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pp Theory at 100 TeV

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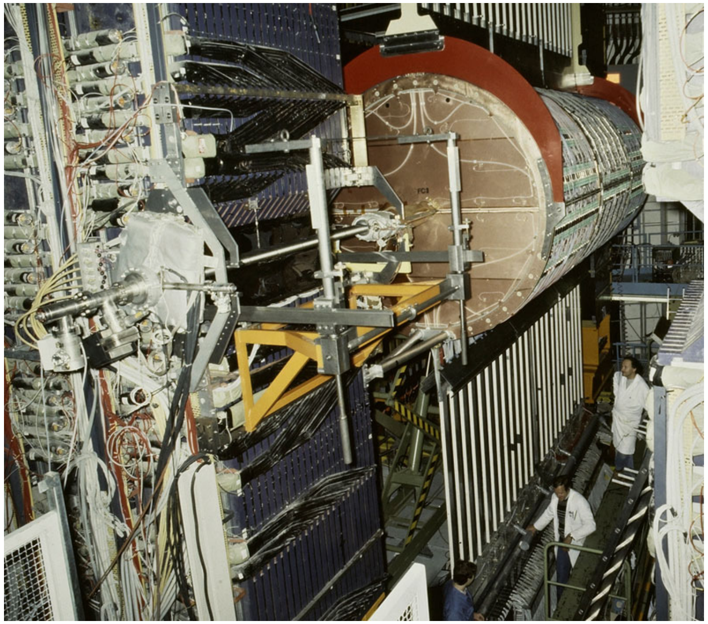
SM (1607.01831) Higgs (1606.09408) BSM (1606.00947)

Particle accelerators are built to answer some of the most fundamental questions about the natural world.

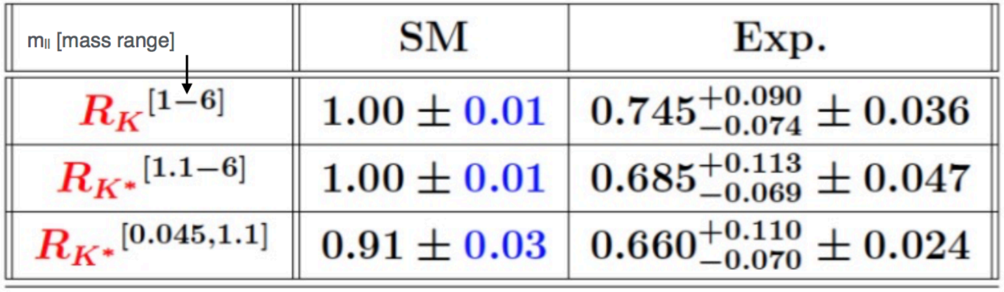
Sp$\bar{p}$S, Tevatron, LEP, LHC



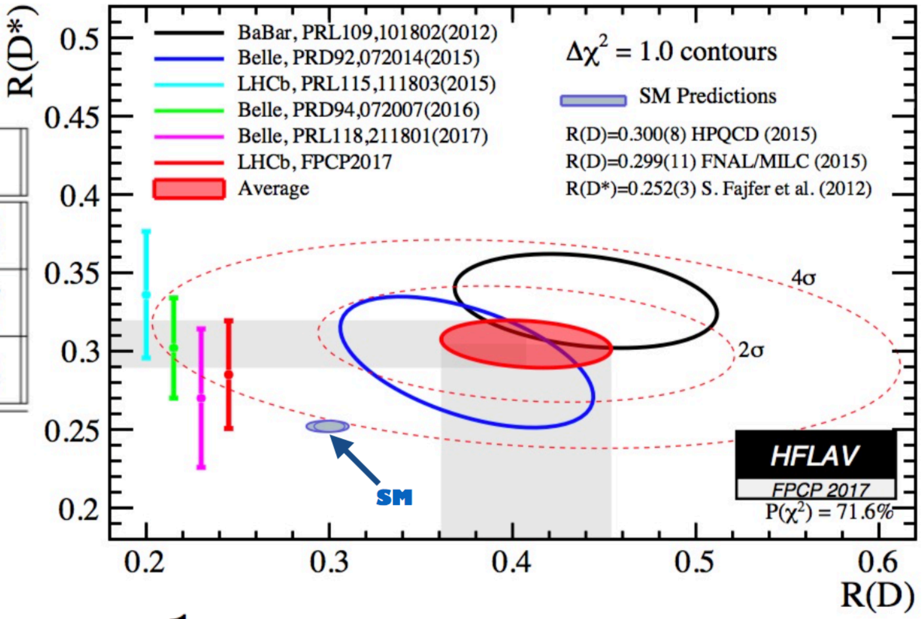
Physics priorities are likely to shift swiftly, as we advance in our exploration, both experimentally and theoretically.

- Today the complete exploration of the WIMP hypothesis is a robust and quantitative criterion for motivating choices of collider energy.

- What if we discover a sub-GeV DM, an axion in the DM window, or a population of primordial BH?



m_{ll} [mass range]	SM	Exp.
$R_K^{[1-6]}$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^*}^{[1.1-6]}$	1.00 ± 0.01	$0.685^{+0.113}_{-0.069} \pm 0.047$
$R_{K^*}^{[0.045,1.1]}$	0.91 ± 0.03	$0.660^{+0.110}_{-0.070} \pm 0.024$



$$\mathcal{L} = \frac{1}{\Lambda_K^2}\,\bar{s}_L\gamma^\mu b_L\,\bar{\mu}_L\gamma_\mu\mu_L - \frac{1}{\Lambda_D^2}\,\bar{c}_L\gamma^\mu b_L\,\bar{\tau}_L\gamma_\mu\nu_L$$

$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)} \quad \Longrightarrow \quad \Lambda_K \sim 30\ \mathrm{TeV}$$

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\mu\nu)} \quad \Longrightarrow \quad \Lambda_D \sim 3\ \mathrm{TeV}$$

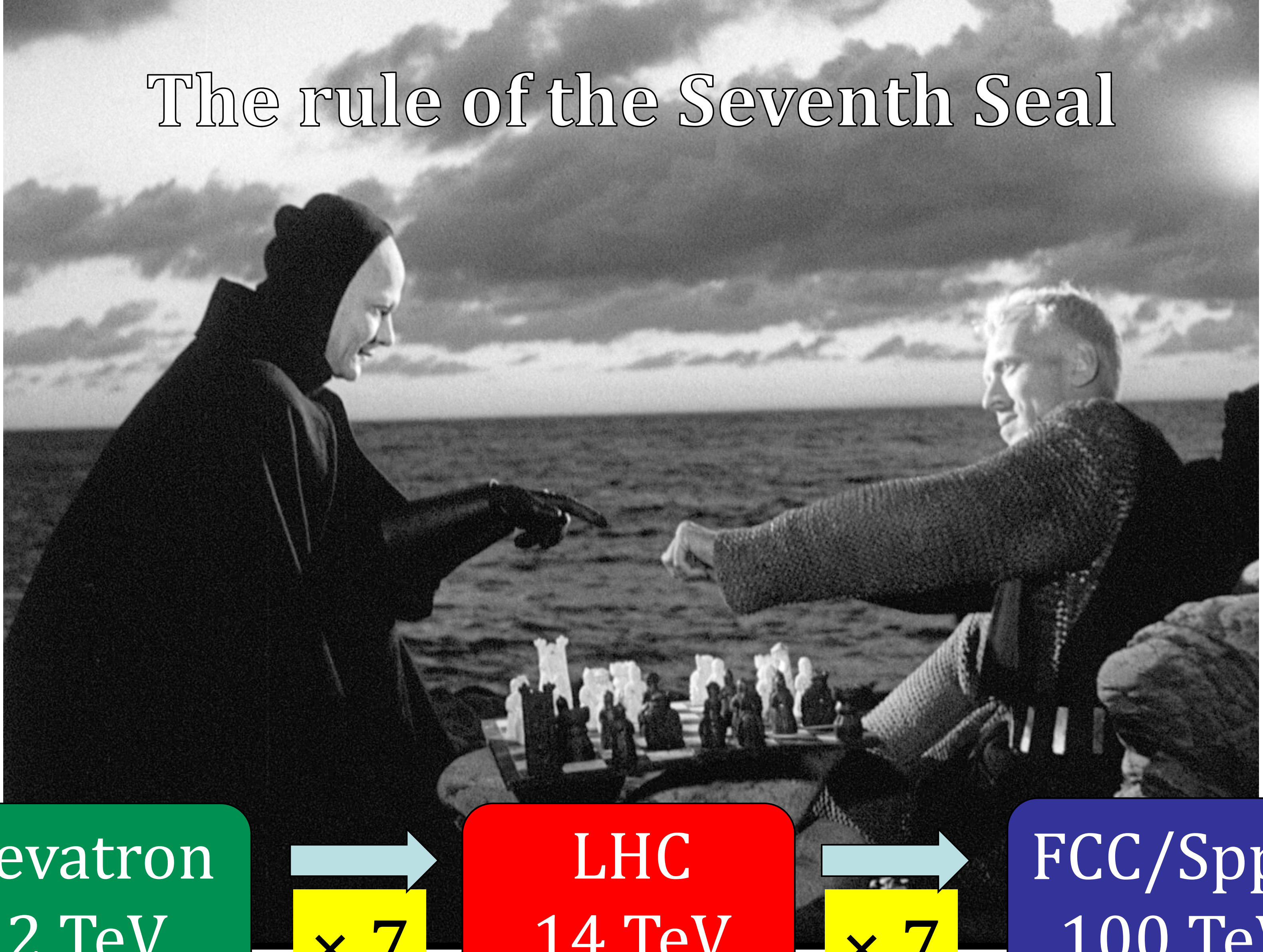
There are many unknowns ahead of us that may reshuffle the cards.

What we need is a broad and bold program, capable of adapting to the swift changes in the physics landscape that are likely to happen.

100 TeV hadron collider

In times of uncertainty, bold exploration is the way to go.

The rule of the Seventh Seal



Tevatron
2 TeV

→ × 7

LHC
14 TeV

→ × 7

FCC/SppC
100 TeV

It must be the right move!

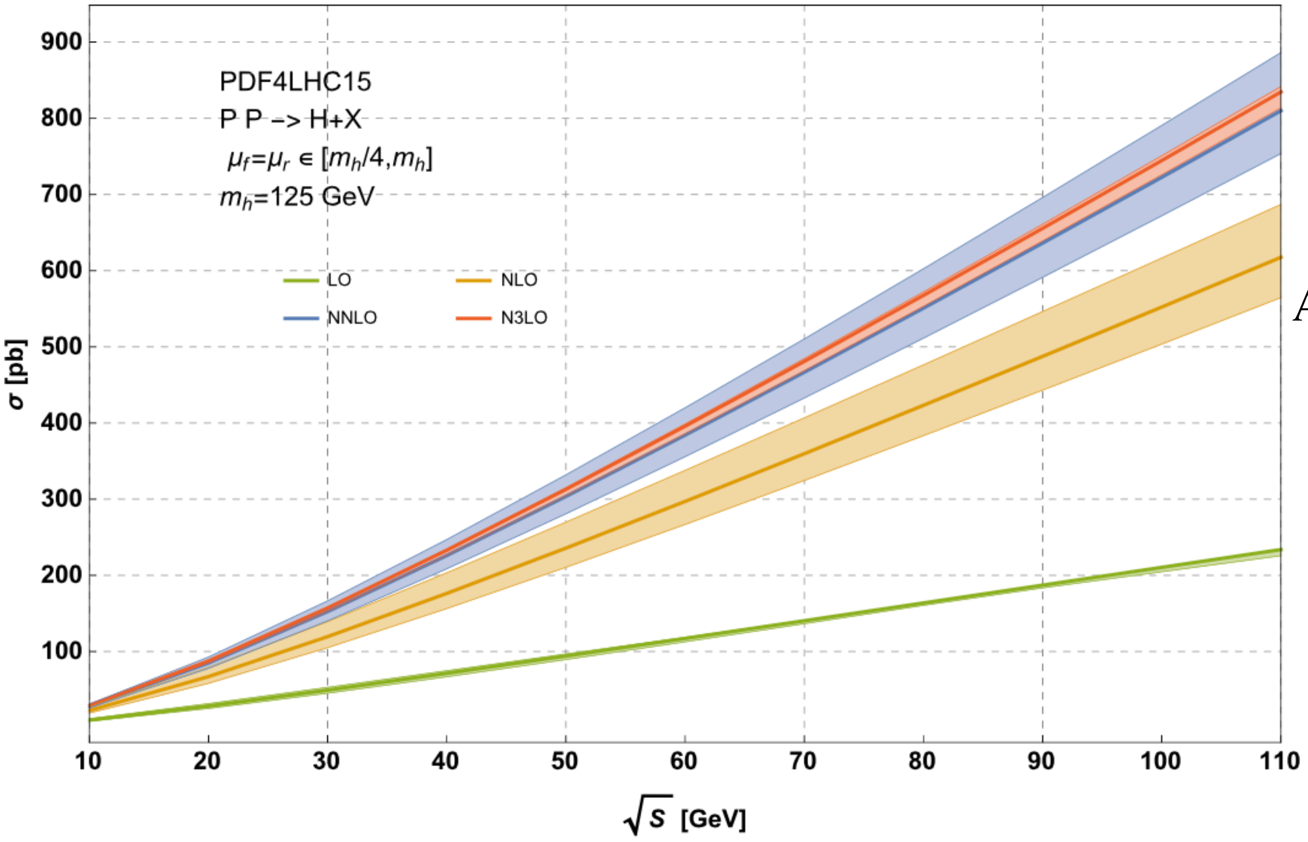
What is a 100 TeV hadron collider going to find?

What is a 100 TeV hadron collider going to find?

What I know is that this machine will be a voyage beyond the frontiers of knowledge, exploring new territories where we are going to test our ideas about nature at the most fundamental level.

Higgs physics

Higgs: 14 new non gauge-like fundamental forces!



N^3LO calculation of $gg \to h$!!!

Anastasiou et al, 1602.00695

$$\boxed{\frac{\sigma(100\ \mathrm{TeV})}{\sigma(14\ \mathrm{TeV})} = 16}$$

	$gg \to H$	VBF	$HW^{\pm}$	HZ	$t\bar{t}H$
σ(pb)	802	69	15.7	11.2	32.1
$N_{events}/20\mathrm{ab}^{-1}$	1.6×10^{10}	1.4×10^{9}	3.1×10^{8}	2.2×10^{8}	6.4×10^{8}
$N(100\ \mathrm{TeV})/N(14\ \mathrm{TeV})$	110	120	65	85	420

Tens of billions of Higgs bosons!

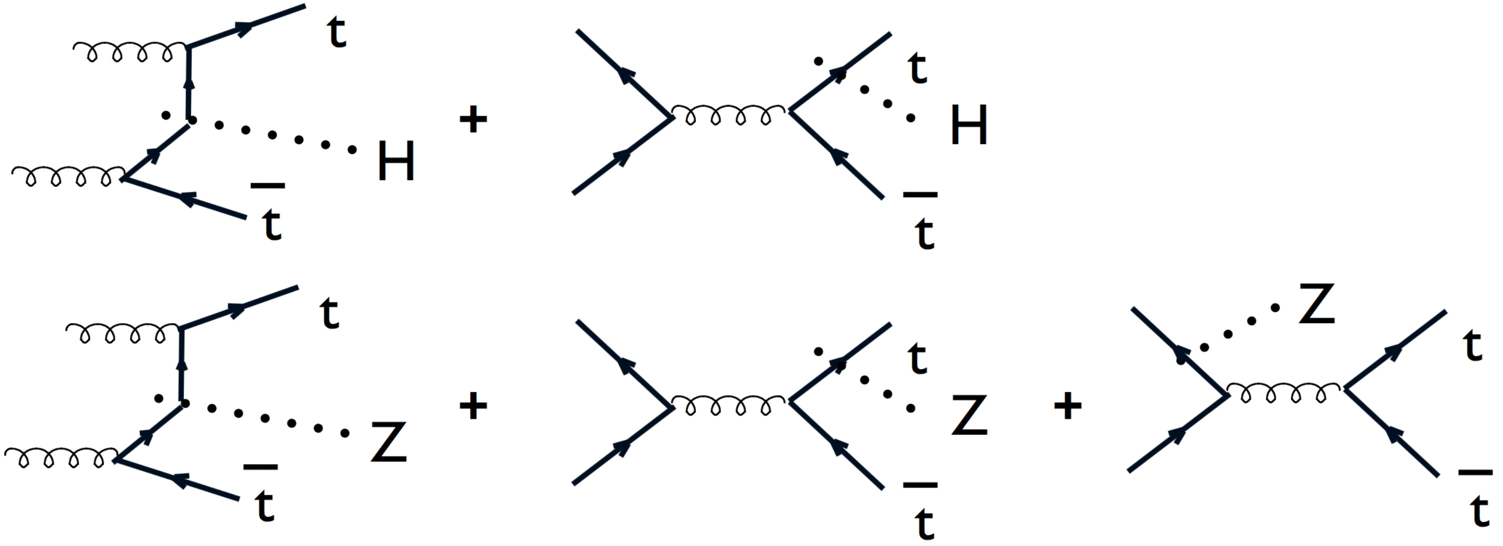
Access to rare decays

- Use ratios of BR to cancel theoretical systematics in rates, absolute luminosity, and some detector effects
- Assuming precise determinations of *HZZ* and *HWW* couplings from e^+e^-

	BR	**(stat.) precision in coupling**
$H \rightarrow \mu\mu$	2.2×10^{-4}	1%
$H \rightarrow Z\gamma$	1.5×10^{-3}	1%
$H \rightarrow \gamma\gamma$	2.3×10^{-3}	0.5%
$H \rightarrow J/\psi\ \gamma$	2.8×10^{-6}	?

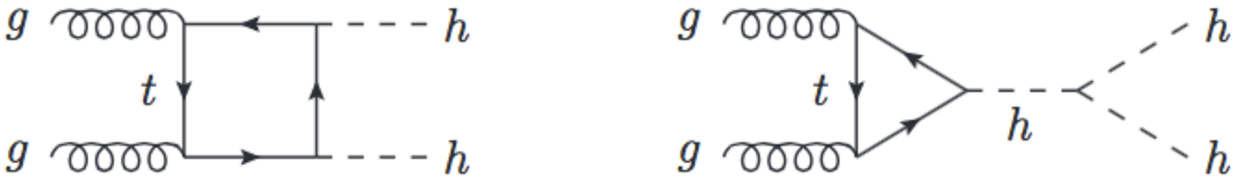
- Flavor ($H \rightarrow bs$) or lepton-family violating ($H \rightarrow \tau\mu$) Higgs decays?
- Test BR($H \rightarrow$ invisible) up to $3{-}5 \times 10^{-4}$ (with 20 ab^{-1}) and measure SM BR($H \rightarrow \nu\nu\nu\nu$) = 1×10^{-3}(with 1 ab^{-1})

Top Yukawa coupling from *ttH/ttZ*

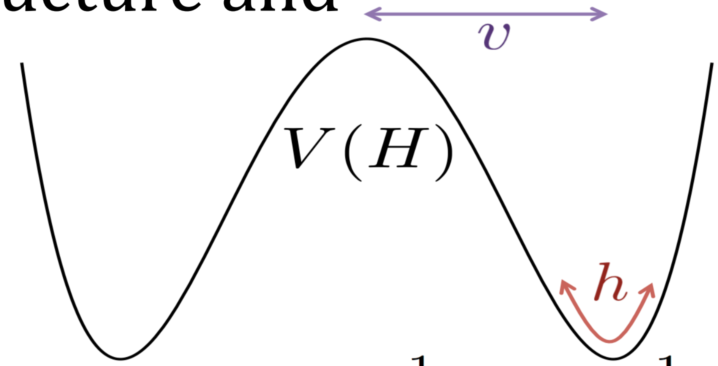


- At 100 TeV, rate dominated by *gg*: same kinematics ($m_H \sim m_Z$), correlated QCD corrections, scale dependence, and PDF systematics
- Possible to measure y_t with 1% precision
- Crucial input for EW vacuum stability, naturalness, Higgs compositeness, susy loop contributions to m_H
- Combined measurements of *ttH(→bb)/tttt*, fitting for y_t and Γ_H, assuming SM y_b (precisely measured at e^+e^-)

Triple Higgs coupling



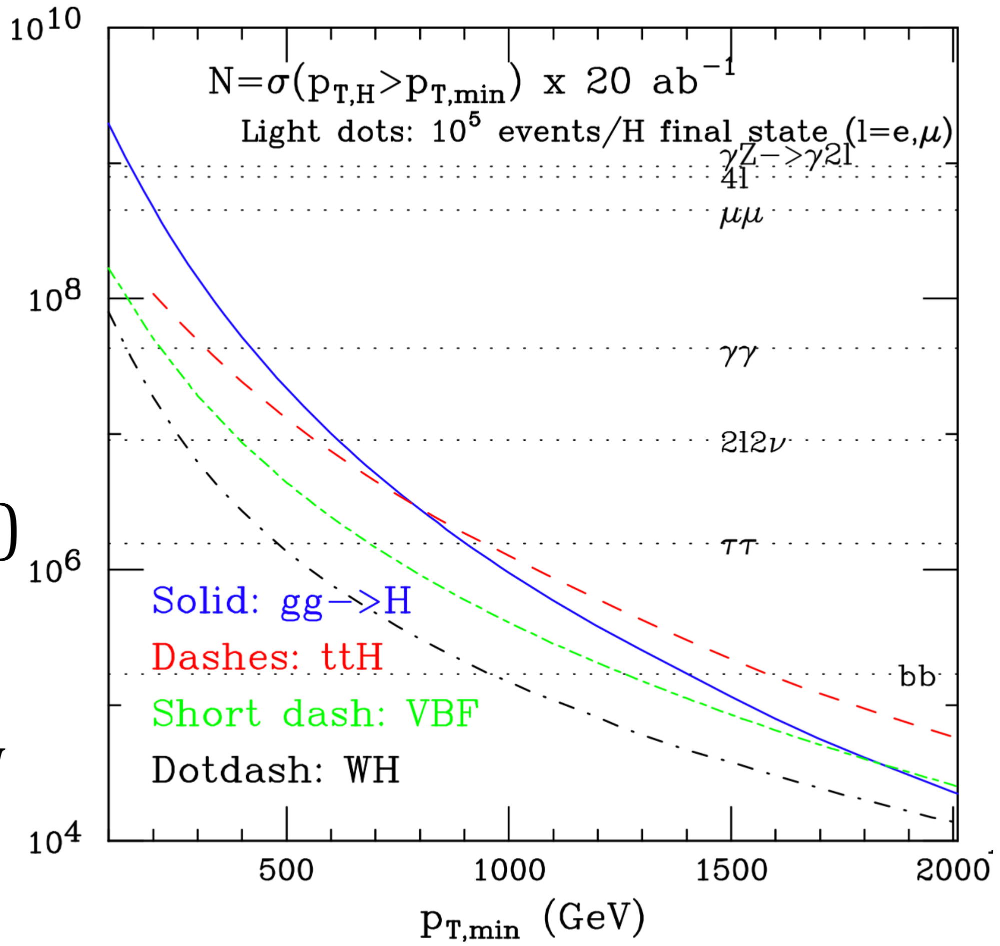
- Energy and statistics great advantage with respect to other colliders
- Most promising channel *HH* → $bb\gamma\gamma$
- Precision on coupling 3.5–5%
- Important test for *V(H)* structure and EW phase transition



$$\underbrace{\frac{1}{2}m_h^2h^2}_{\text{Mass}} + \underbrace{\frac{1}{6}\lambda h^3}_{\text{Self Interaction}} + \ldots$$

Higgs at high p_T

- Large statistics of Higgs at high p_T:
  10^6 H with $p_T > 1.5$ TeV and
  10 H with $p_T > 8$ TeV (20 ab^{-1})



- For $p_T > 0.8$ TeV, $ttH > gg \to H$
  For $p_T > 1.8$ TeV, VBF $> gg \to H$

- Background and systematics considerations can be very different from LHC
- At high p_T better discriminating power
  $H \to bb$ with jet sub-structure
- Test of Higgs couplings at high energy

Direct production

- Energy frontier: increase $\sqrt{s}$ to explore larger M
- Intensity frontier: increase $\mathcal{L}$ to explore smaller g_*

Indirect production

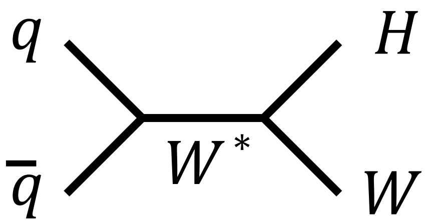
- Precision frontier: use $\mathcal{L}$ and exp. accuracy to study EW observables or Higgs BR, probing effects m_Z^2/M^2
- HE probe frontier: use $\sqrt{s}$, $\mathcal{L}$, and exp. accuracy to study high-p_T processes, probing effects E^2/M^2

Example of HE probe

Take $$\mathcal{L} = \frac{i g_{\mathrm{SM}}}{M^2}(H^\dagger \overleftrightarrow{D}^\mu H)(\partial^\nu B_{\mu\nu})$$

This changes the Higgs BR: $$\frac{\mathrm{BR}(H \to VV)}{\mathrm{BR}(H \to VV)_{\mathrm{SM}}} - 1 = \mathcal{O}\left(\frac{m_V^2}{M^2}\right)$$

It also changes the Higgs couplings at HE: $$\frac{g_{HVV}}{g_{HVV\,\mathrm{SM}}} - 1 = \mathcal{O}\left(\frac{E^2}{M^2}\right)$$



at high HW invariant mass

10% precision at E = TeV probes New Physics as much 0.1% precision in Higgs decays

- The HE probe frontier is a powerful weapon for a 100 TeV collider
- It is a test of physics beyond the kinematical reach with enhanced sensitivity
- Sociology: instructive and creative work for experimentalists

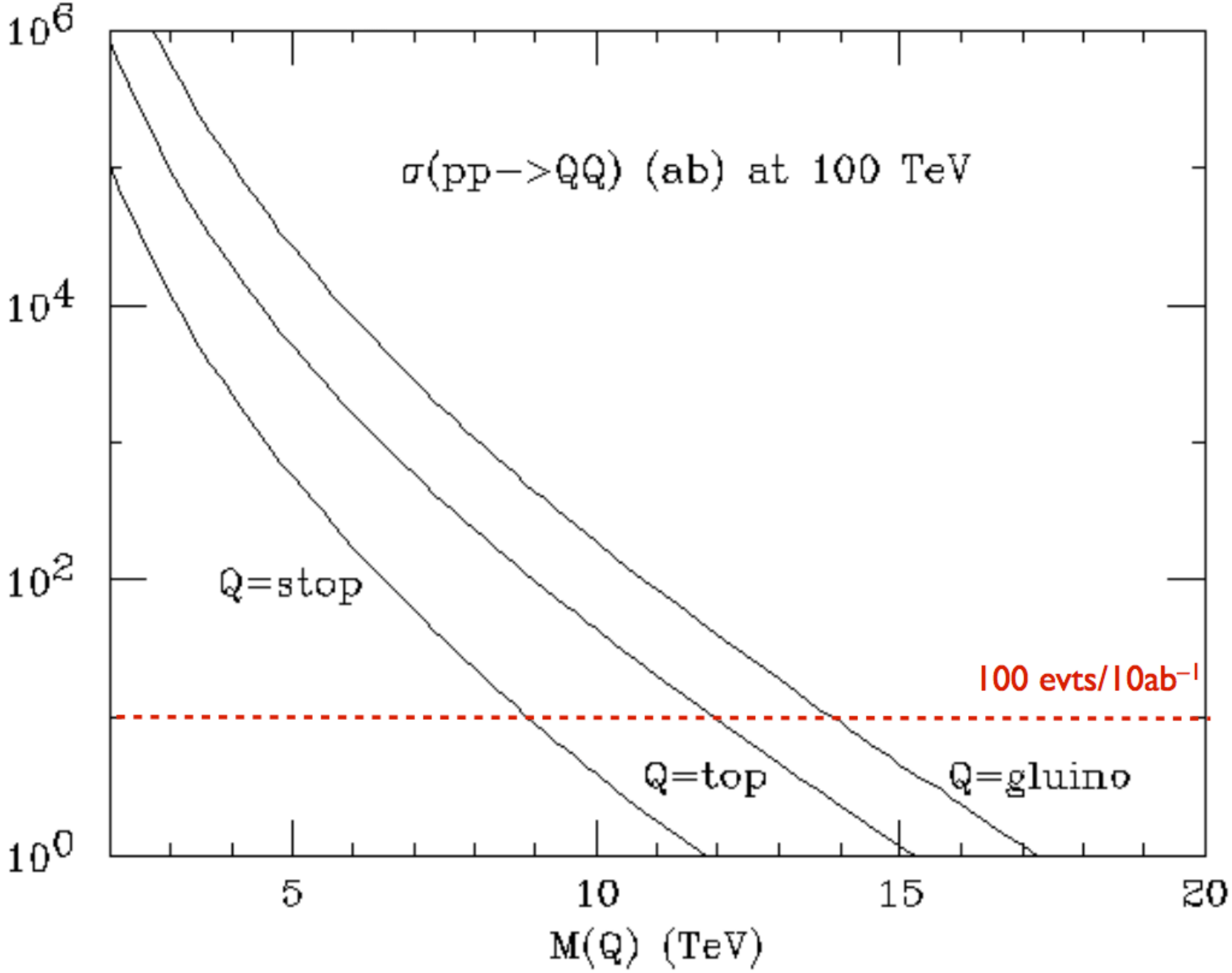
Hunting for new physics with top quarks

- $\sigma_{\mathrm{top}}(100\ \mathrm{TeV}) \sim 35\ \sigma_{\mathrm{top}}(14\ \mathrm{TeV})$
- About 10^{12} top quarks in 20 ab^{-1}
- Use one semileptonic top decay to trigger and use the other top to study rare decays
- Exceptional potential for rare or SM-forbidden decays and tests of top properties

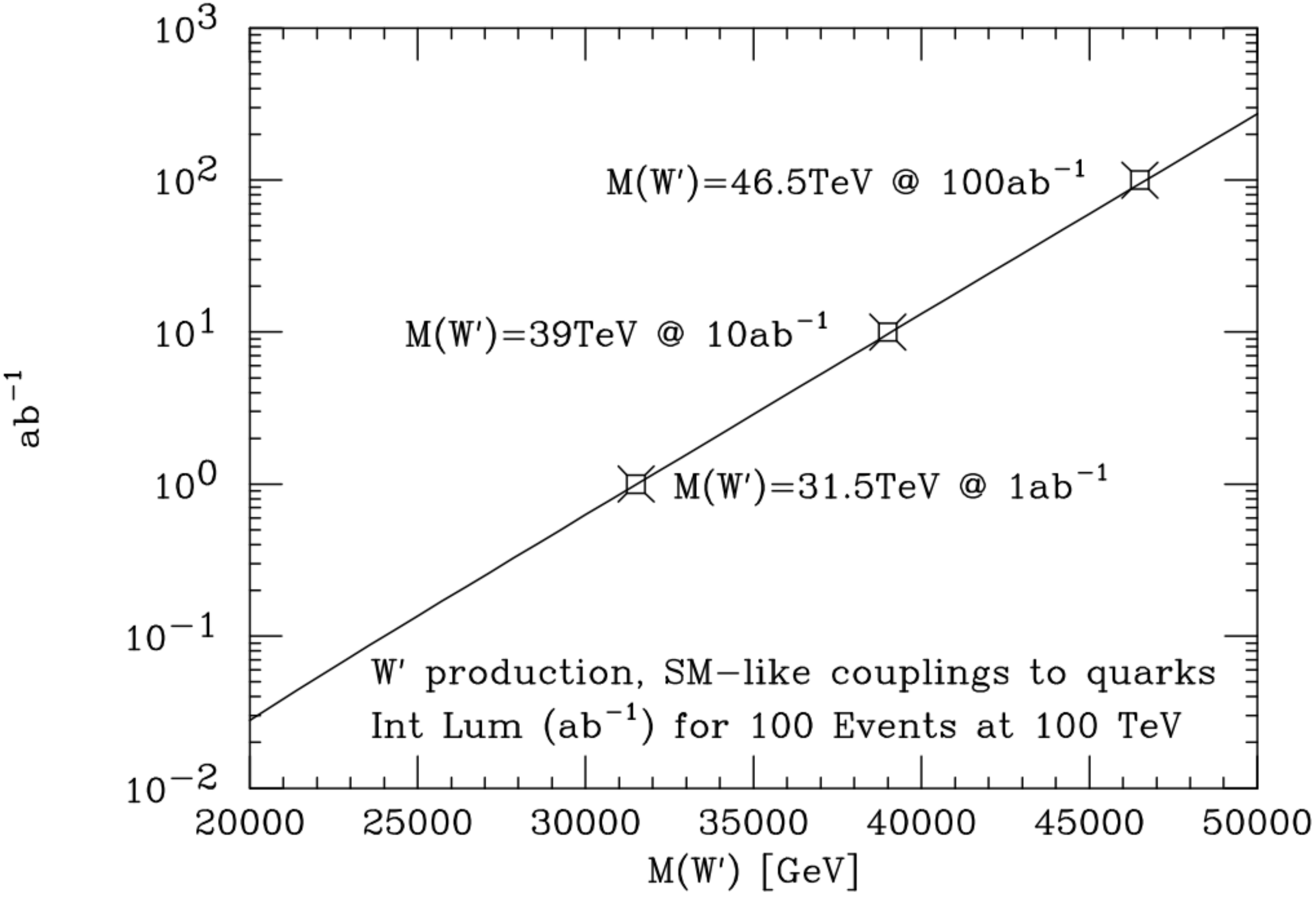
Exploration of new physics in direct production

- This is the main objective and the main asset of a 100 TeV collider

- Mass reach follows the “rule of the Seventh Seal”: gain of about a factor of 7 wrt LHC

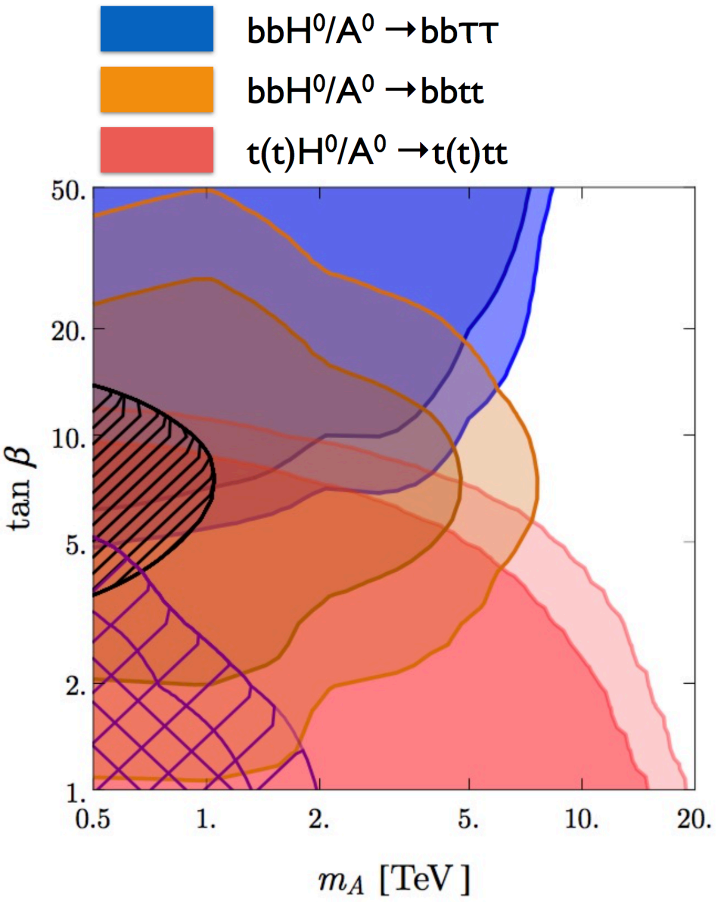


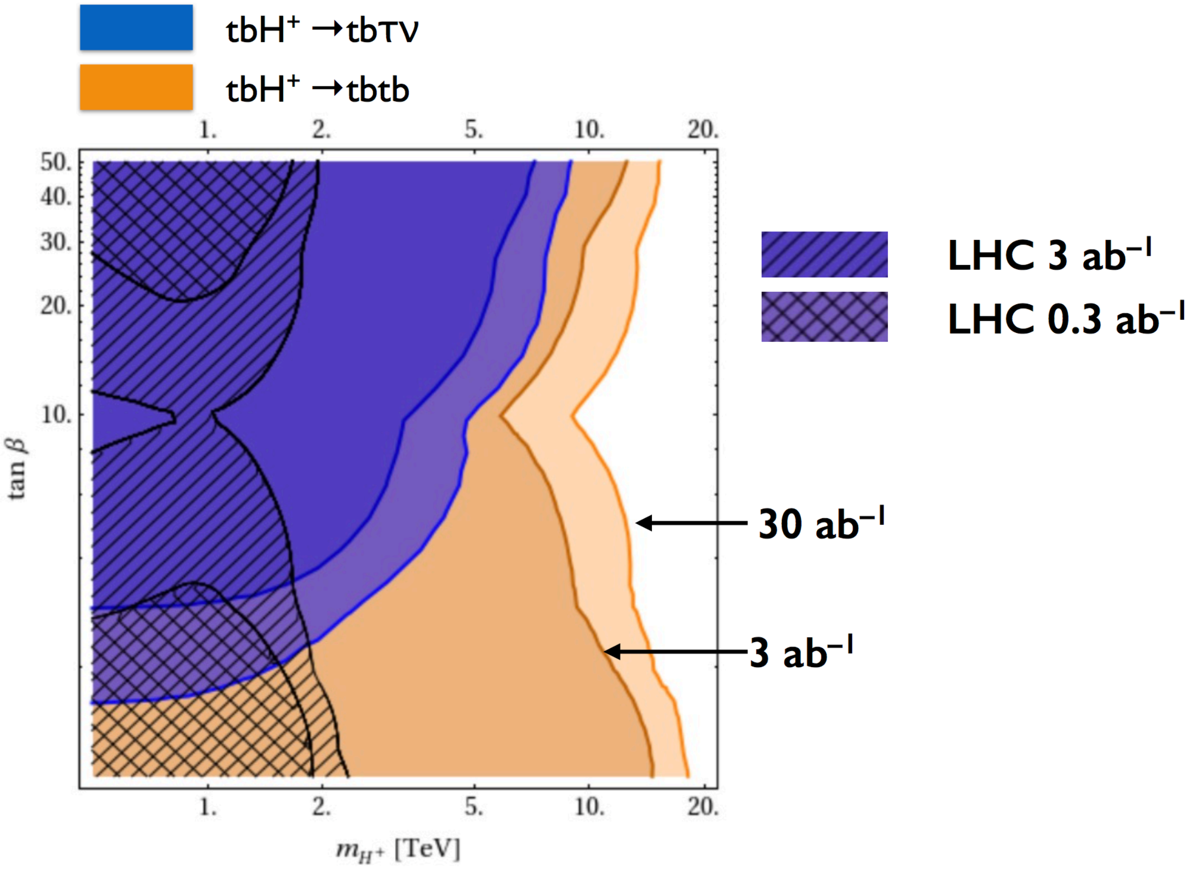
With 10 ab^{-1} reach for M(fermion octet) ~ 14 TeV, M(fermion triplet) ~ 12 TeV, M(scalar triplet) ~ 9 TeV



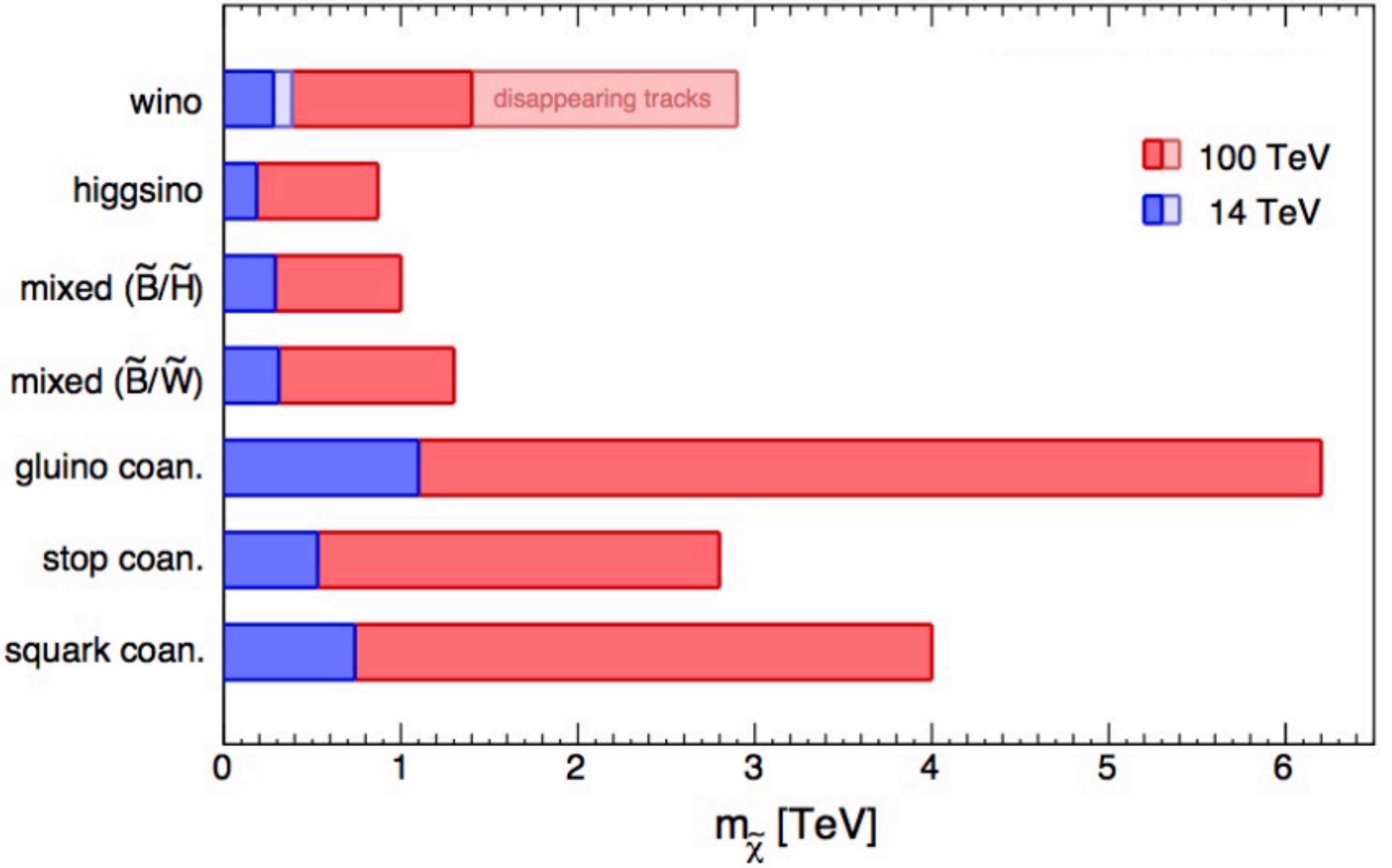
With 10 ab^{-1} reach for SM-like heavy gauge bosons:
M(W') ~ 40 TeV and M(Z') ~ 30 TeV

MSSM Higgs @ 100 TeV





Complete exploration of many WIMP models



Conclusions

- A 100 TeV collider provides an ambitious research program with a formidable exploration power into the mysteries of matter at short distances.
- The LHC has shown that “Protons equal energy, leptons equal precision” doesn't catch the full story. Thanks to extraordinary developments in theoretical calculations of SM backgrounds and excellent detector performances, hadron colliders are players in precision physics.
- High energy, combined with precision, opens up a new frontier of exploration.