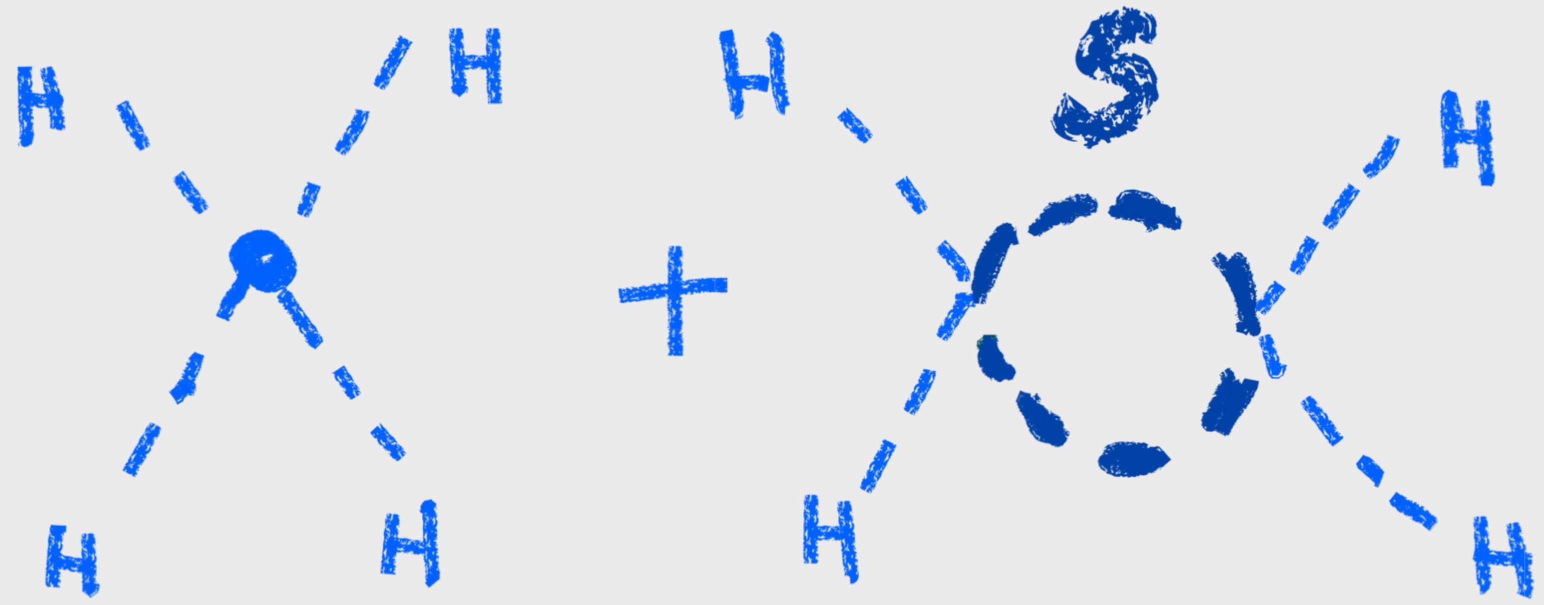
EW phase transition

Electroweak phase transition



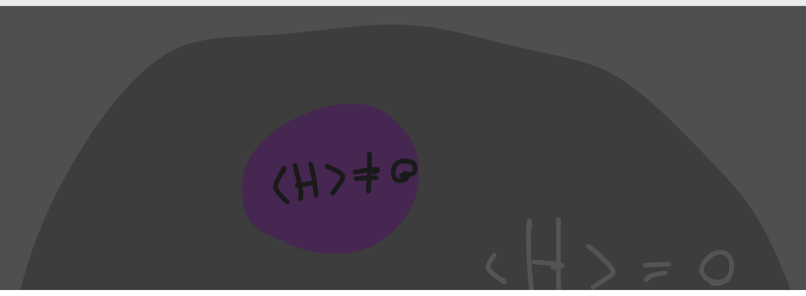
- Modifications of the Higgs potential ⇒ Out of Equilibrium transition from one vacuum to a new energetically favorable one





Singlet loop makes V(0,v) deeper

Electroweak phase transition



- We need to study all possible new states that induce a change in the Higgs boson potential.
- For these new state to have sizable effects in the early Universe they must be light, around 1 TeV at most.
- All searches for new Higgs bosons (or general electroweak particles) probe such fundamental issue of the origin of matter in the early Universe!

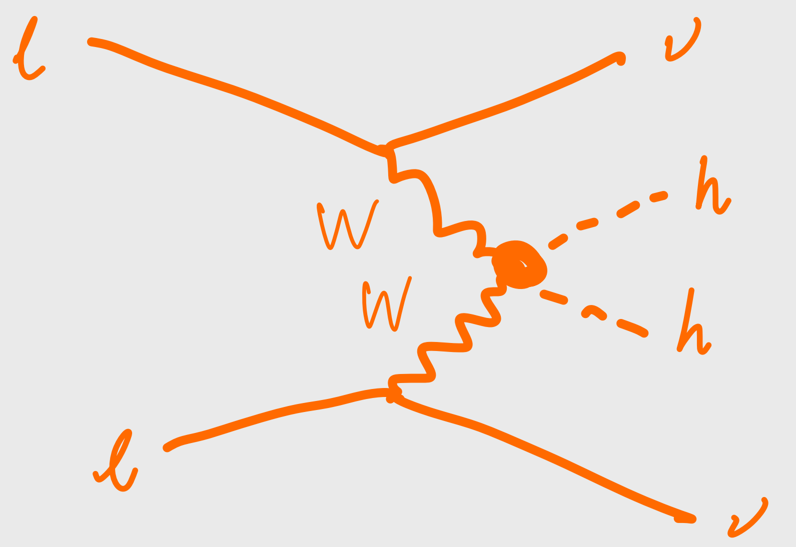
$V_{therm} \sim T^2$

V(0,v) deeper

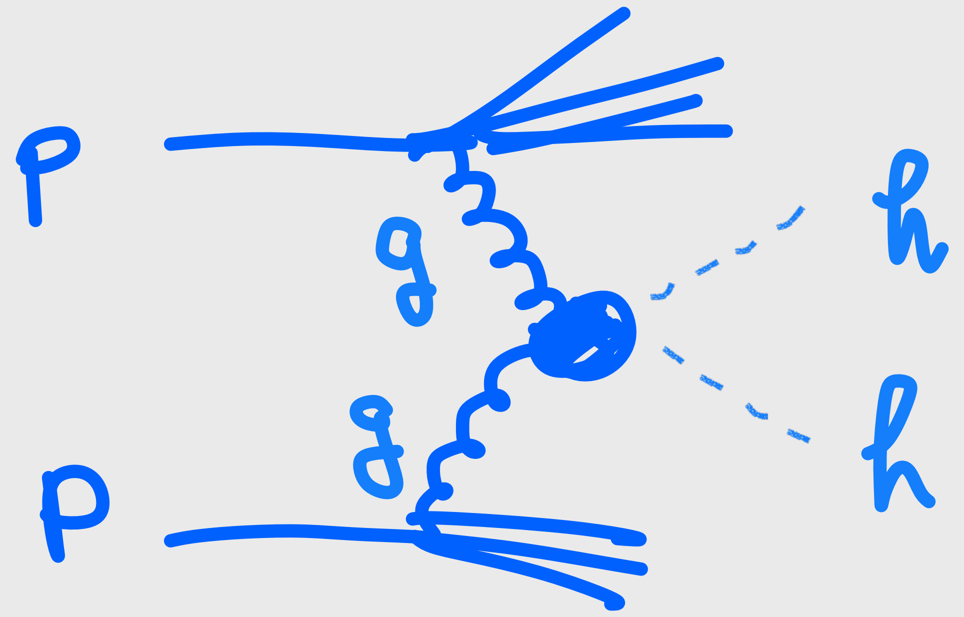
pp or $\ell^+\ell^- \to hh$

W BOSON COLLIDER

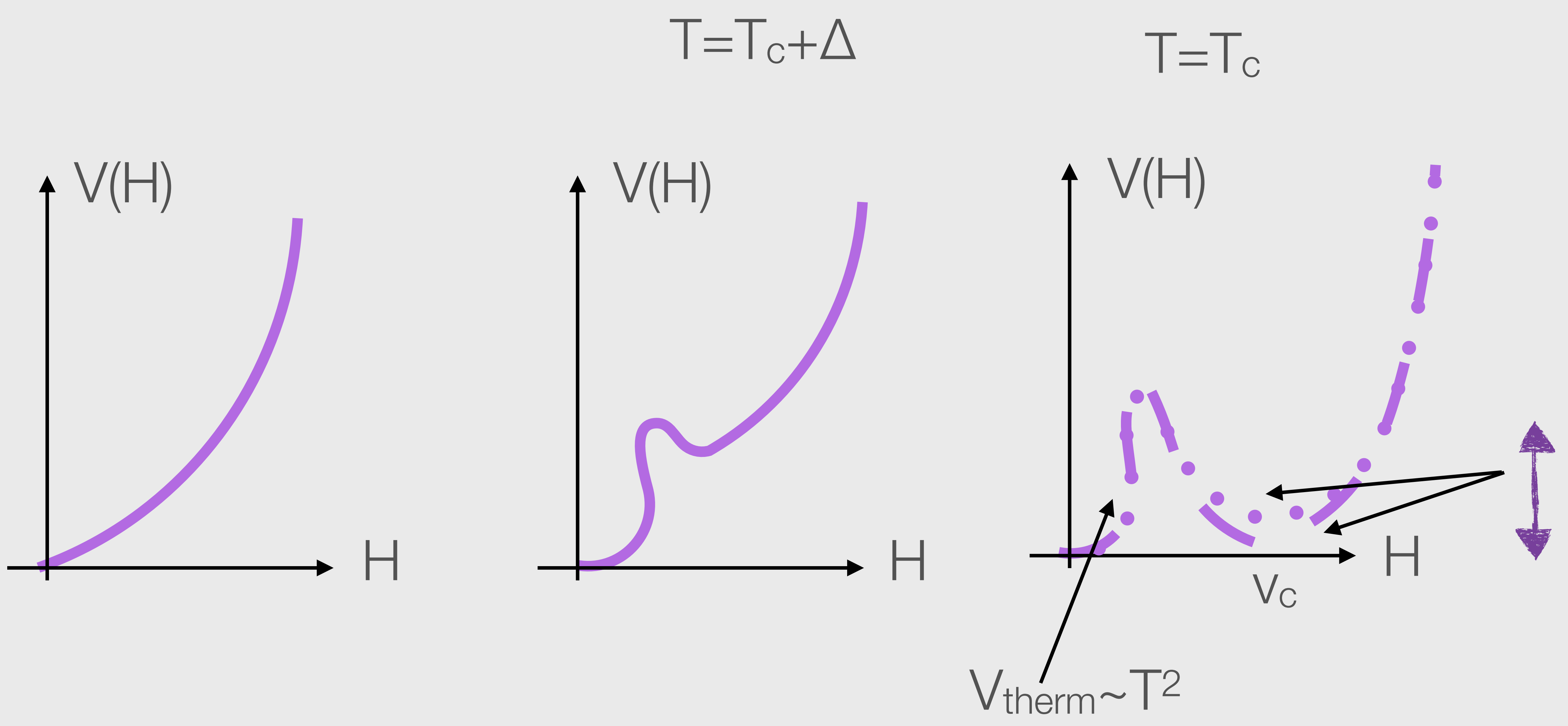
- High-Energy lepton collider has large flux of “partonic” W bosons

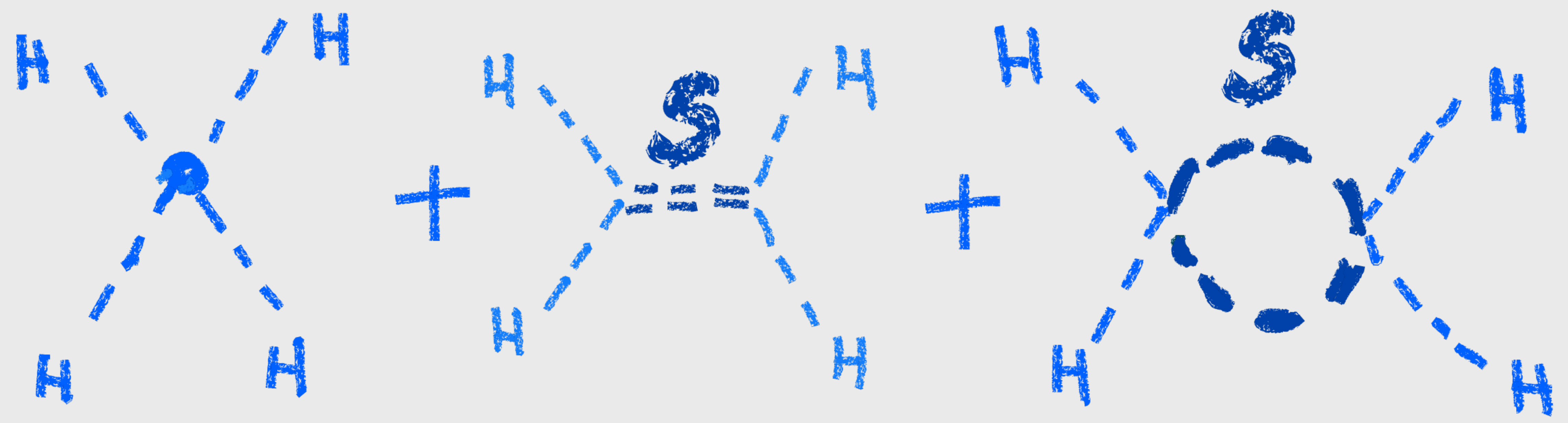


- gg collisions as usual



Electroweak phase transition





Singlet tree and loop makes V(0,v) deeper

EW phase transition

DIRECT & INDIRECT INTERPLAY

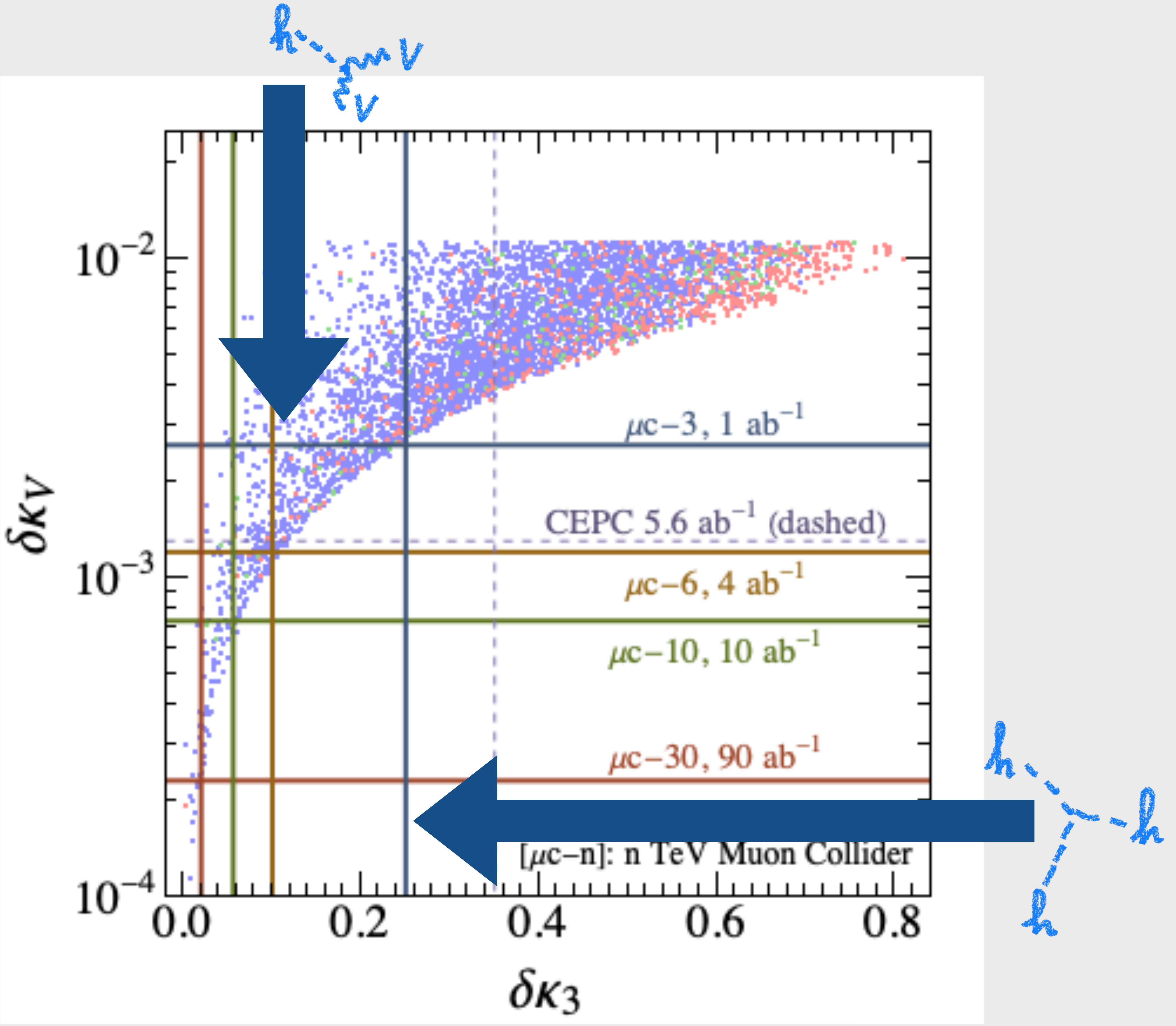
$$V(\Phi, S) = -\mu^2 \left(\Phi^\dagger\Phi\right) + \lambda \left(\Phi^\dagger\Phi\right)^2 + \frac{a_1}{2}\left(\Phi^\dagger\Phi\right) S + \frac{a_2}{2}\left(\Phi^\dagger\Phi\right) S^2 + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4.$$

independent parameters

$$\{M_{h_2}, \theta, v_s, b_3, b_4\}$$

strong First Order EW phase transition on all points

→ Gravity Wave SNR



EW phase transition

DIRECT & INDIRECT | INTERPLAY

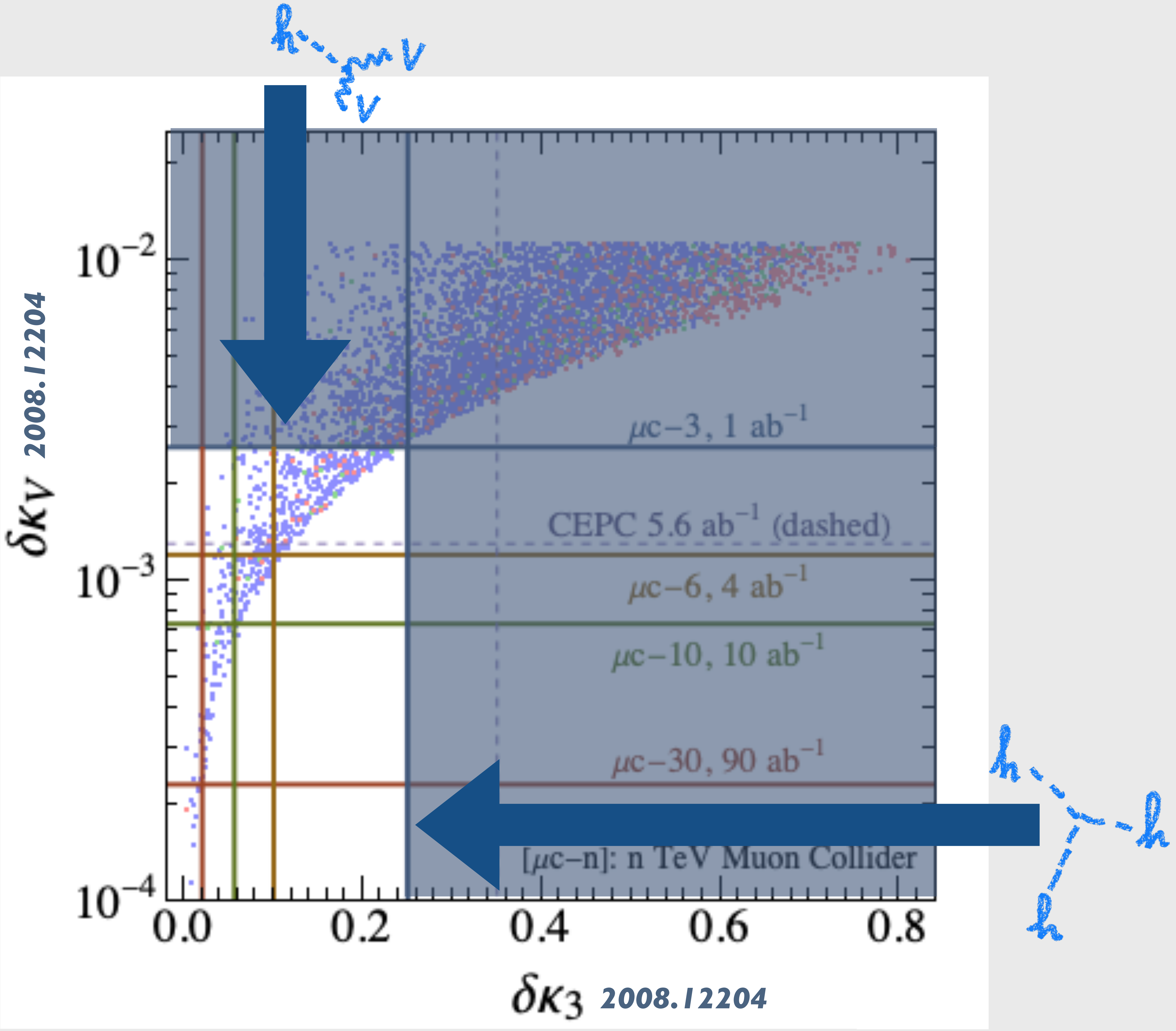
$$V(\Phi, S) = -\mu^2\left(\Phi^\dagger\Phi\right) + \lambda\left(\Phi^\dagger\Phi\right)^2 + \frac{a_1}{2}\left(\Phi^\dagger\Phi\right)S + \frac{a_2}{2}\left(\Phi^\dagger\Phi\right)S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

independent parameters

$$\{M_{h_2}, \theta, v_s, b_3, b_4\}$$

strong First Order EW phase transition on all points

Gravity Wave SNR

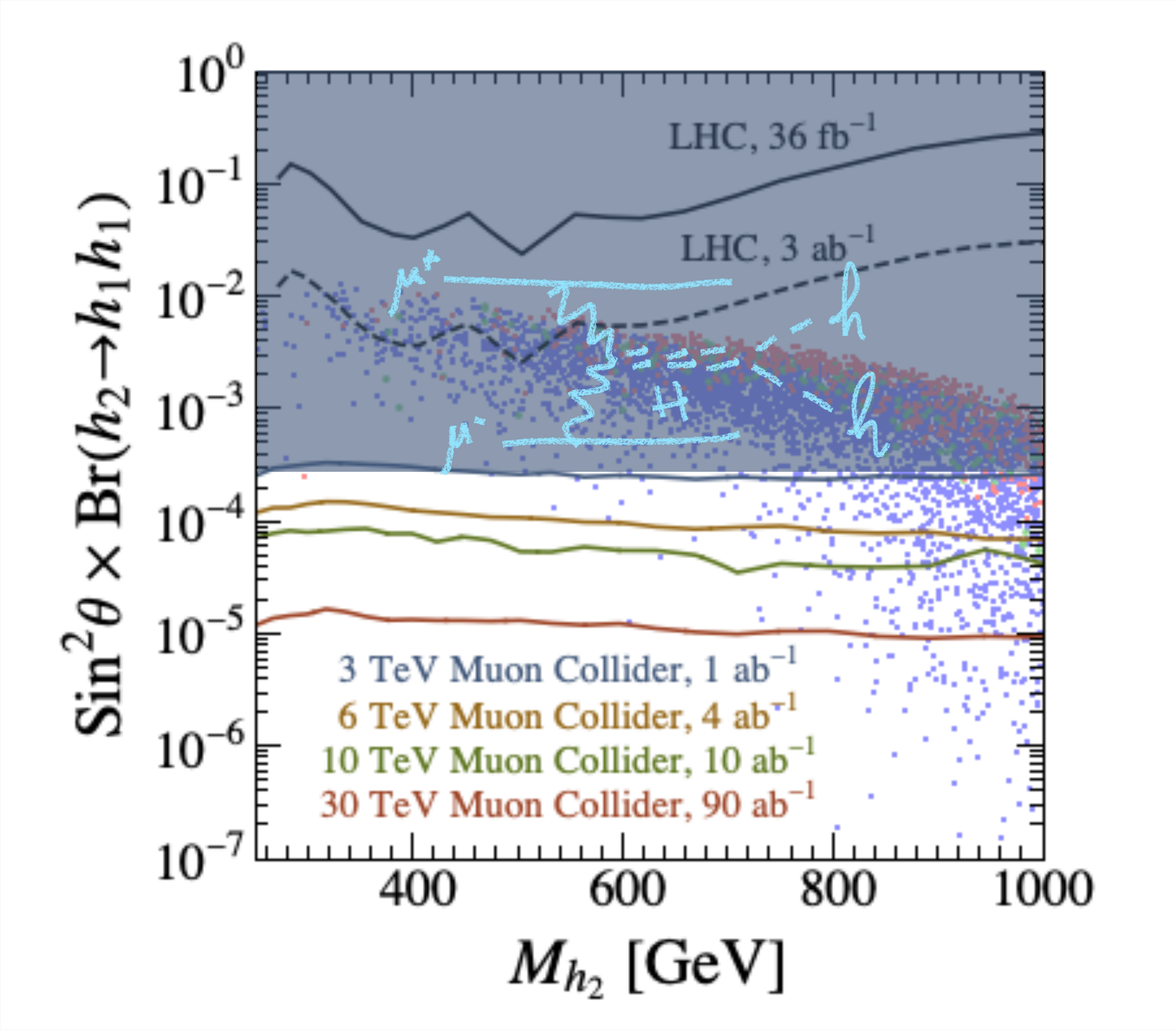


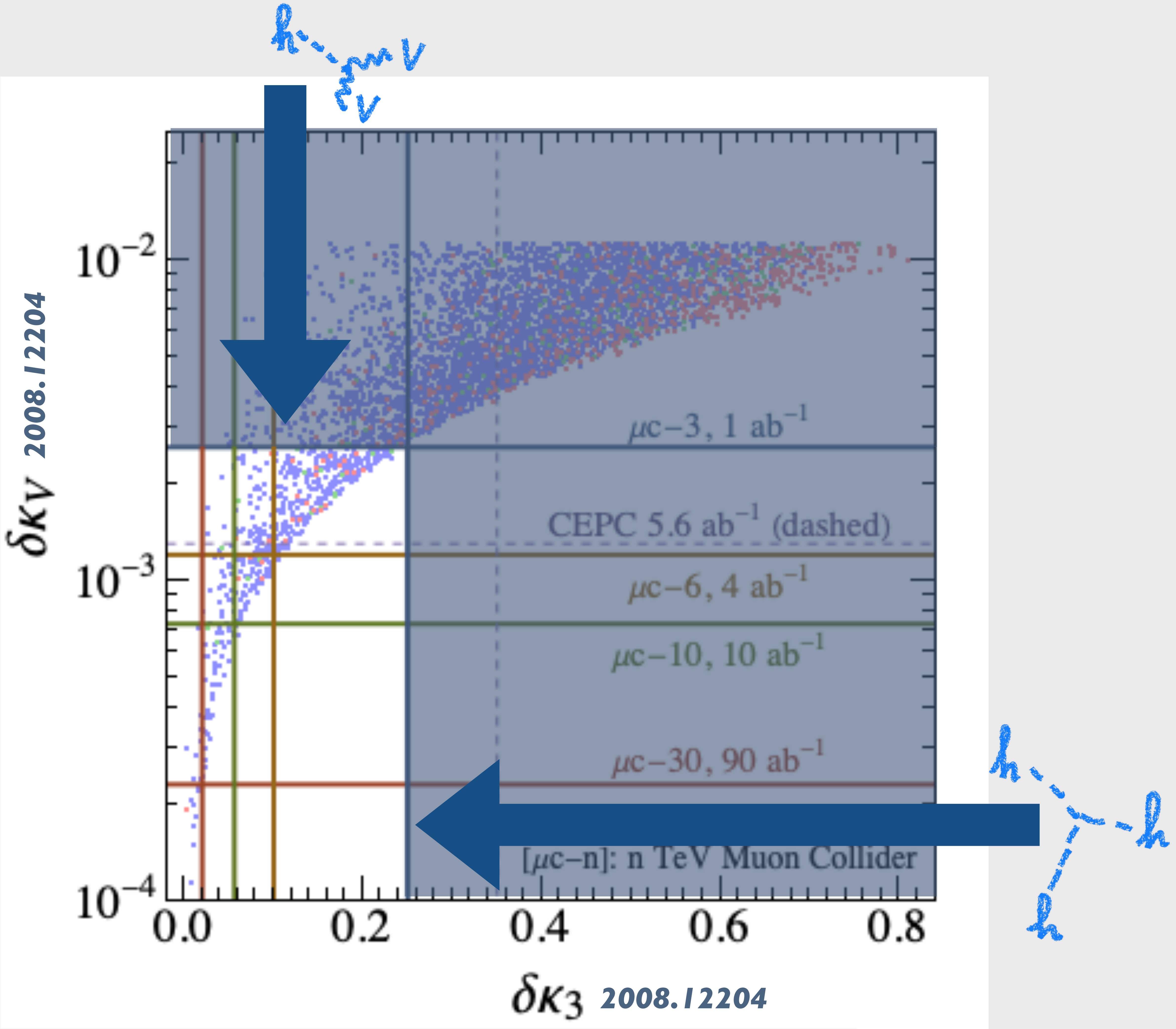
EW phase transition

DIRECT & INDIRECT | INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR



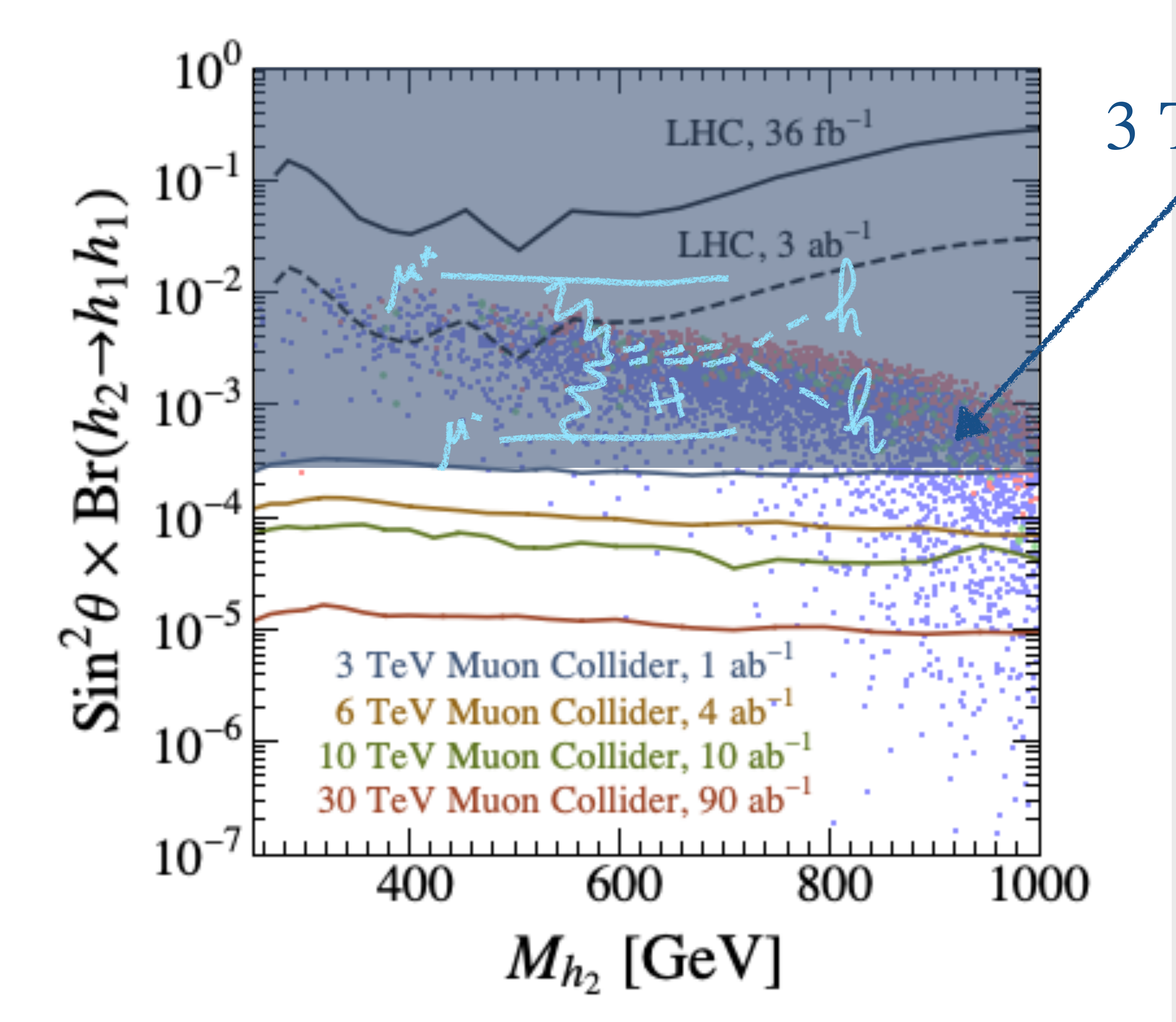


EW phase transition

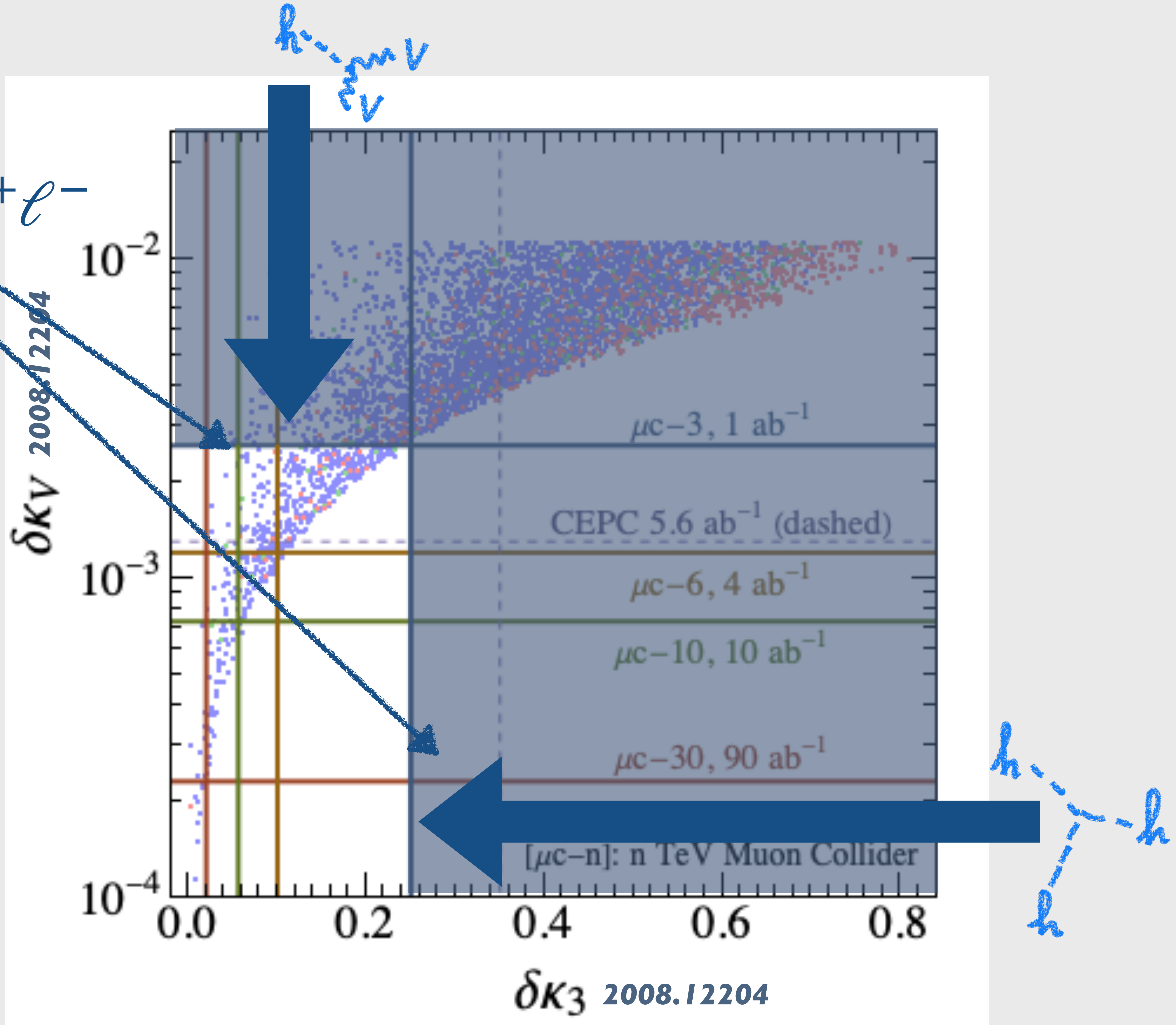
DIRECT & INDIRECT | INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR



3 TeV $\ell^+\ell^-$

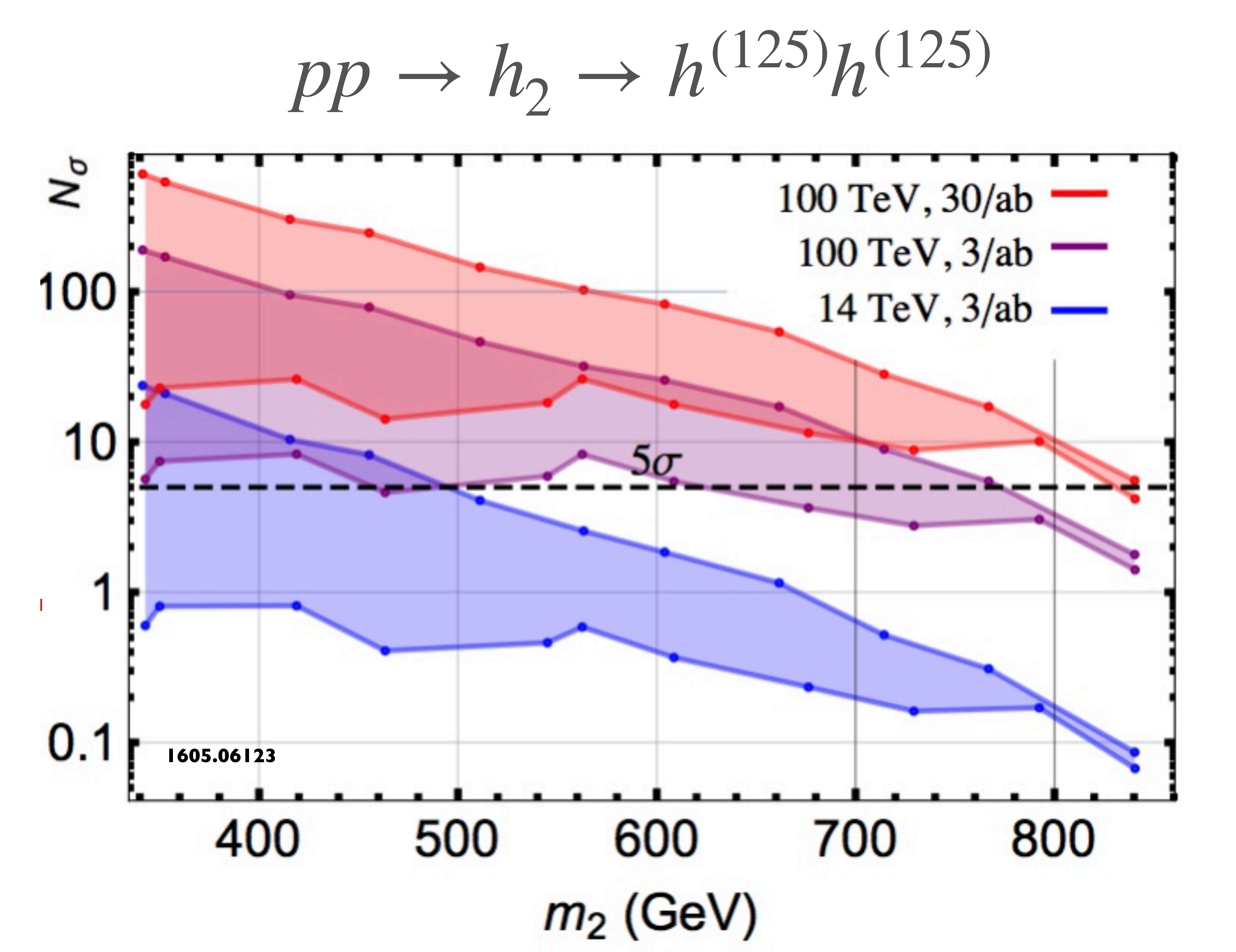


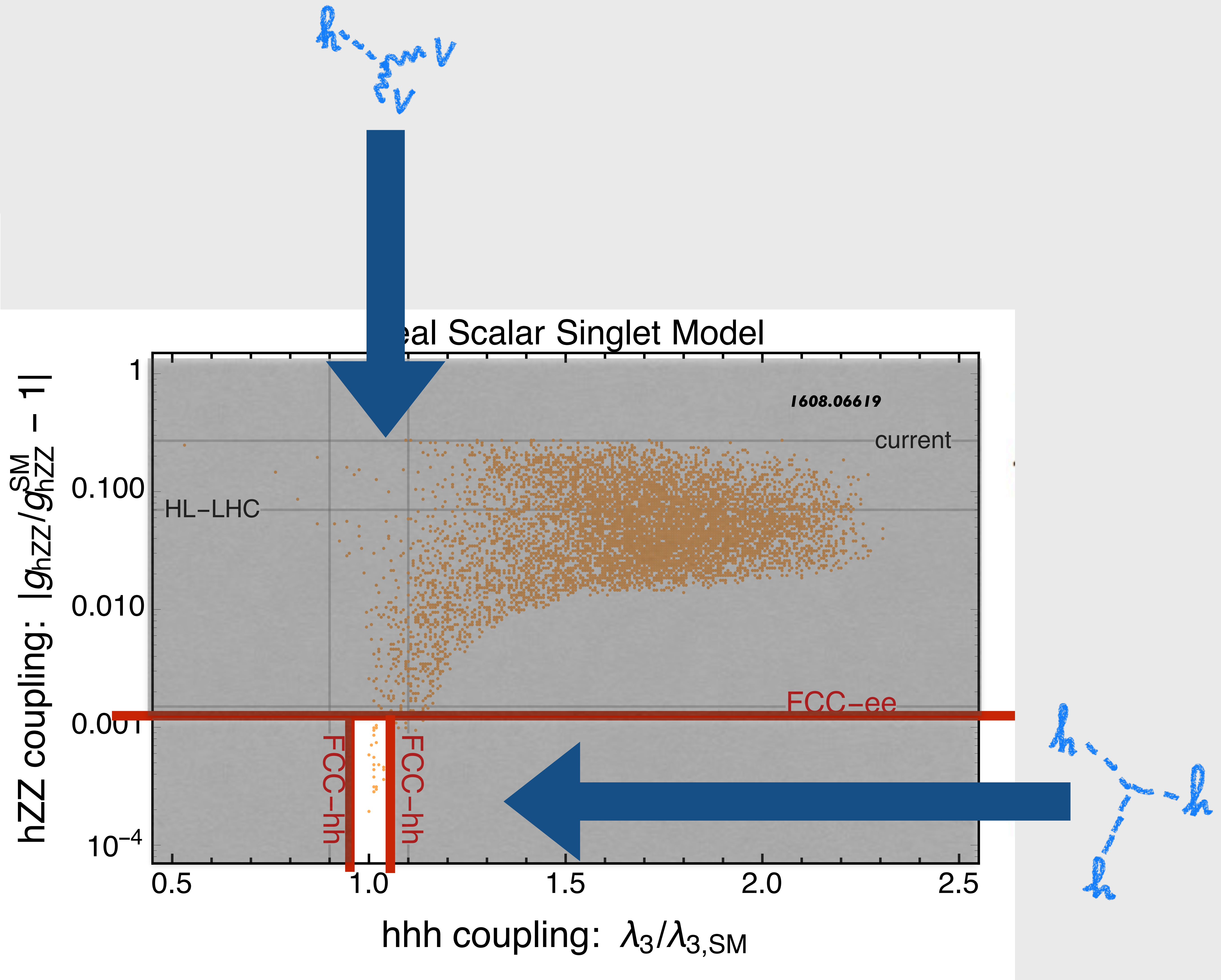
parameters space of 1st order phase transition accessible by **several measurements available at the** 3 TeV $\ell^+\ell^-$ **collider**

EW phase transition

DIRECT & INDIRECT

INTERPLAY

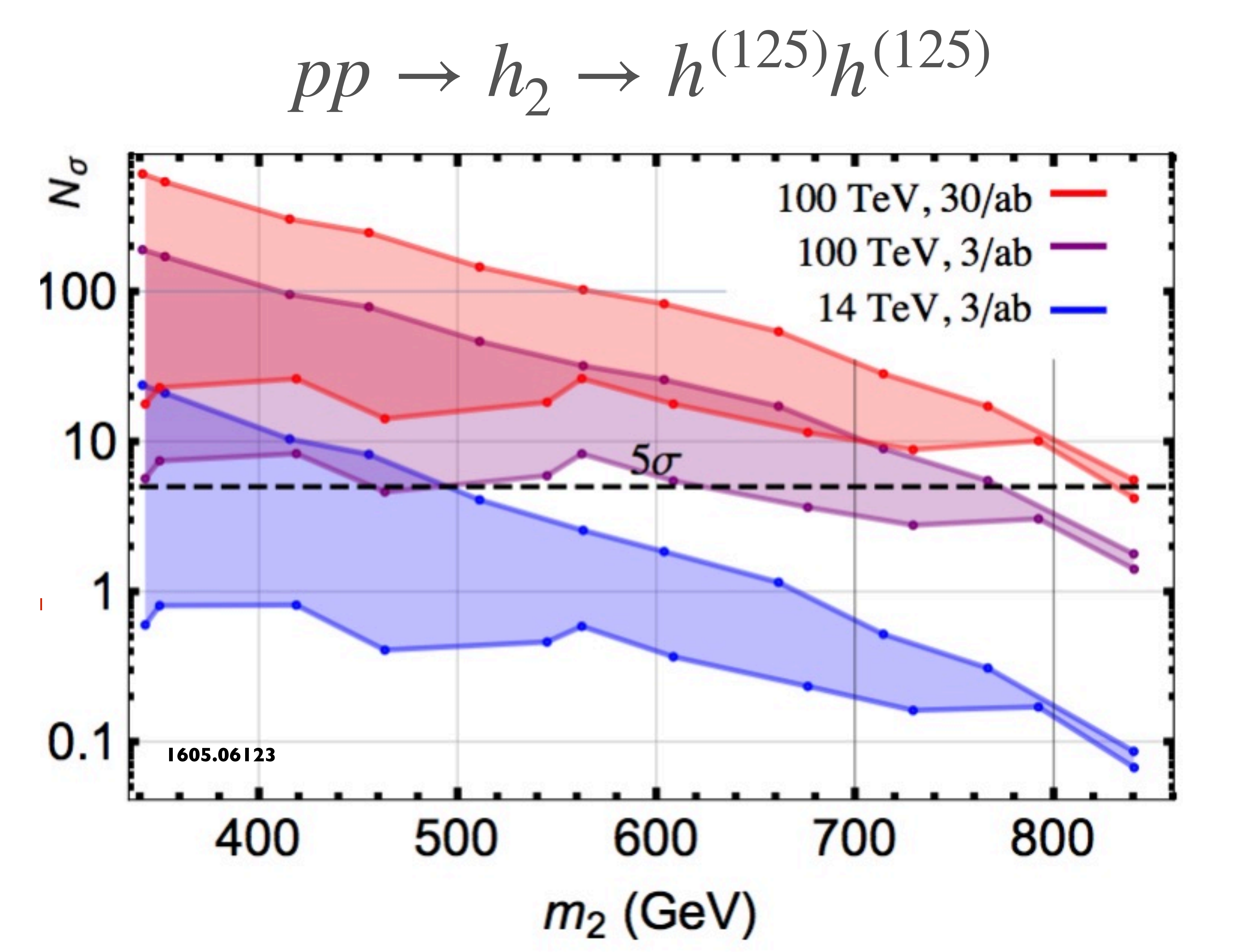


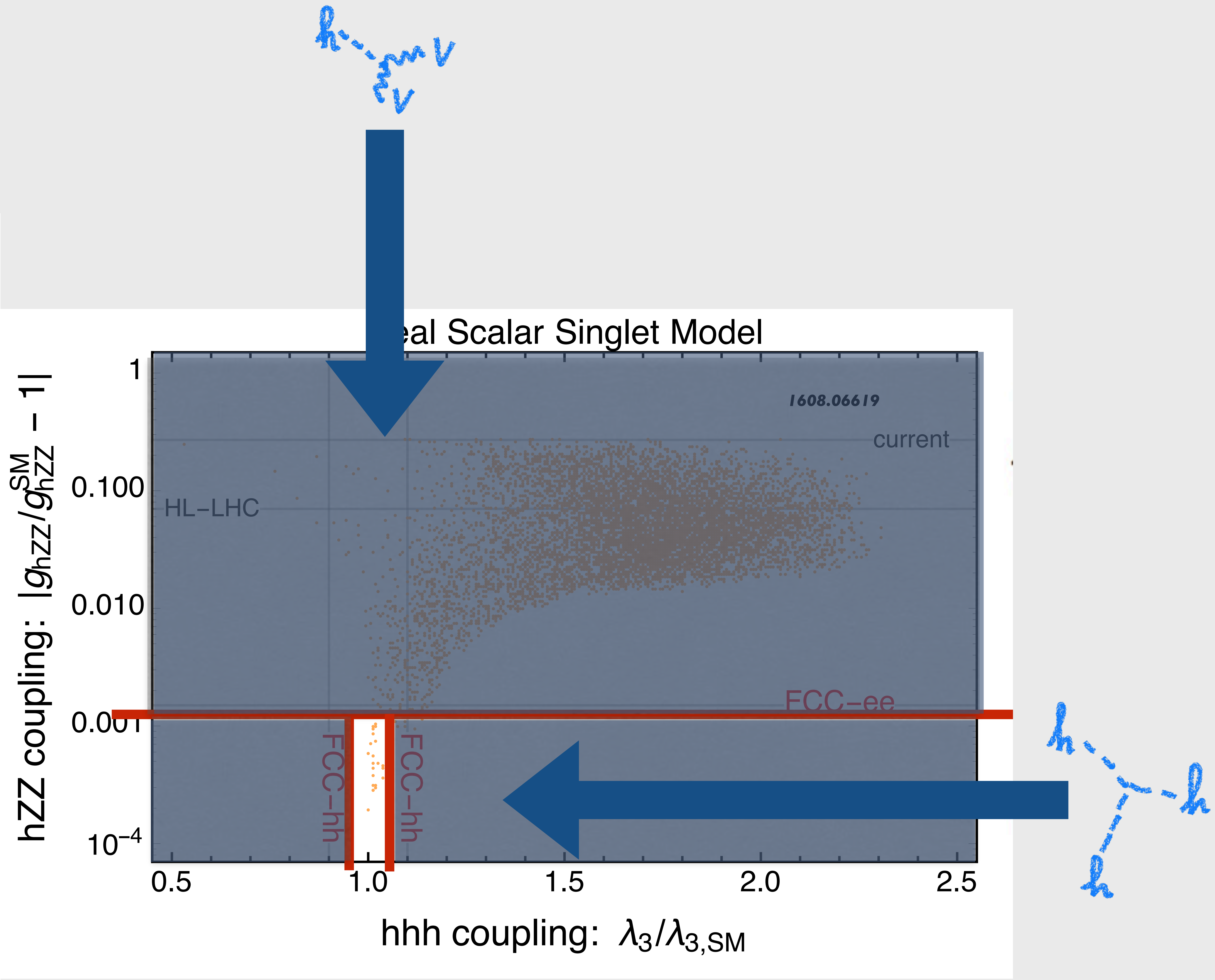


EW phase transition

DIRECT & INDIRECT

INTERPLAY





EW phase transition

DIRECT & INDIRECT

INTERPLAY

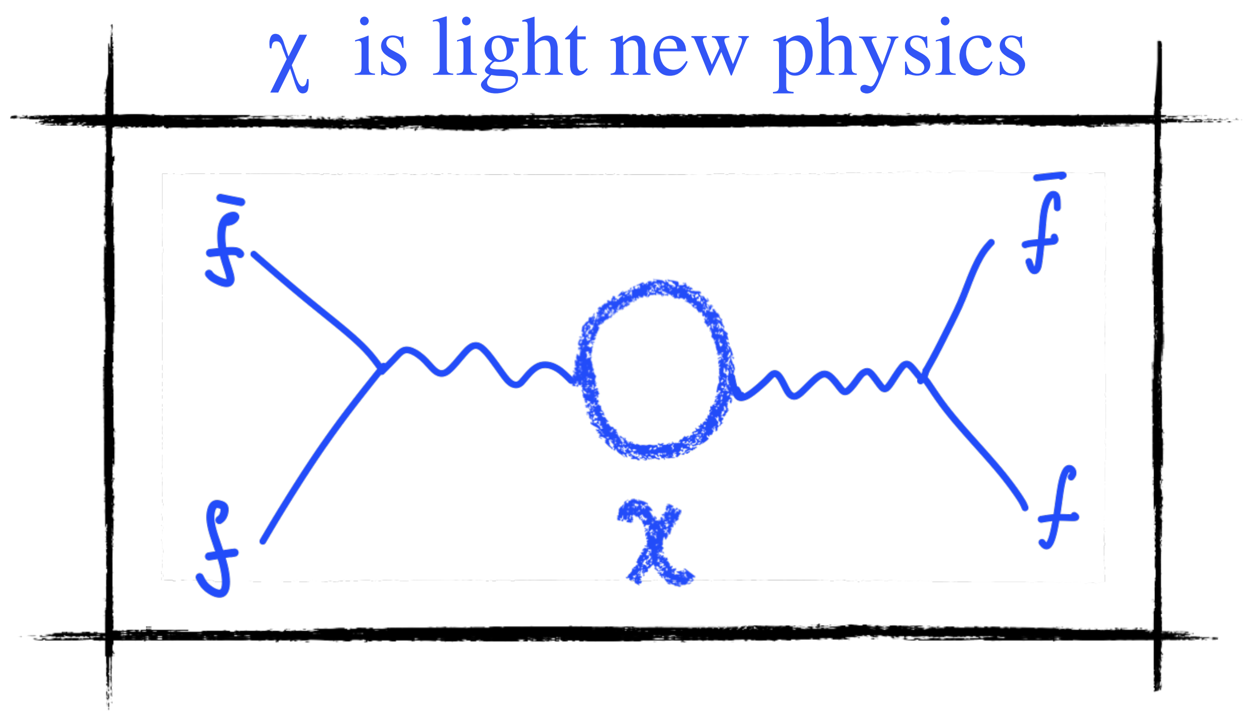
parameters space of 1st order phase transition accessible by **several measurements available at the** 100 TeV pp **collider** flashing concrete results for

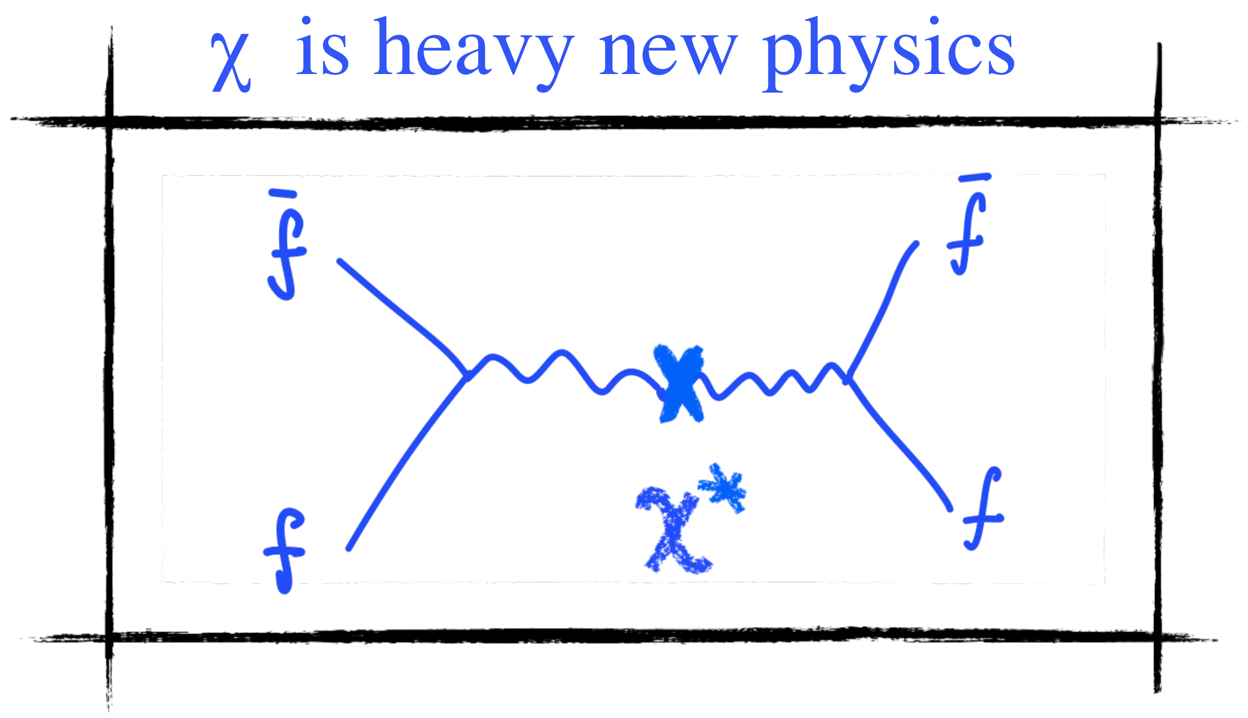
Dark Matter at the weak scale

pp or $\ell^+\ell^- \to f\bar{f}, W^+W^-$

PRECISION

TOTAL CROSS-SECTION

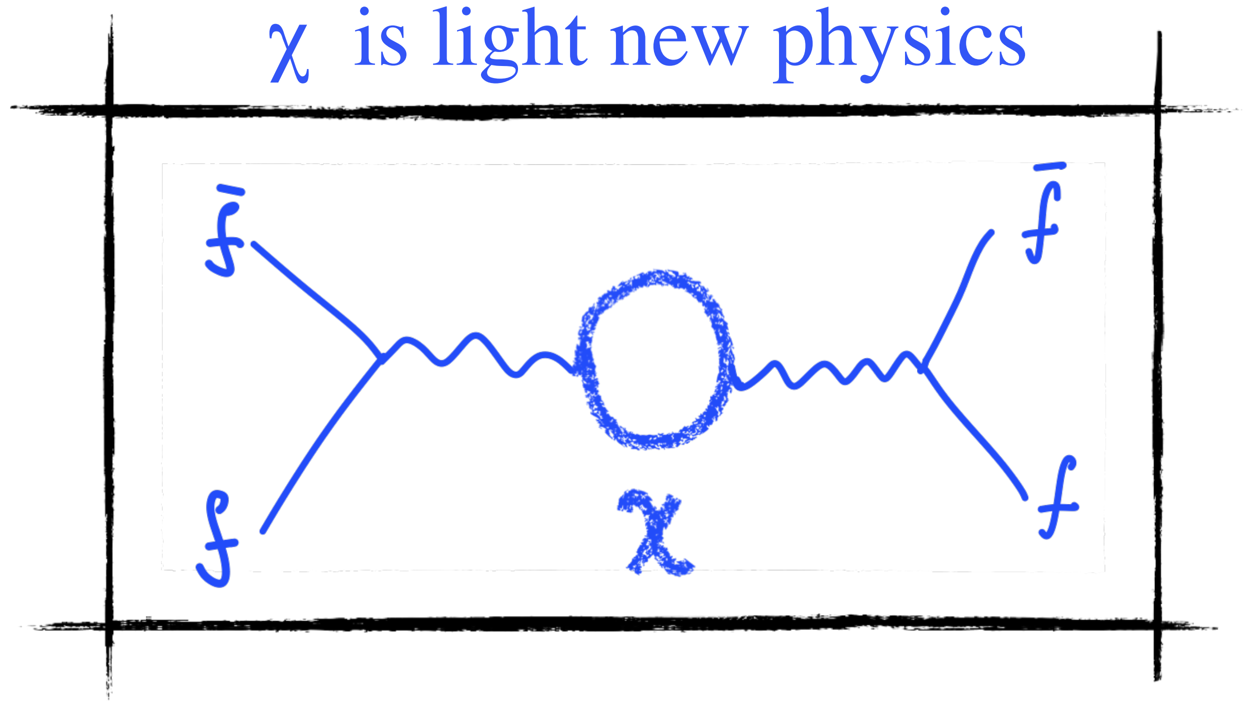


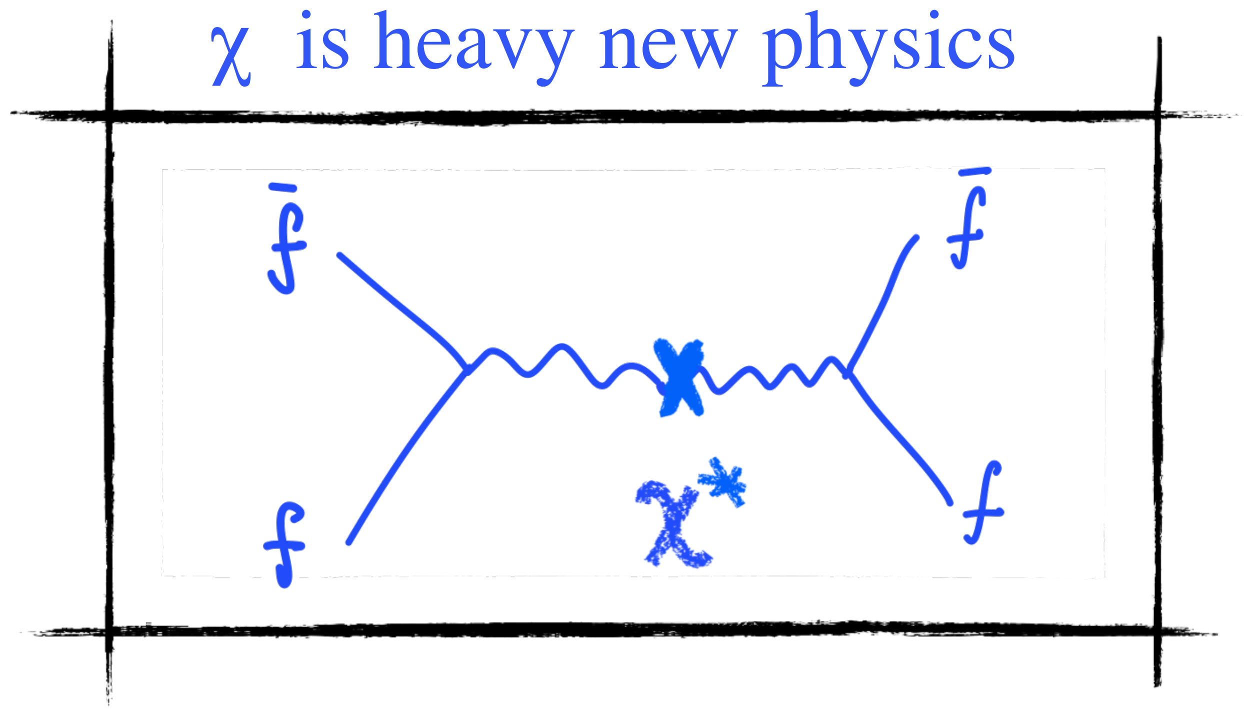


- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach

pp or $\ell^+\ell^- \to f\bar{f}, W^+W^-$

PRECISION | TOTAL CROSS-SECTION





- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach

χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{\rm DF}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{\rm CS}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{\rm DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{\rm MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{\rm CS}{}^*$	6.6	0.2	0.4	1.0	0.5 & [0.7,1.6]	1.6
$(1,5,\epsilon)_{\rm DF}{}^*$	6.6	1.5	2.8	7.1	3.9	11
$(1,5,0)_{\rm MF}$	14	0.9	1.8	4.4	2.9	3.5 & [5.1, 8.7]
$(1,7,\epsilon)_{\rm CS}$	54	0.6	1.3	3.2	2.4	2.5 & [3.5, 7.4]
$(1,7,\epsilon)_{\rm MF}$	48	2.1	4.0	11	6.4	18

- Comprehensive tool to explore new electroweak particles
- Can probe valid dark matter candidates!

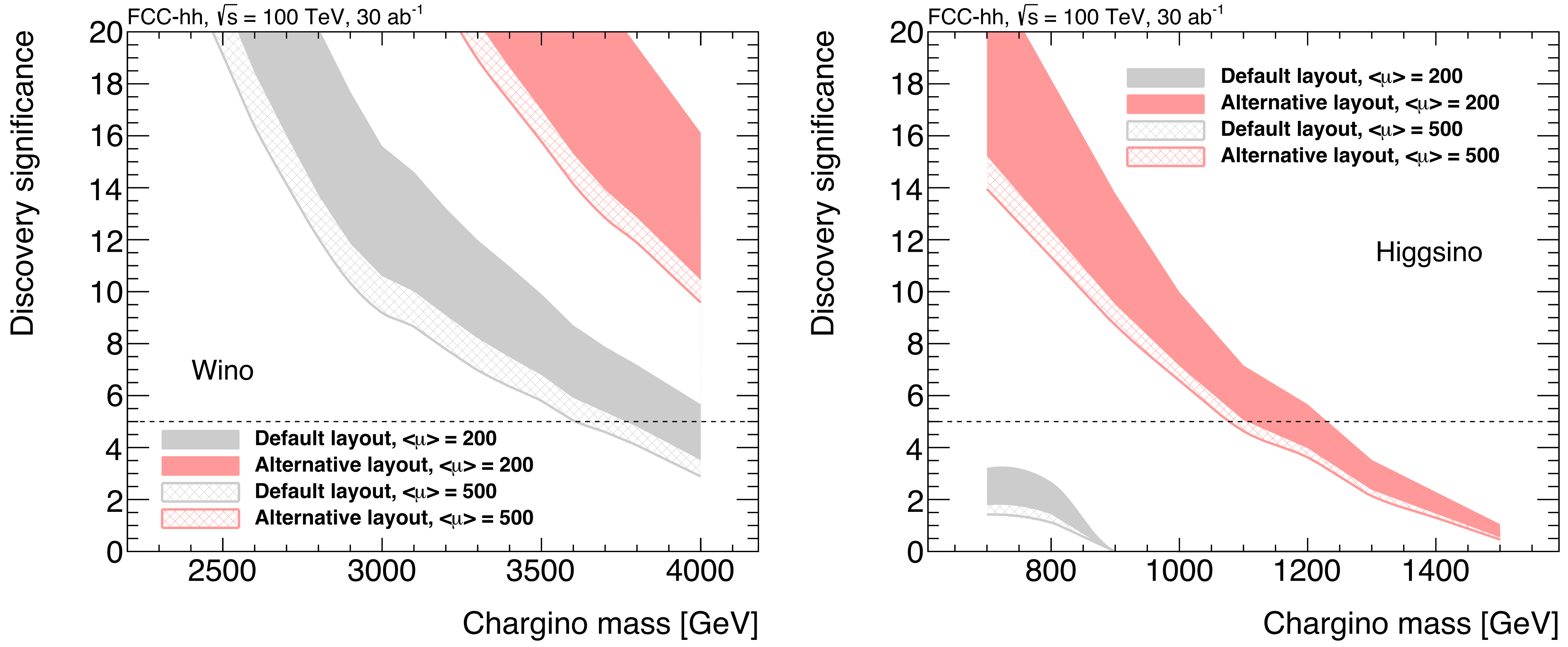
Direct Dark Matter production $pp \to \chi\chi$

Disappearing charged track analyses

(at ~full pileup)

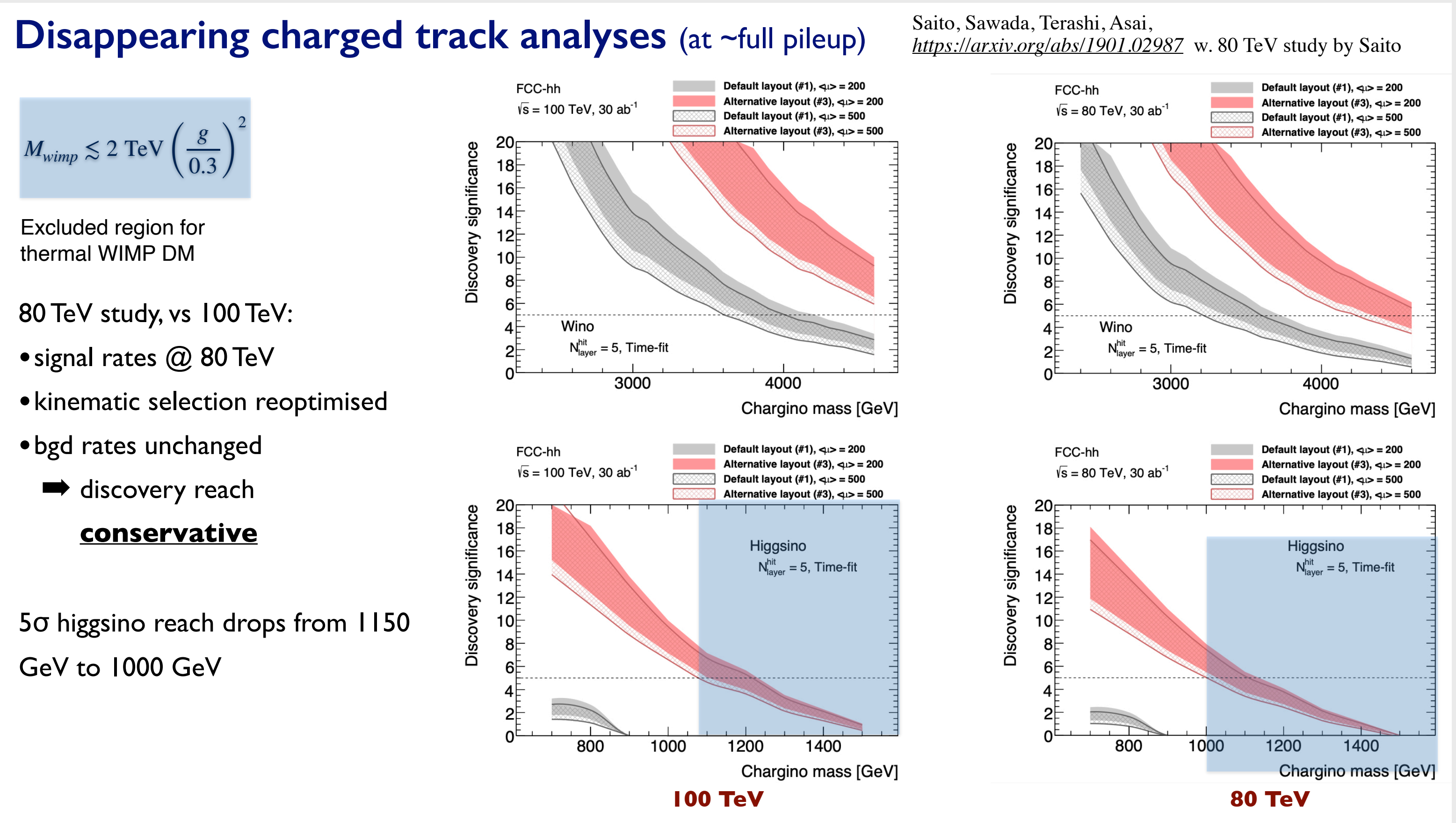
M. Mangano on Wed.

K. Terashi, R. Sawada, M. Saito, and S. Asai, *Search for WIMPs with disappearing track signatures at the FCC-hh*, (Oct, 2018) . https://cds.cern.ch/record/2642474.



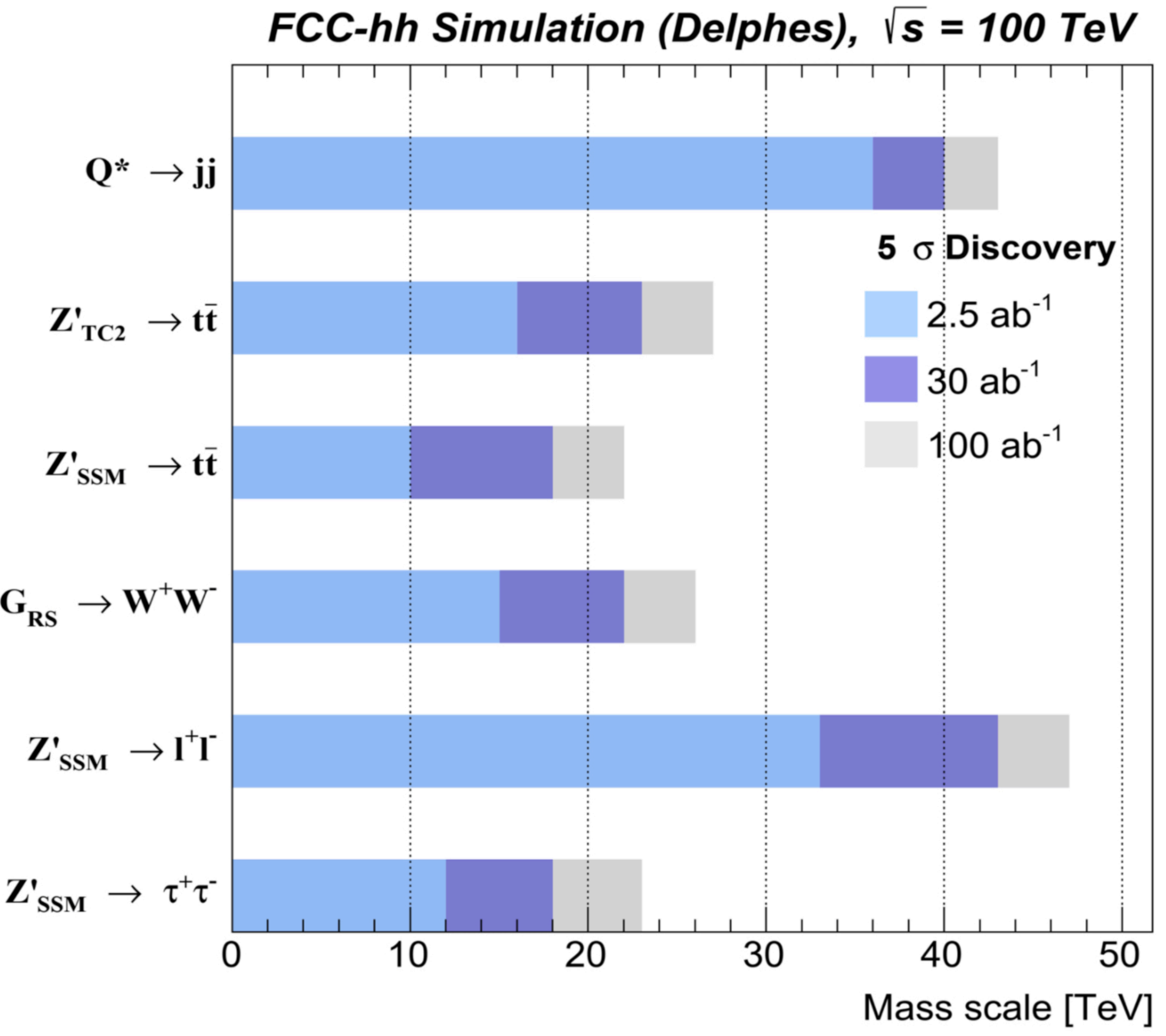
=> coverage beyond the upper limit of the thermal WIMP mass range for both higgsinos and winos !!

$$M_{wimp} \lesssim 2\ \text{TeV} \left(\frac{g}{0.3}\right)^2$$



s-channel resonances

M. Mangano on Wed.



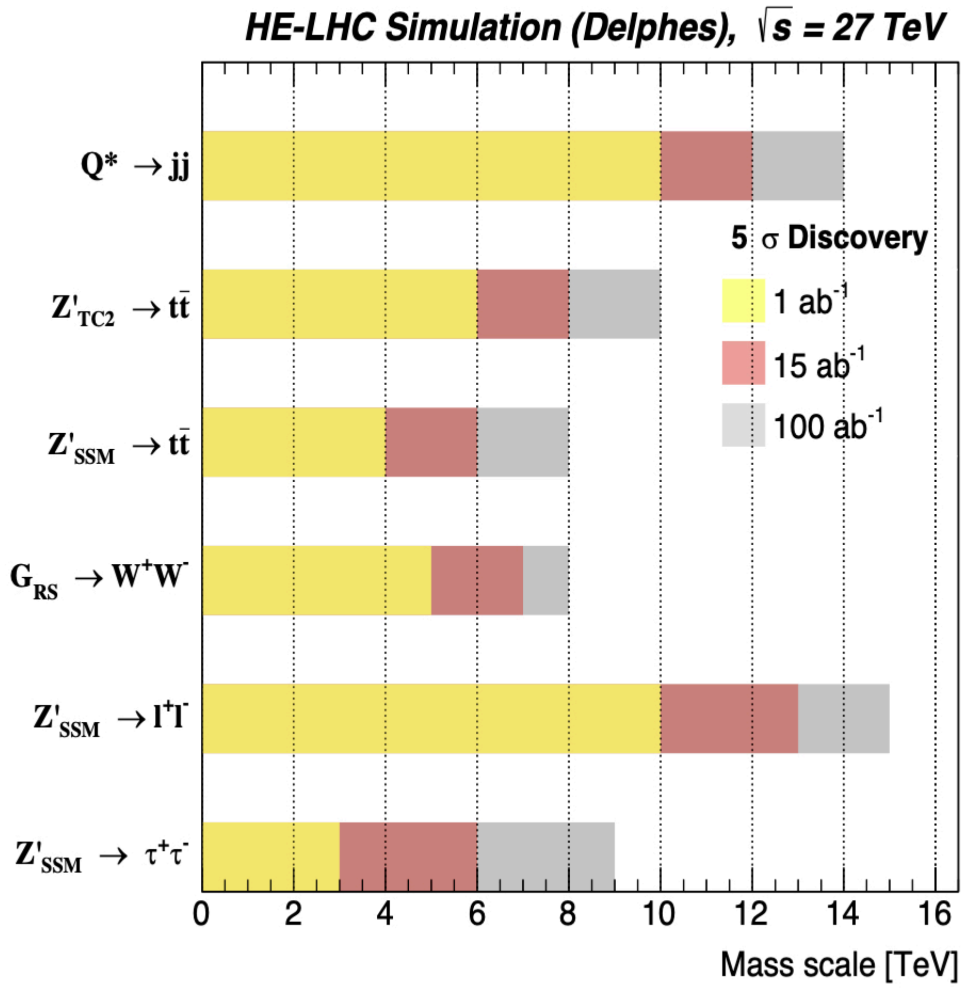
ColliderReach ECM extrapolation of 5σ 30ab⁻¹ discovery reach

	100 TeV	80 TeV	120 TeV
Q*	40	33	46
Z'TC2→tt	23	20	26
Z'SSM→tt	18	15	20
GRS→WW	22	19	25
Z'SSM→ll	43	36	50
Z'SSM→ττ	18	15	20

- 10-15% reach increase at 120 TeV
- 15-20% reach loss at 80 TeV

24

High-mass reach



WIMP DM reach

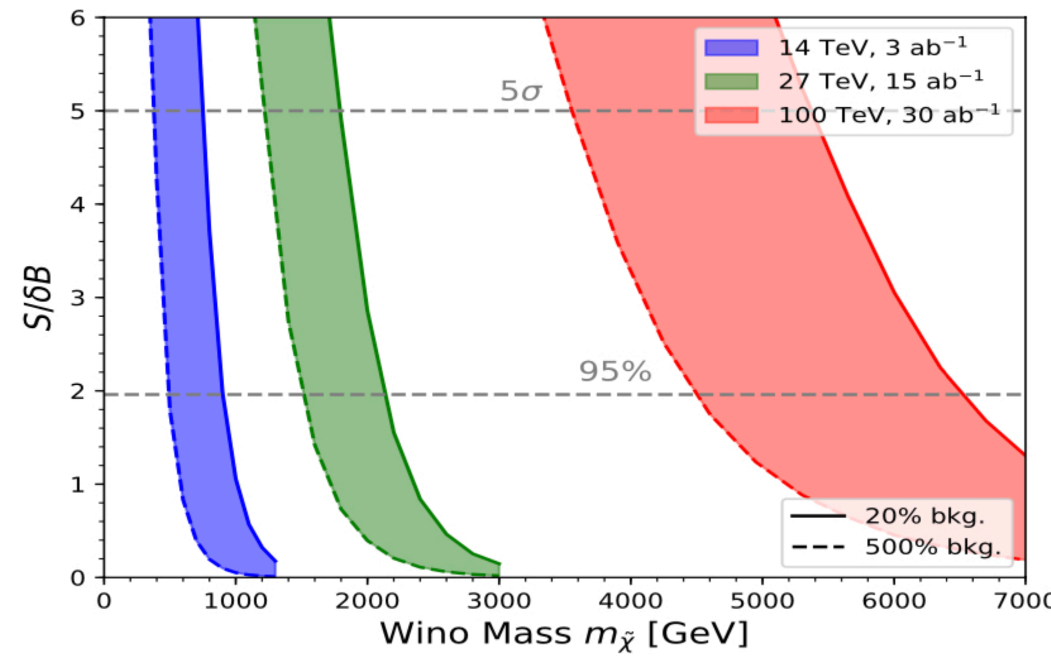


Figure 3: Sensitivity reach for wino-like DM WIMP candidates.

=> loss of yes/no answer to WIMP DM scenarios

2018 costs as documented in the FCC CDR

HE-LHC

Domain	Cost in MCHF
Collider	5,000
Injector complex	1,100
Technical infrastructure	800
Civil Engineering	300
TOTAL cost	**7,200**

assumes 2.3 MCHF/dipole ~2.9 BCHF (cfr ~ 1 MCHF/ LHC dipole)

includes SC SPS

FCC-ee

Domain	Cost [MCHF]
Collider and injector complex	3,100
Technical infrastructure	2,000
Civil Engineering	5,400
TOTAL cost	**10,500**

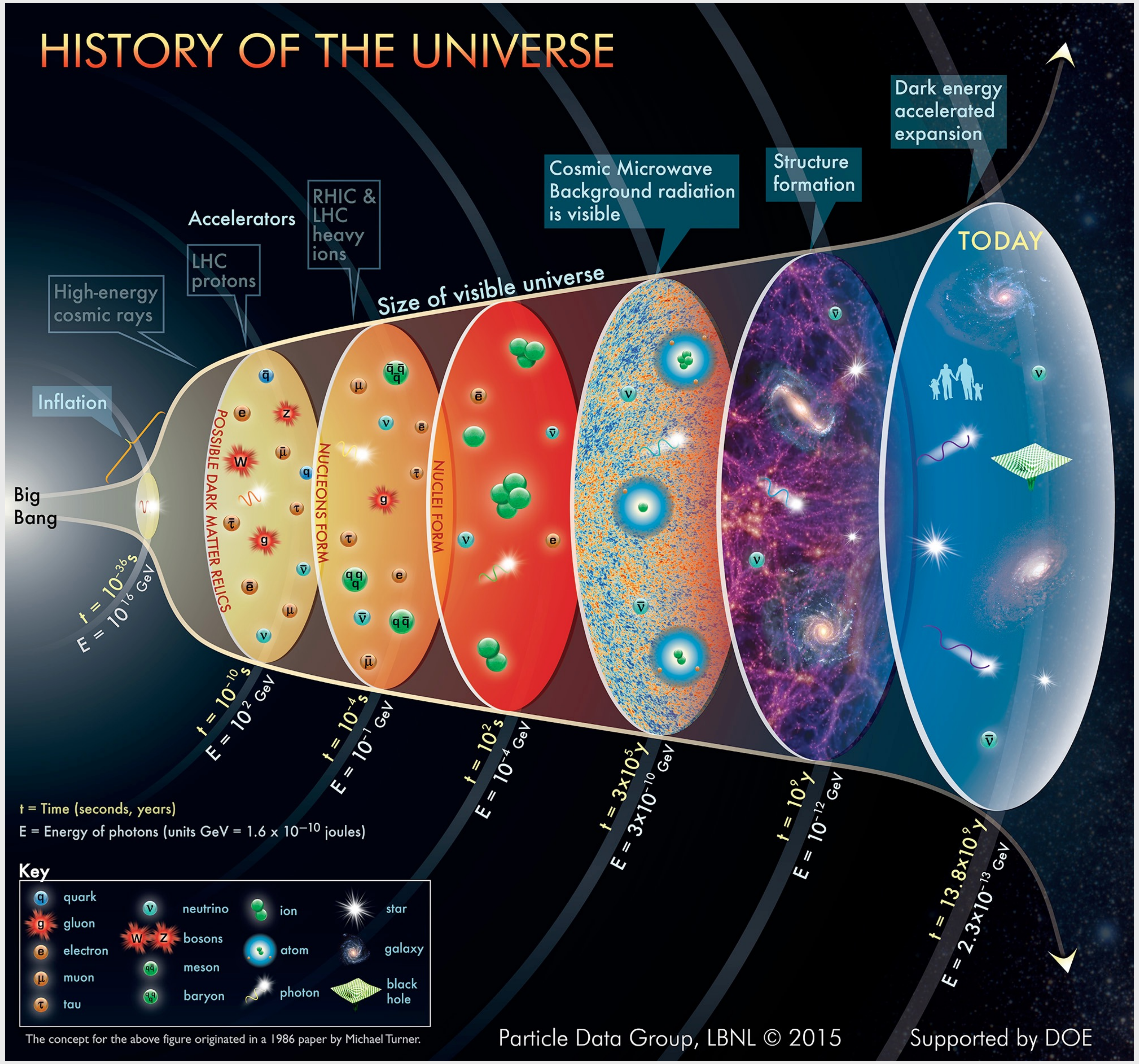
NB: FCC-ee new estimate (2024) ~13B.
No update available for HE-LHC

NB: If no 90km tunnel built, HE-LHC to be compared with LEP3 for prioritization: a different talk…

Thank you!

open questions

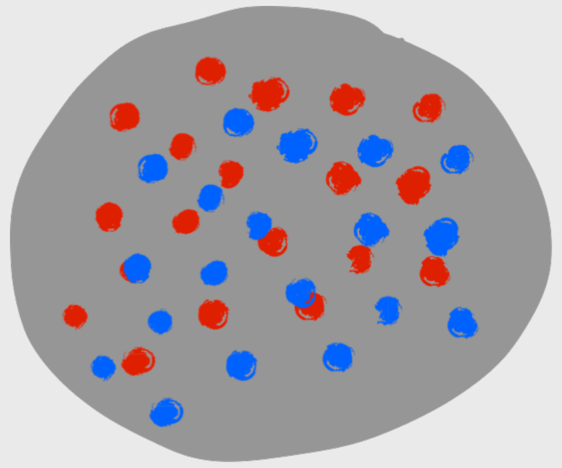
Open Questions on the "big picture" on fundamental physics circa 2020



Nothing we have measured in high energy physics makes so much of a distinction between particles and anti-particles.

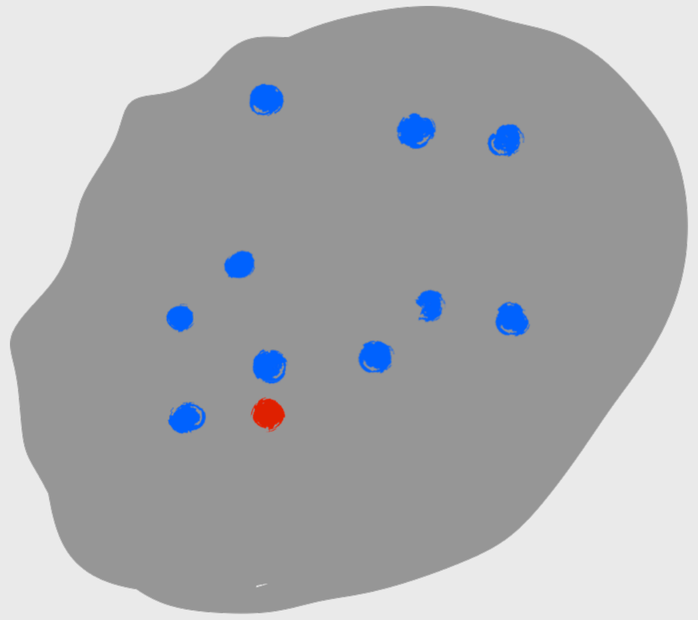
The observable Universe is made of matter, no antimatter

We need to go from this



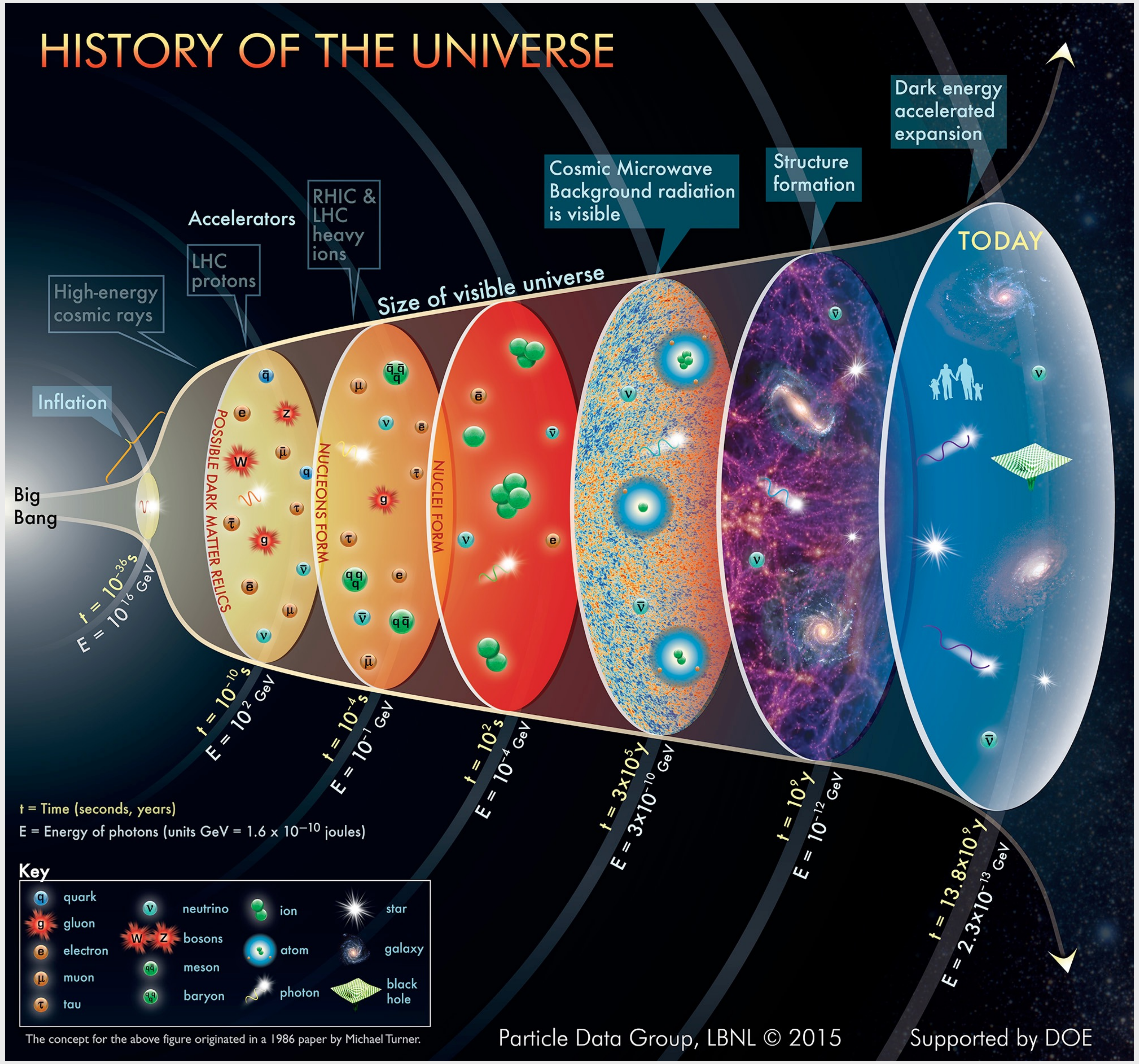
particles
antiparticles

to this



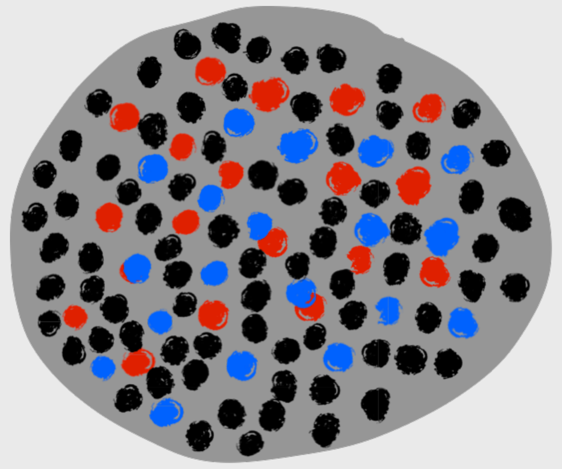
out-of-equilibrium processes are necessary

Open Questions on the “big picture” on fundamental physics circa 2020



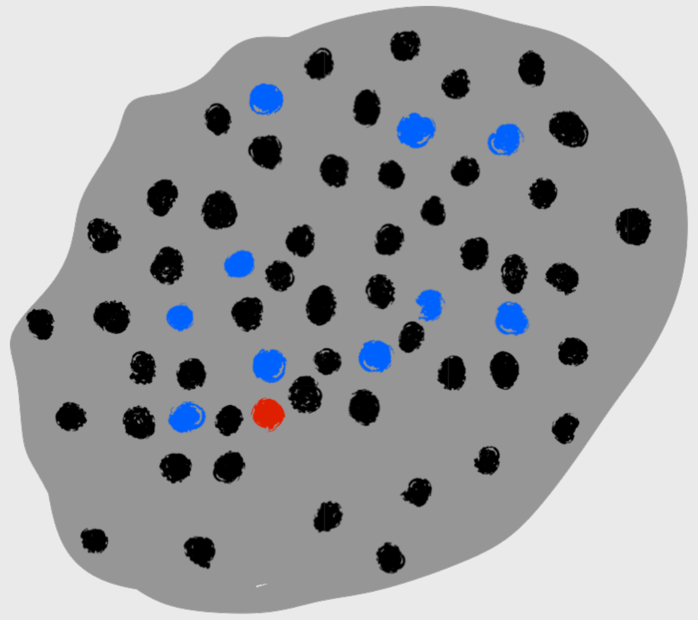
The observable Universe is made of matter, plus about 5 times as much dark matter

We need to go from this



normal particles
dark matter
antiparticles

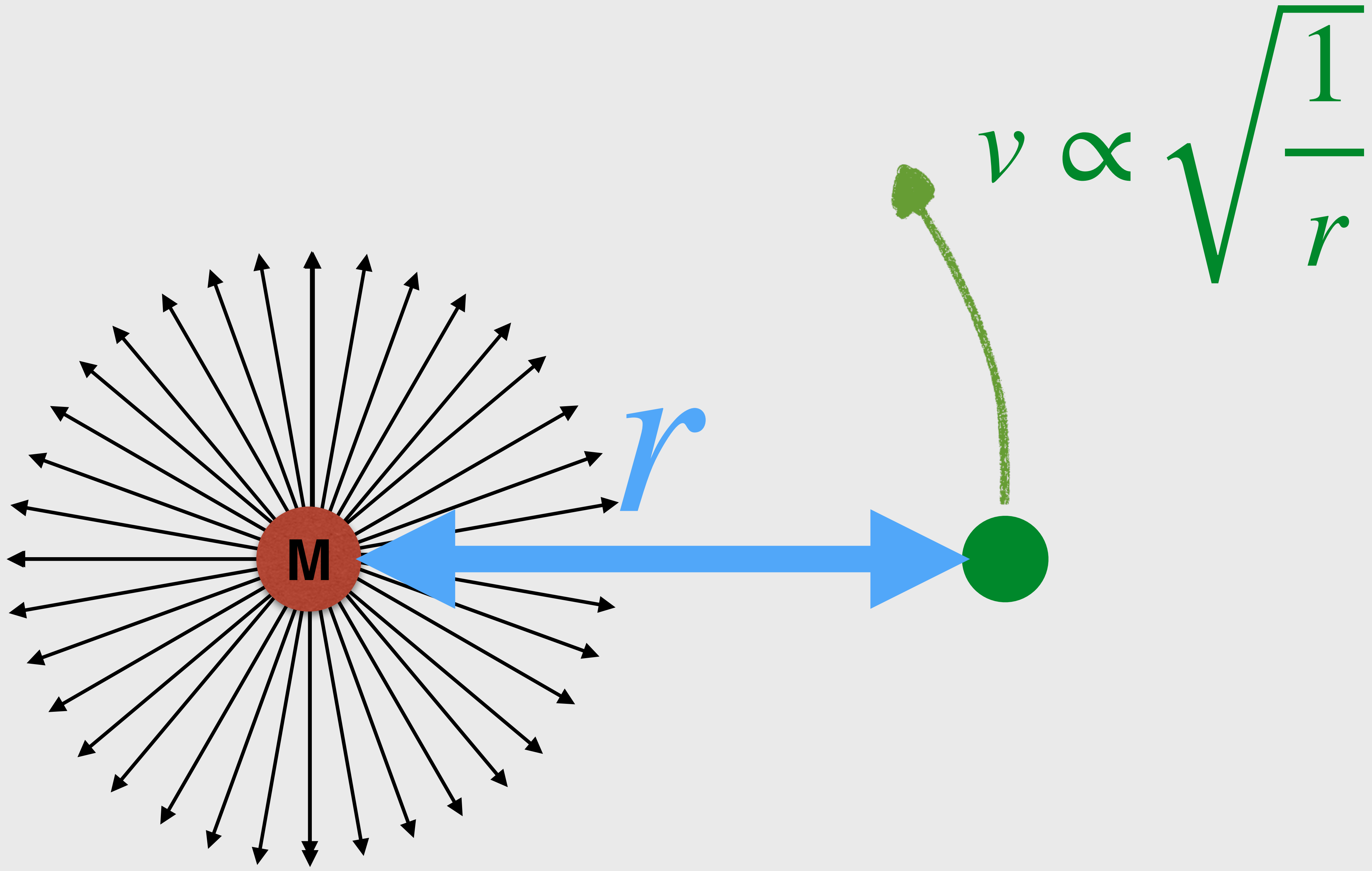
to this



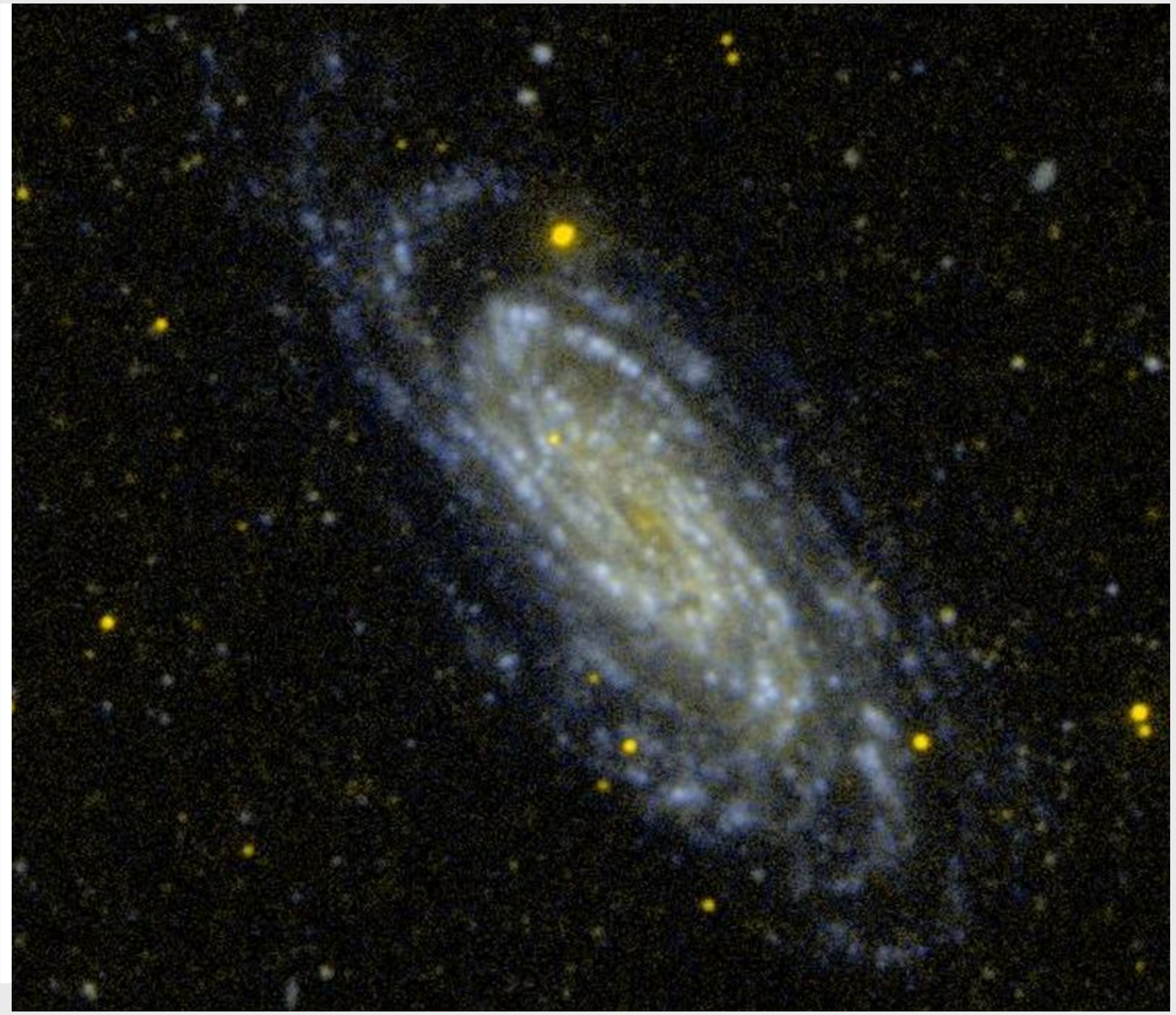
interactions rate from $\sigma = \left(\frac{g_{weak}}{M_{weak}}\right)^2$ are just about right!

A puzzle we have no idea how to solve

NEWTONIAN MECHANICS FAILS?

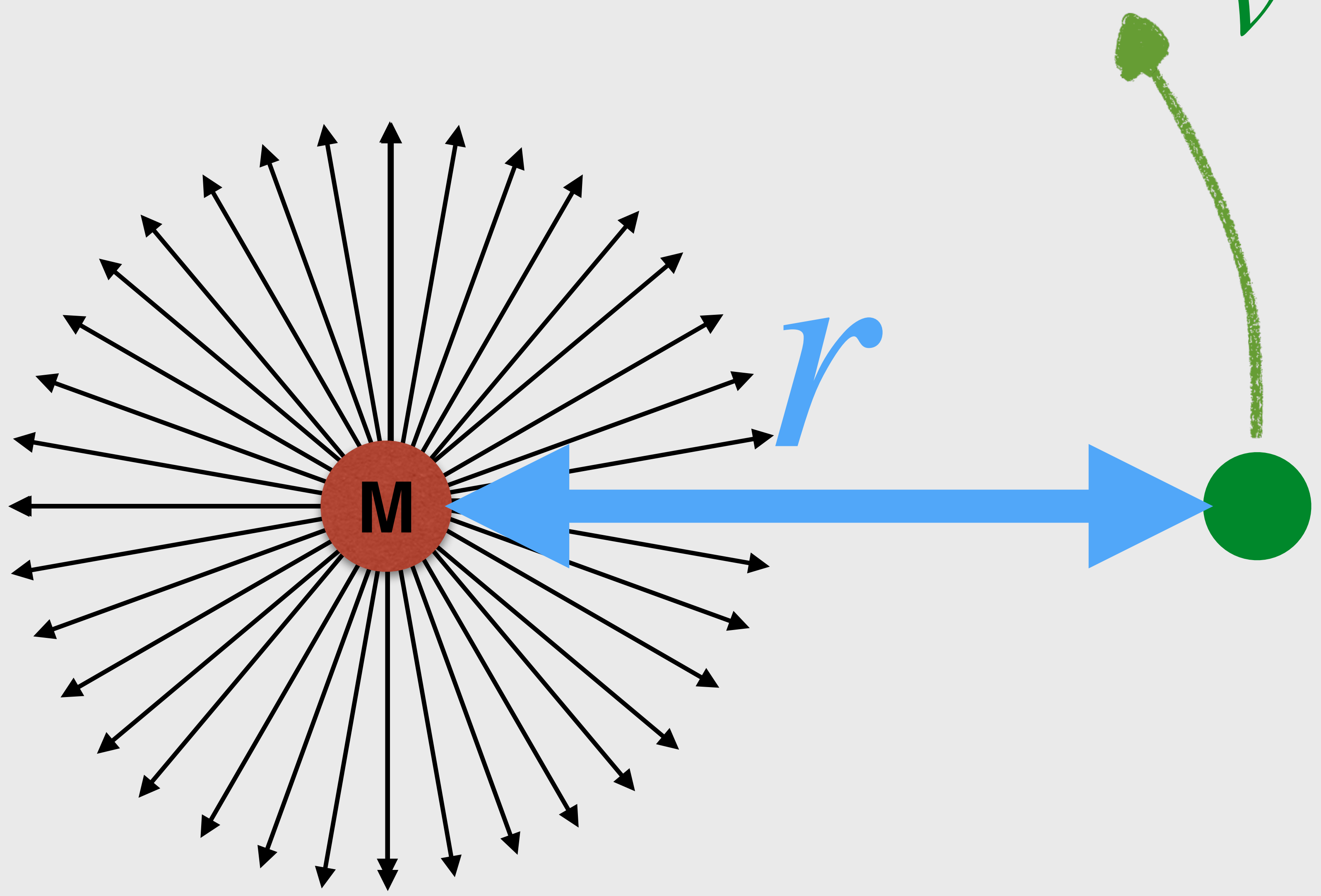


Perfect in our "neighborhood"



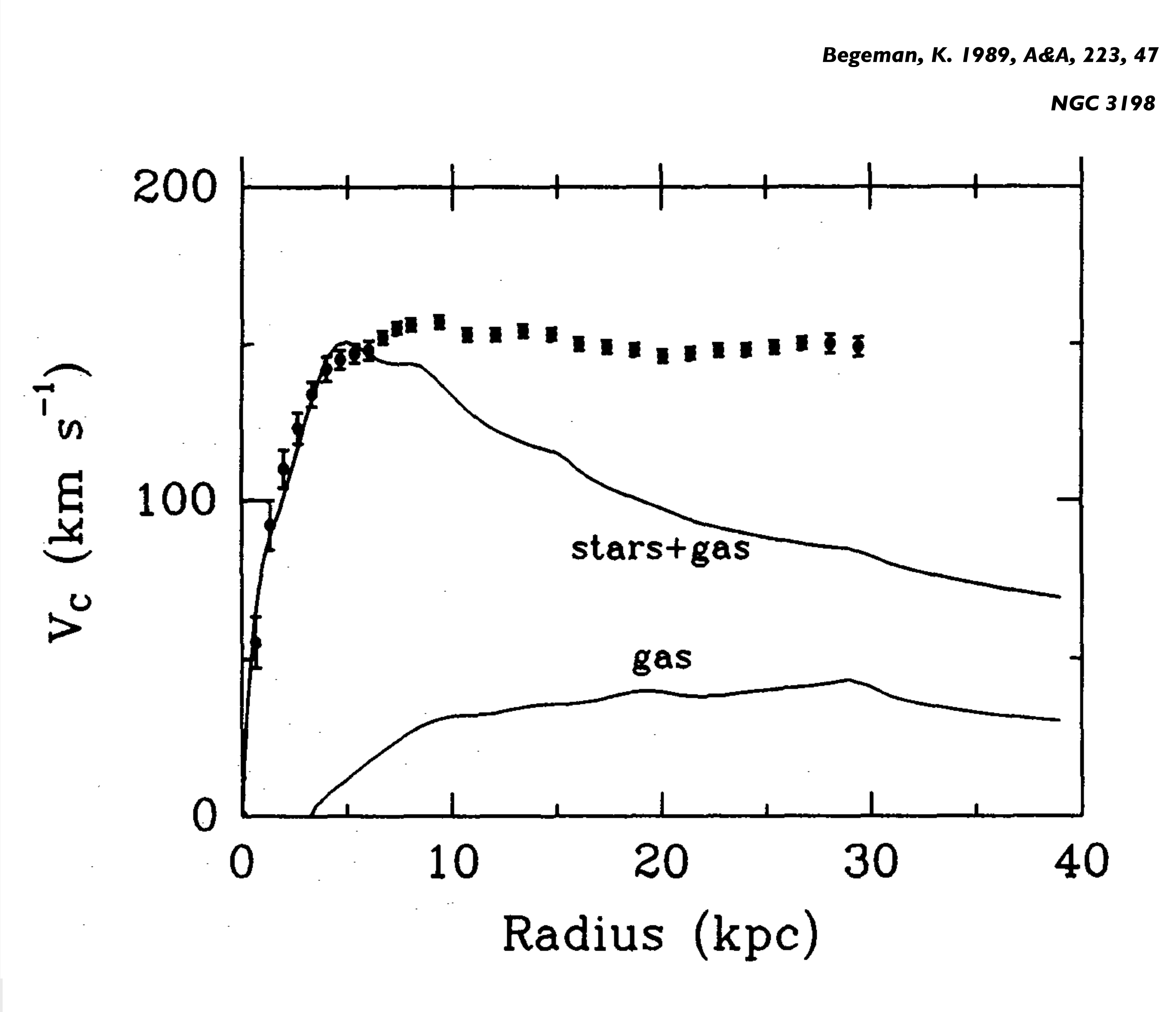
A puzzle we have no idea how to solve

NEWTONIAN MECHANICS FAILS?



$$v \propto \sqrt{\frac{1}{r}}$$

Perfect in our "neighborhood"



A puzzle we have no idea how to solve

A number of observations (including CMB from early Universe) suggest

a new form of matter must exist

It may well be not of the kind we are used to:

- It may have only weak interactions (even possible it feels only gravity)
- There are candidates "particles" with Compton length 1/M ranging from the size of a Galaxy down to High Energy Physics scales (GeV-TeV) and even beyond

It is not necessarily material for particle physics and accelerators

A puzzle we have no idea how to solve

A number of observations (including CMB from early Universe) suggest

- We know the scope of the search for Dark Matter is huge
- In principle, it can be very elusive (to all experiments)
- The simplest history of the early Universe suggests the "TeV" mass range
- Accelerators are the only way to go see it and study it in detail

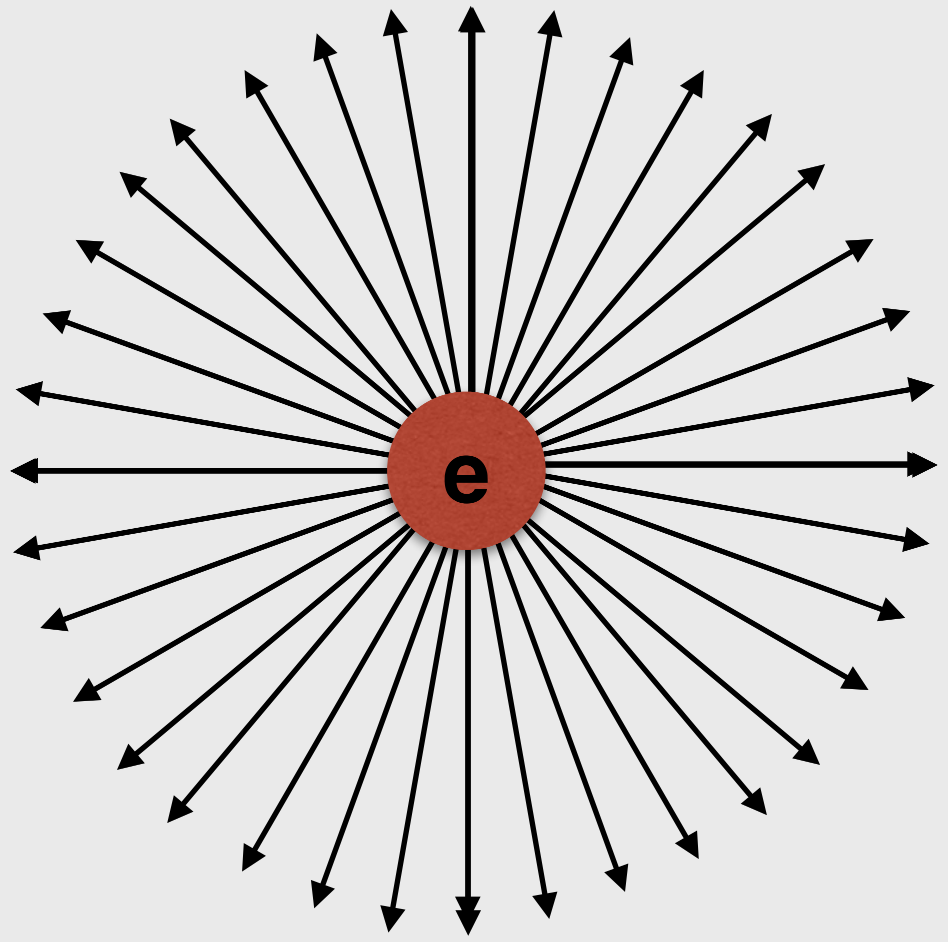
Open Questions on the "big picture" on fundamental physics circa 2020

- what is the dark matter in the Universe?
- why QCD does not violate CP?
- how have baryons originated in the early Universe?
- what originates flavor mixing and fermions masses?
- what gives mass to neutrinos?
- why gravity and weak interactions are so different?
- what fixes the cosmological constant?

EACH of these issues one day will teach us a lesson

A puzzle (today) we know how to solve

AFTER RELATIVITY



$$m_e = m_e^{(0)} + \int_{r_e}^{\infty} \mathcal{E}$$

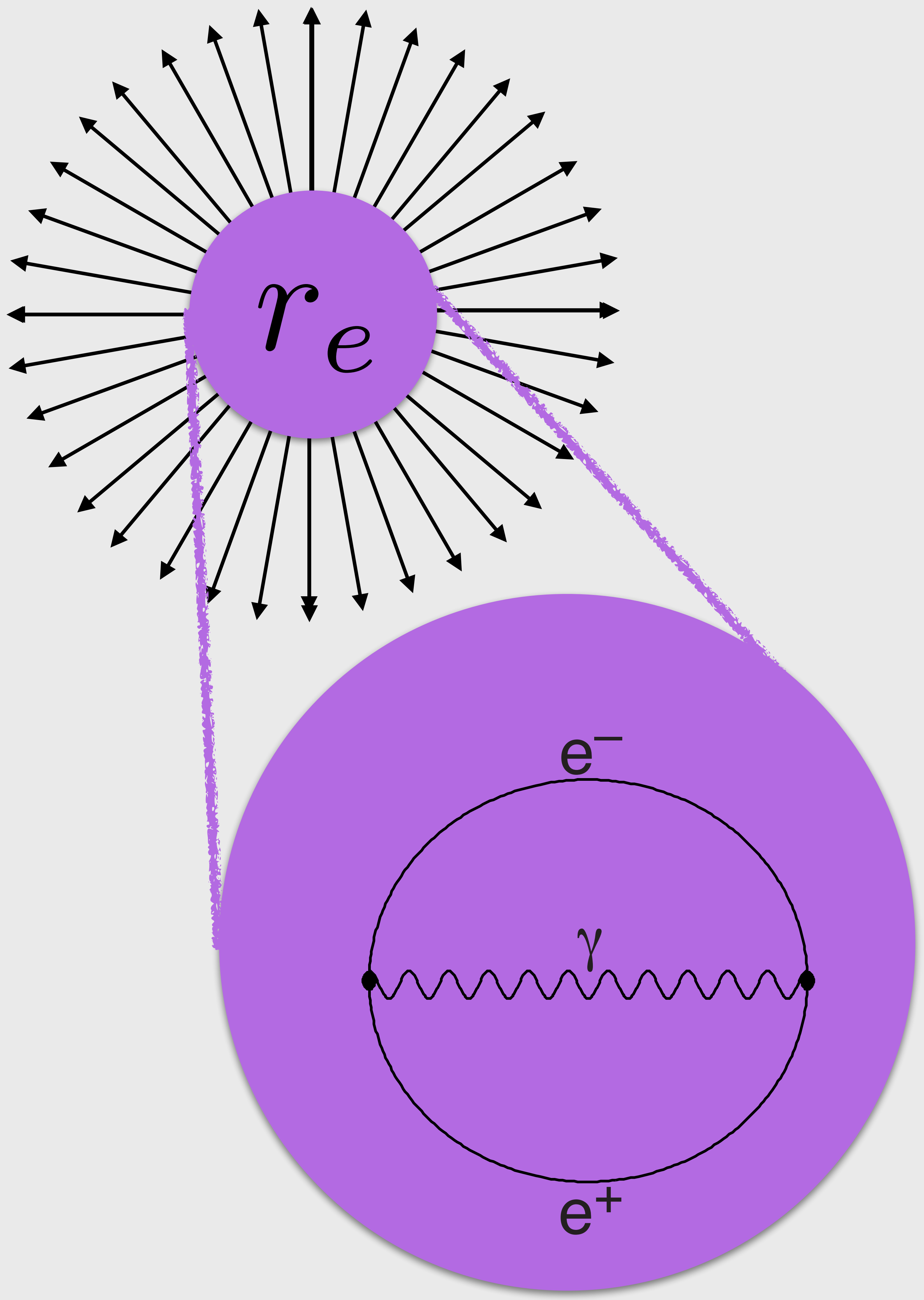
$$\int_{r_e}^{\infty} \mathcal{E} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

$$\delta m_e \simeq \frac{\alpha_{em}}{r_e} \xrightarrow{r_e \to 0} \infty$$

A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS



$$m_e = m_e^{(0)} + \int_{r_e}^{\infty} \mathcal{E}$$

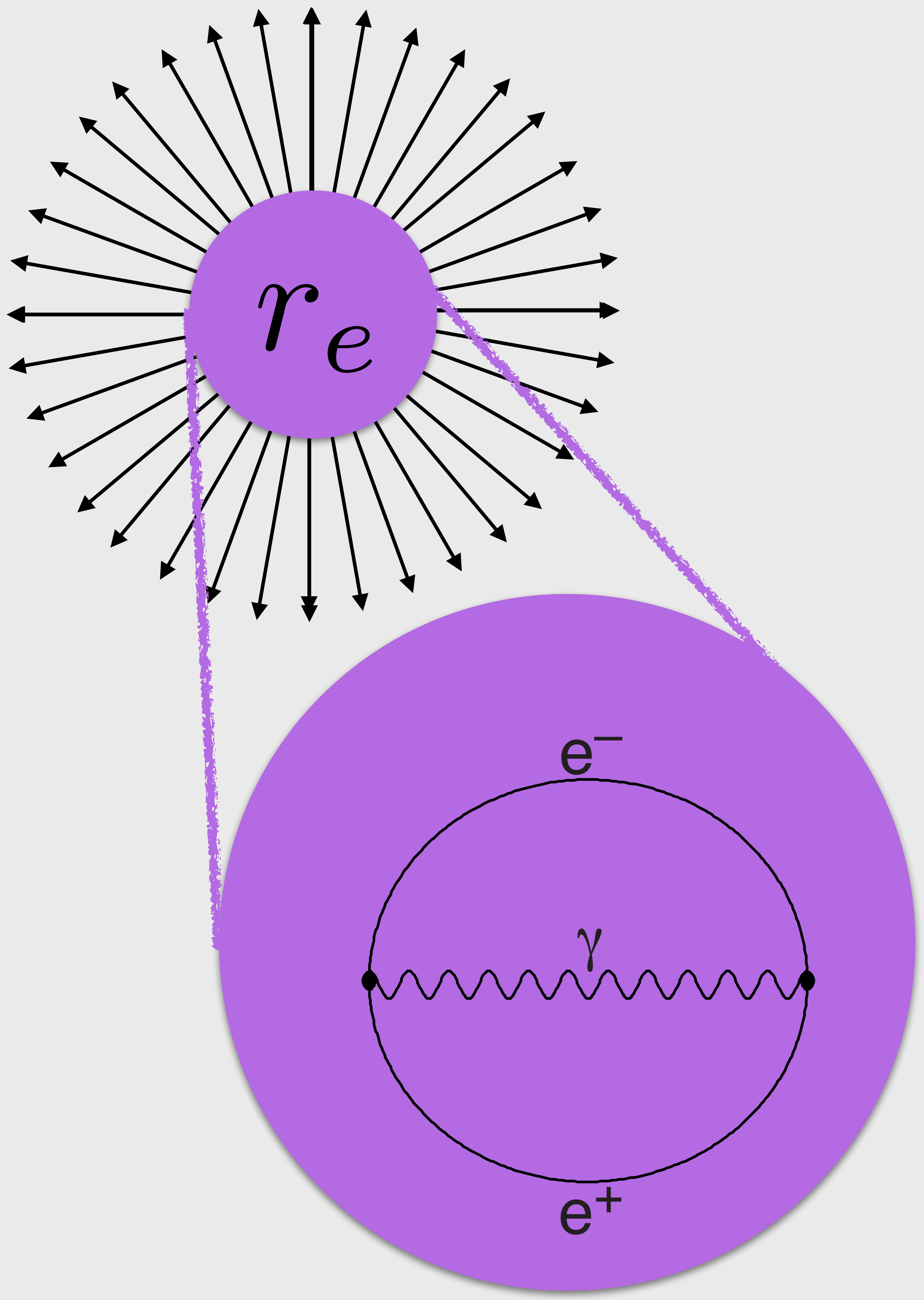
$$\int_{r_e}^{\infty} \mathcal{E} = \frac{1}{4\pi\epsilon_0} \frac{e^2}{r_e}$$

$$\delta m_e \simeq \frac{\alpha_{em}}{r_e} \xrightarrow{r_e \to 0} \infty$$

A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS



New symmetry (particle-antiparticle) which brought a new particle: the positron

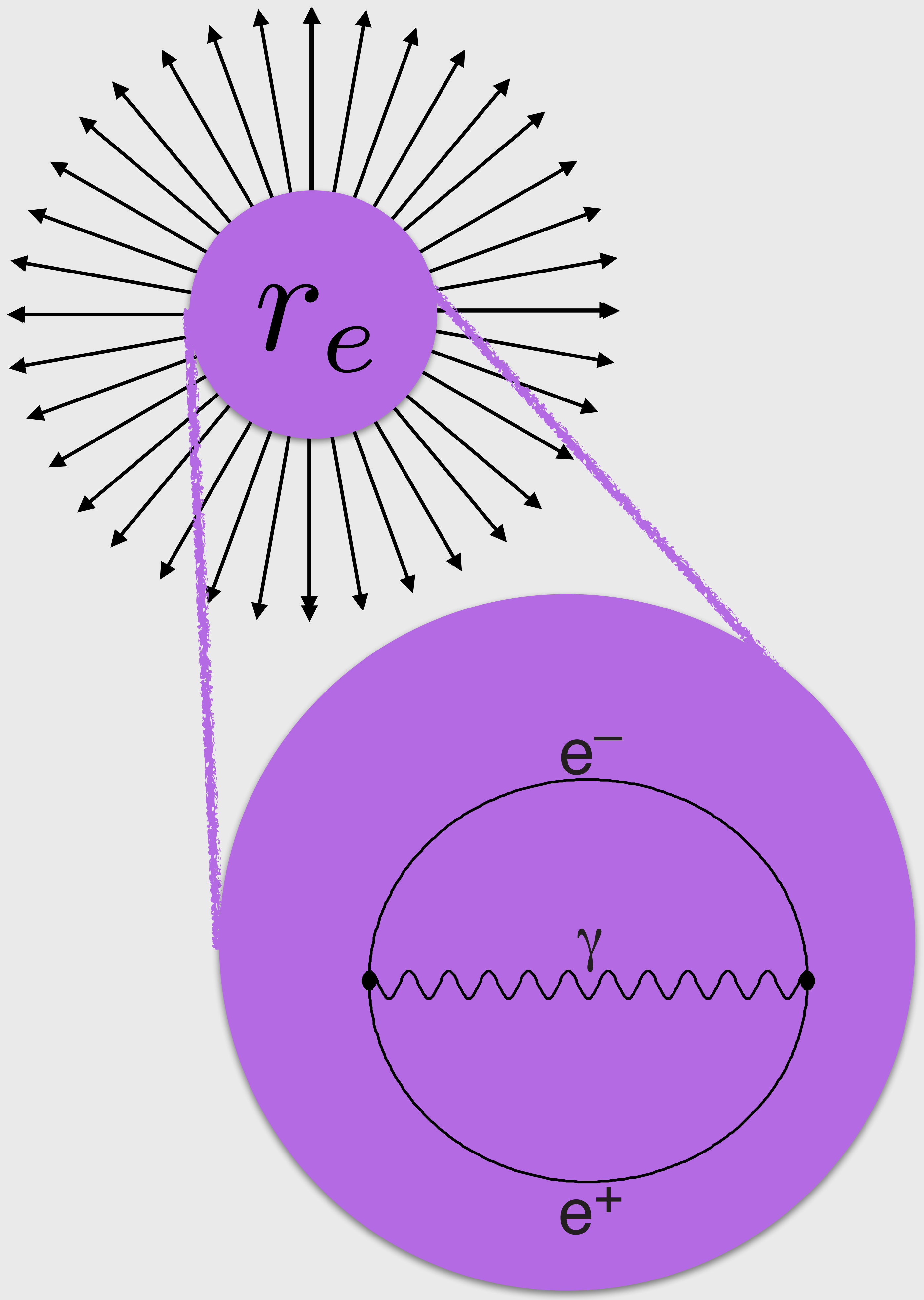
We learned a lesson on physics **at the same mass scale** as where the puzzle arises:

$$m_{positron} = m_{electron} \ll m_{electron}/\alpha_{em}$$

A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS



New symmetry (particle-antiparticle) which brought a new particle: the positron

We learned a lesson on physics **at the same mass scale** as where the puzzle arises:

$$m_{positron} = m_{electron} \ll m_{electron}/\alpha_{em}$$

A puzzle (today) we know how to solve

AFTER

RELATIVITY & QUANTUM MECHANICS

- Similar arguments would require a contribution of the electric filed to the mass of the charged pion

- In that case the solution is not an antiparticle, but a "heavy photon", the ρ meson, somewhat heavier than the pion

- In the grand picture, both the positron and the ρ meson appear at the same scale where the problem arises.