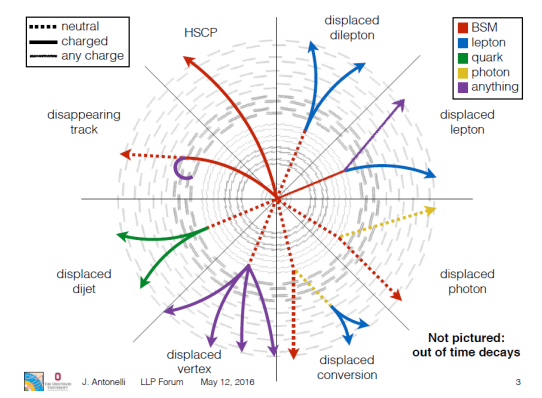
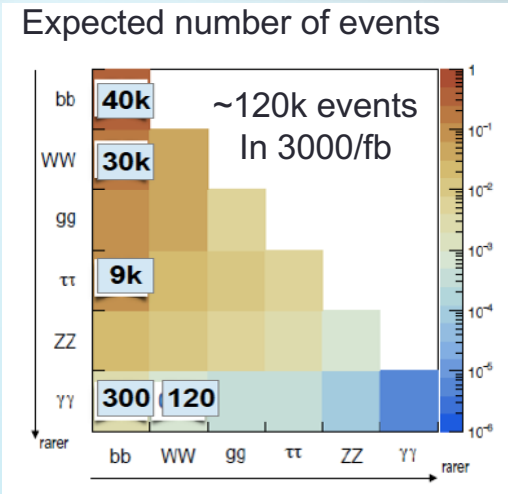


Future hadron colliders: HL-LHC, HE-LHC, FCC-hh, ….



Disclaimer: focus on the **CERN machines,** but most physics outputs are machine-independent, *e.g.* also valid for the **Chinese SppC**

Lepton Colliders vs Hadron Colliders

Hadrons

- large mass reach ⇛ exploration?
- S/B ~ 10^{-10} (w/o trigger)
- S/B ~ 0.1 (w/ trigger)
- requires multiple detectors
  (w/ optimized design)
- only pdf access to $\sqrt{\hat{s}}$
- ⇛ couplings to quarks and gluons

Leptons

- S/B ~ 1 ⇛ measurement?
- polarized beams
  (handle to chose the dominant process)
- limited (direct) mass reach
- identifiable final states
- ⇛ EW couplings

Circular

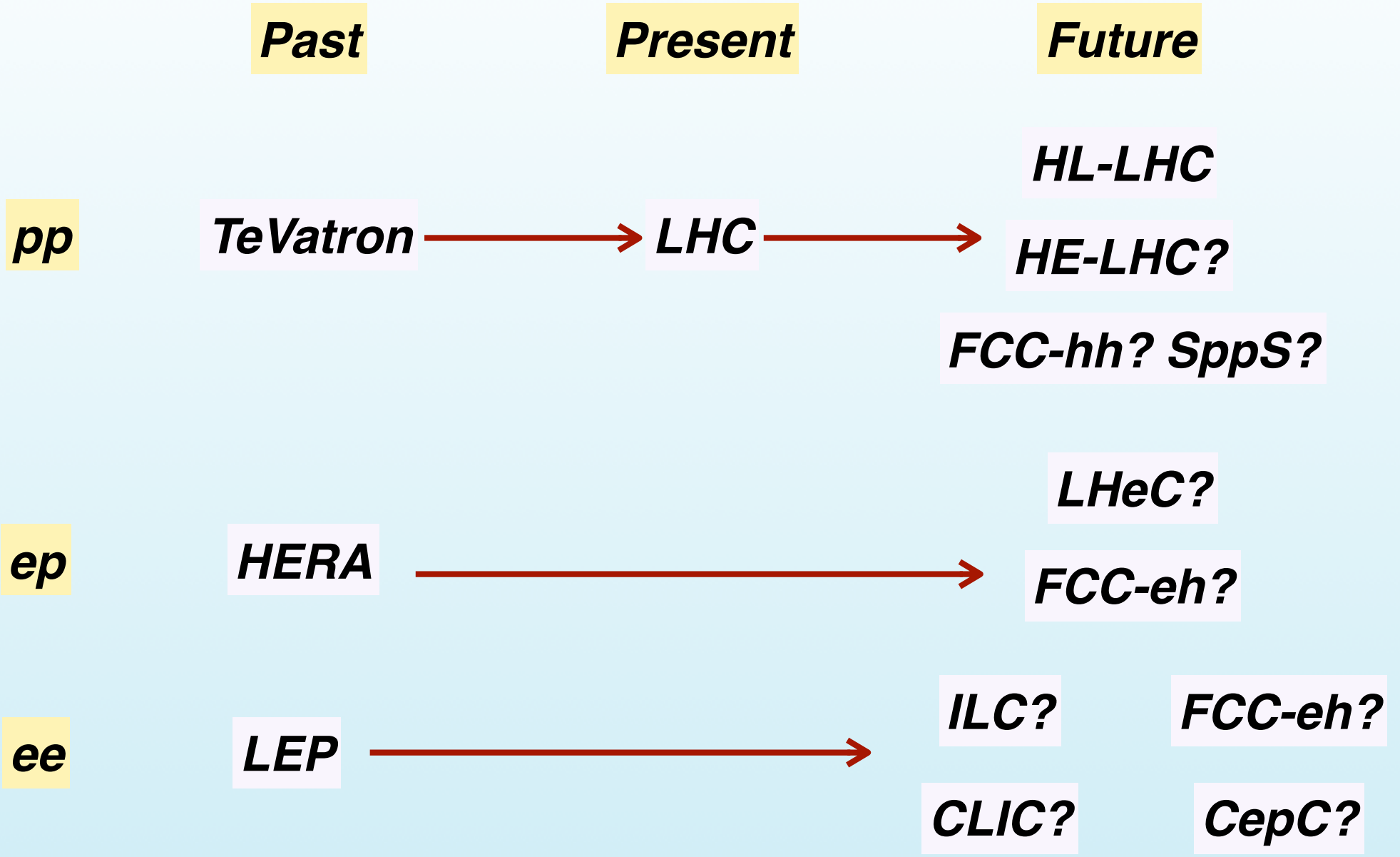
- $\sqrt{s}$ limited by synchroton radiation
- higher luminosity
- several interaction points
- precise E-beam measurement
  (O(0.1MeV) via resonant depolarization)

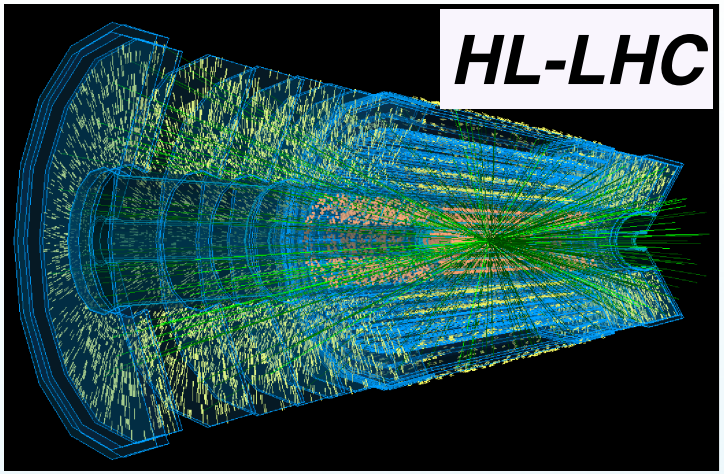
Linear

- easier to upgrade in energy
- easier to polarize beams
- large beamsthralung
- greener: less power consumption

Grojean, "Physics at CLIC" 2017

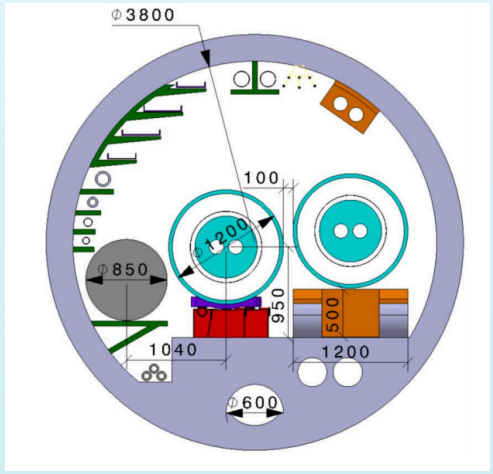
Past, present, and future of HEP



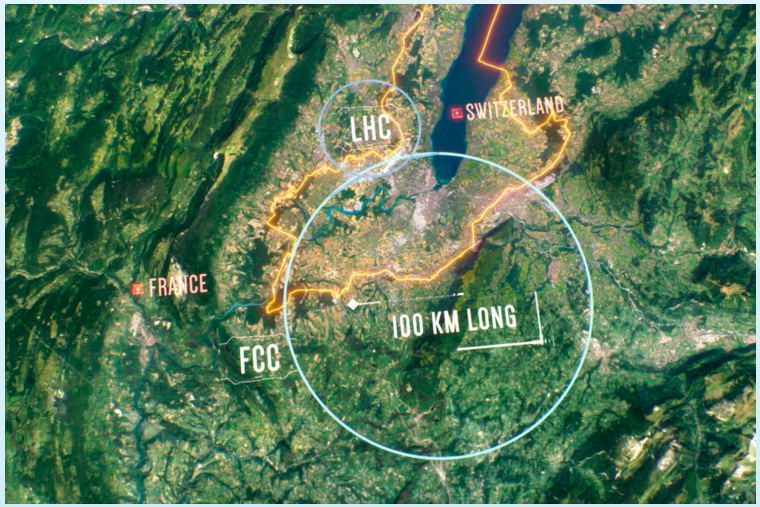


Future High-Energy Hadron Colliders

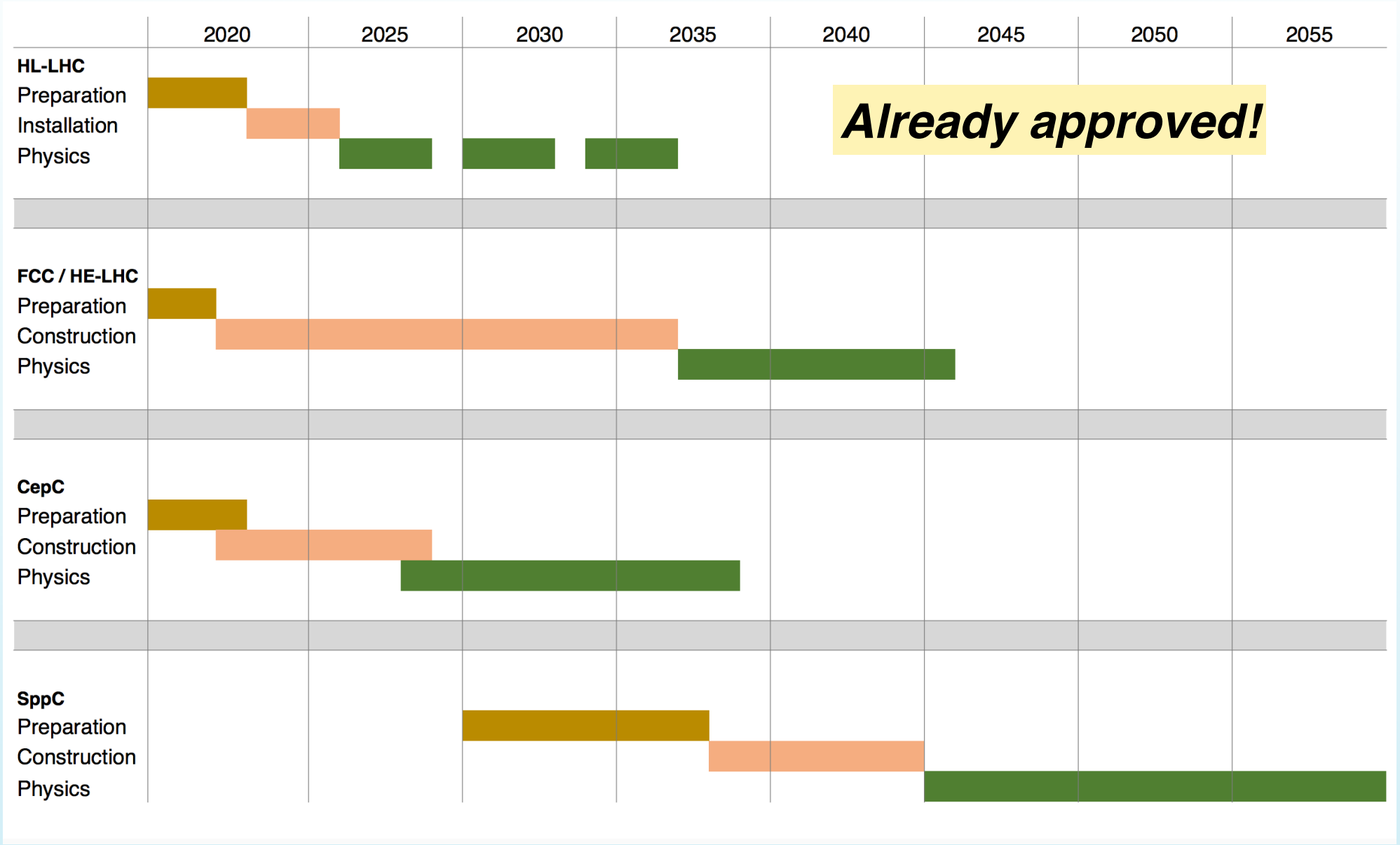
HE-LHC

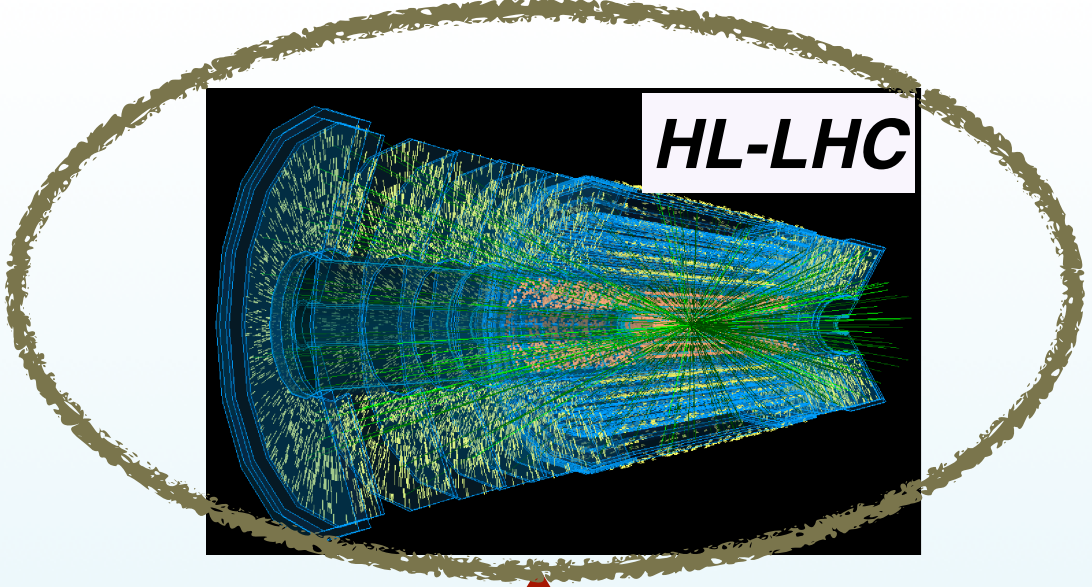


FCC-hh



Timeline of future colliders





Future High-Energy Hadron Colliders

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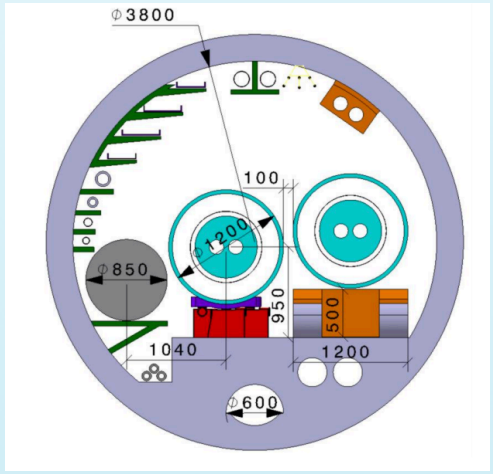

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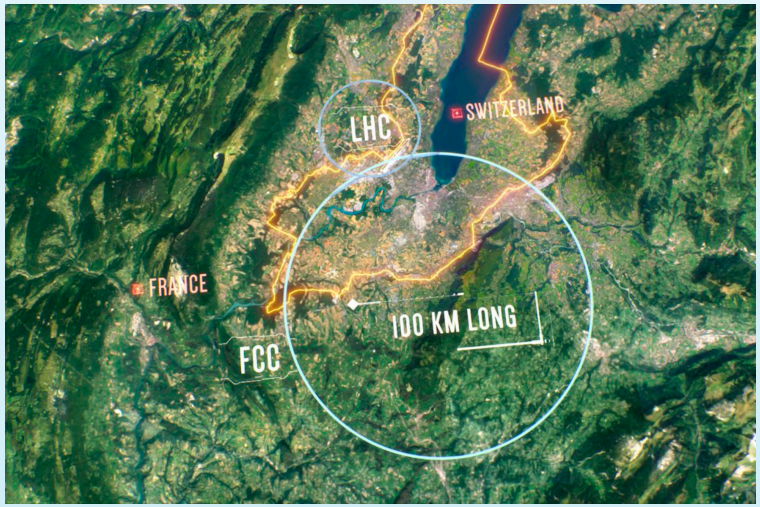
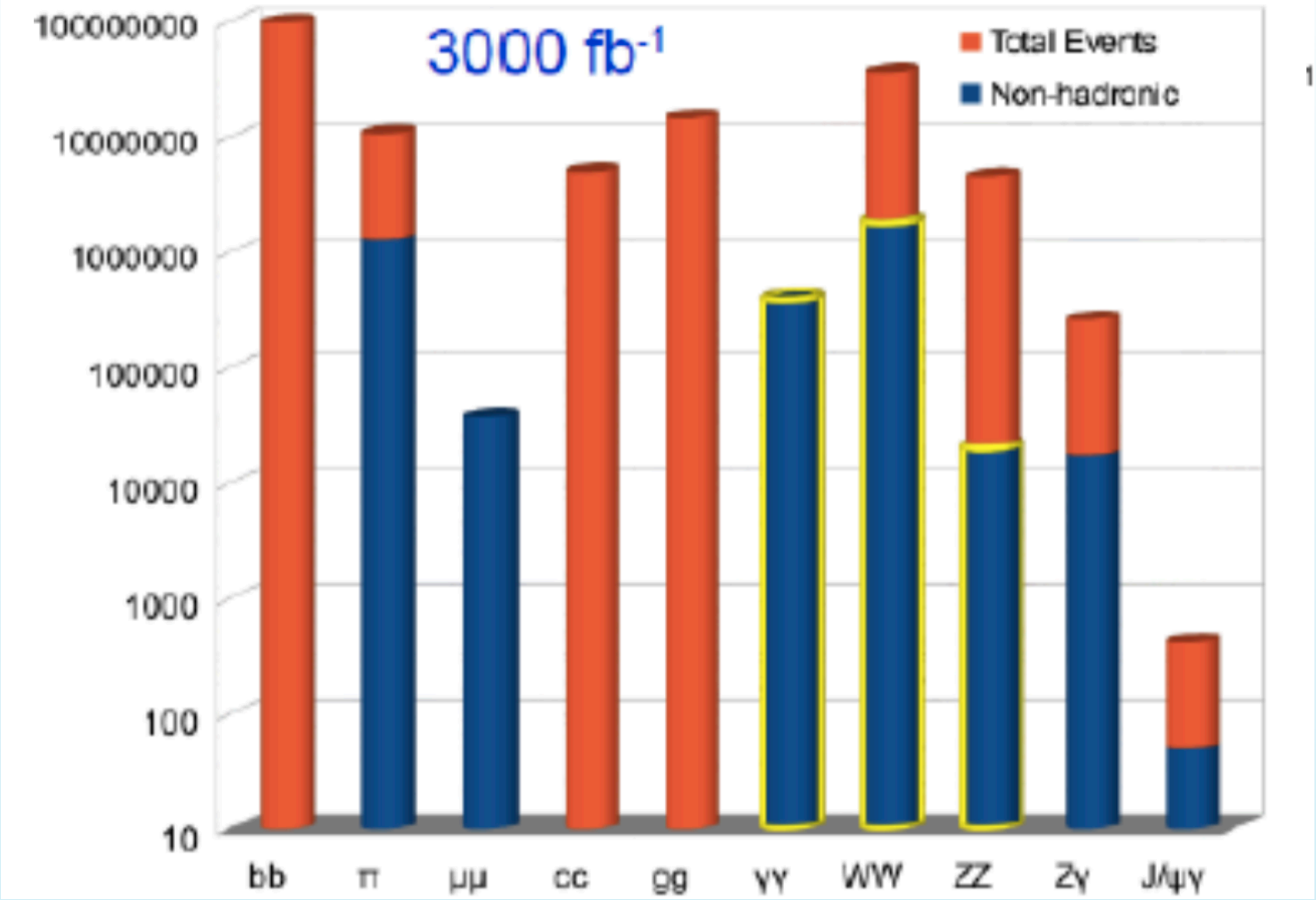


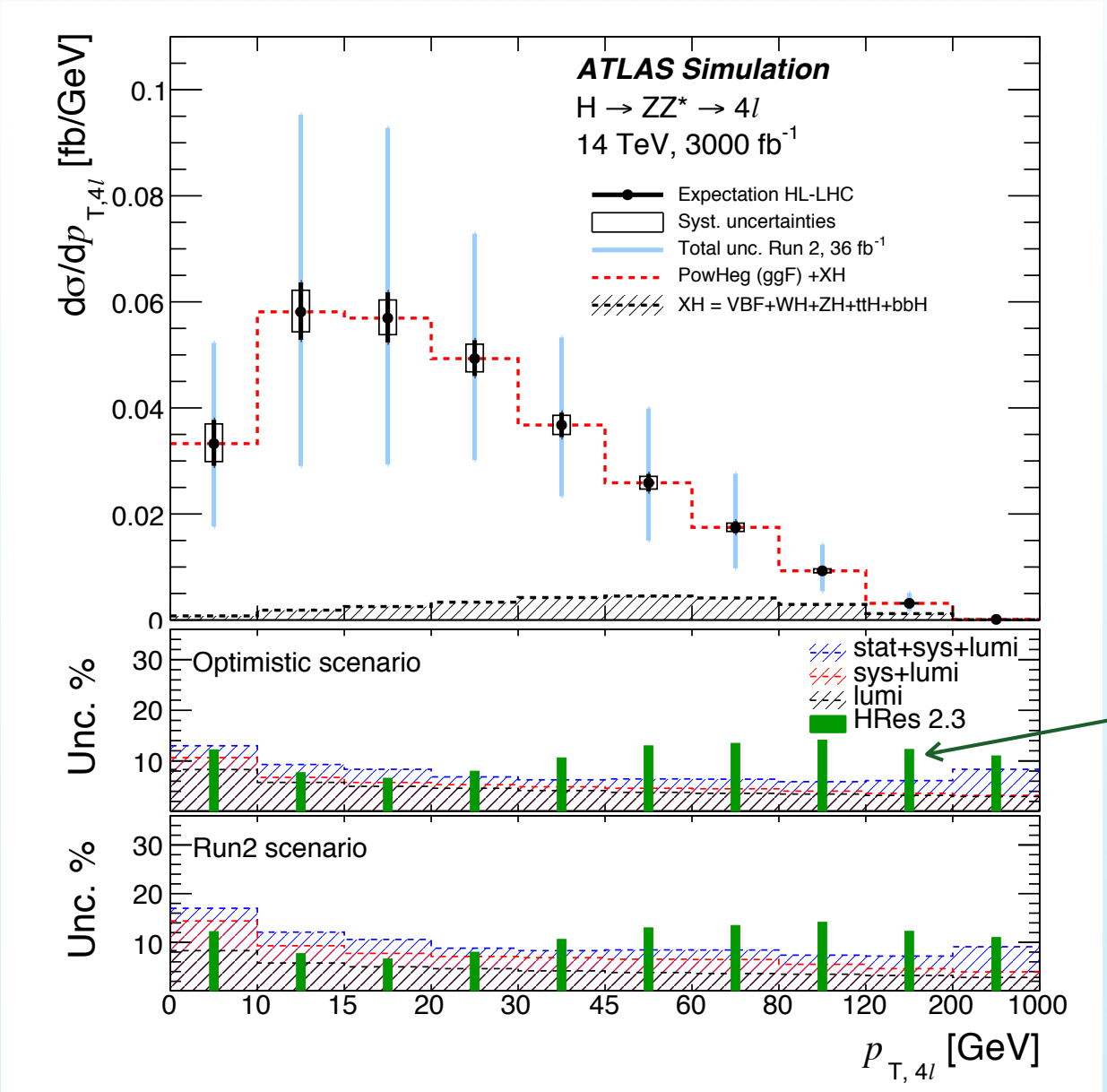
Fingerprinting the Higgs sector at the HL-LHC

The **increased statistics** will make possible study in great detail the **properties of the Higgs sector**



Fingerprinting the Higgs sector at the HL-LHC

This is particularly true for **differential distributions,** characterised by an **enhanced BSM reach** as compared to the inclusive cross-sections



Current TH errors larger than EXP uncertainties!

Fingerprinting the Higgs sector at the HL-LHC

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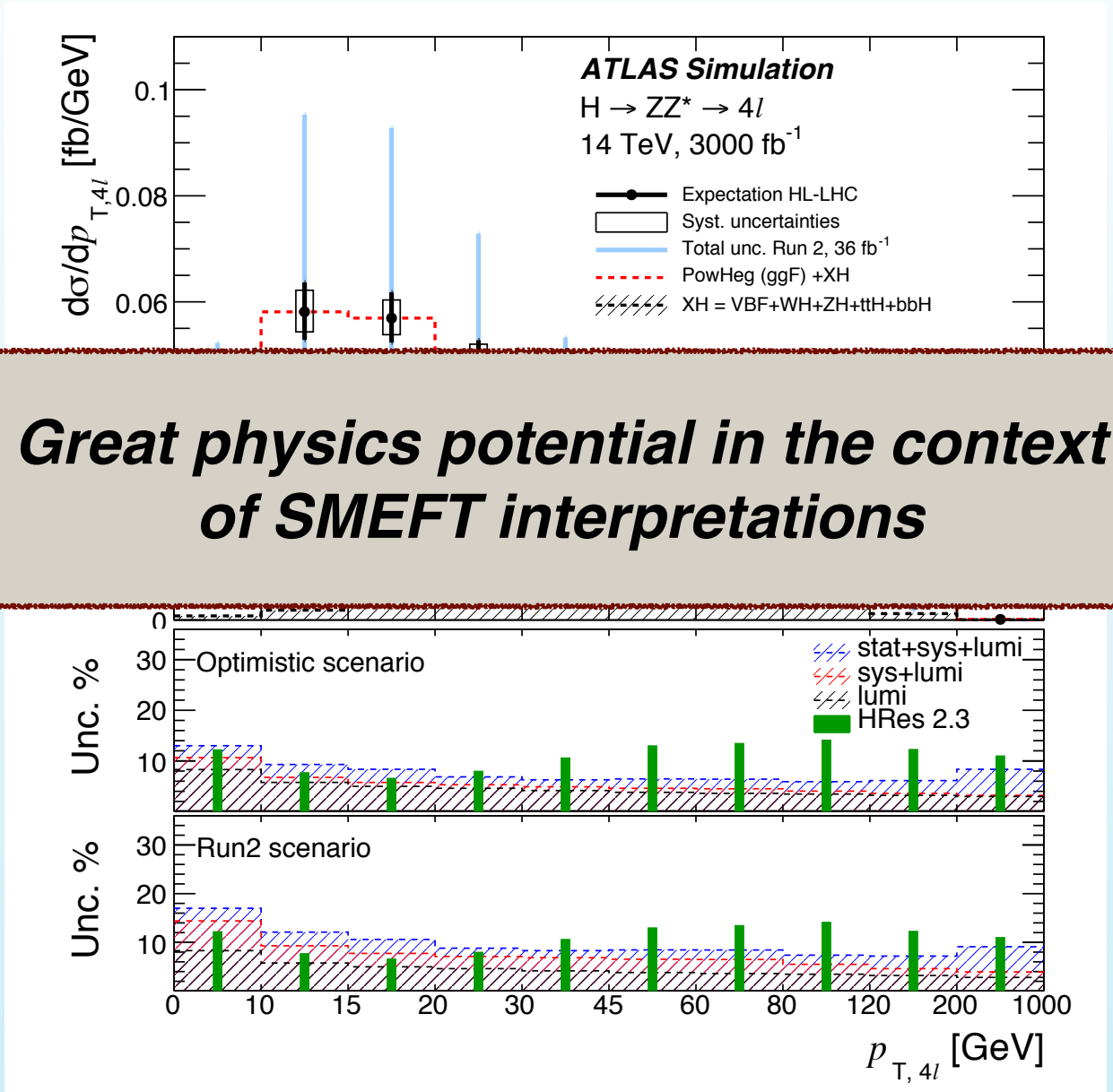
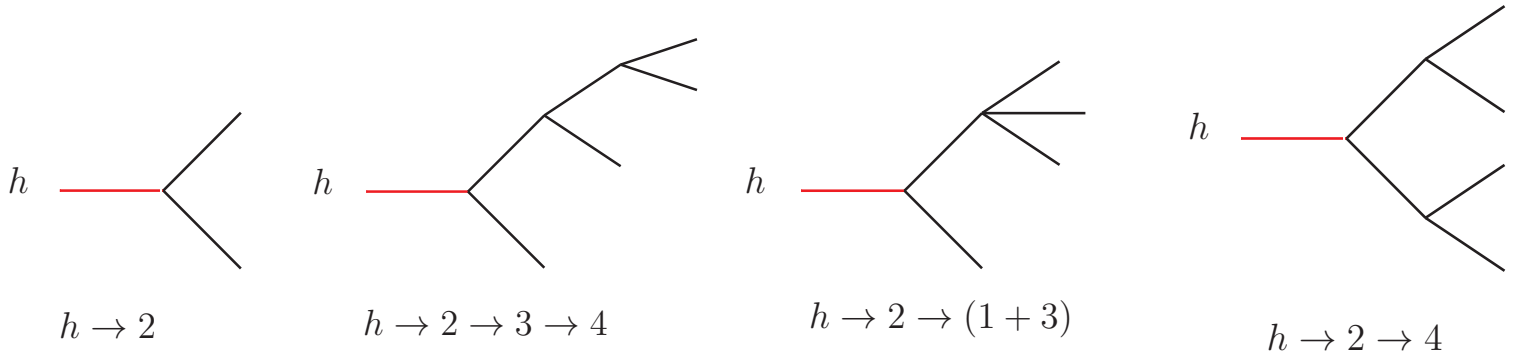


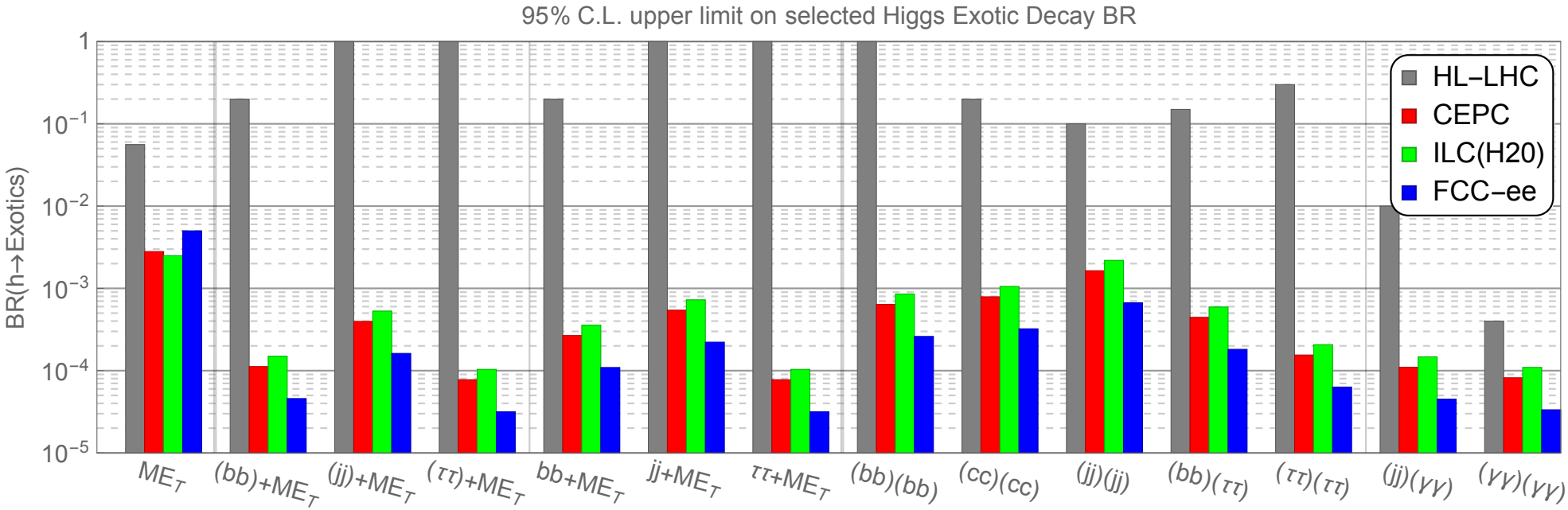
Great physics potential in the context of SMEFT interpretations

Exotic Higgs decays

Sensitivity to **non-standard decay modes** of the Higgs boson

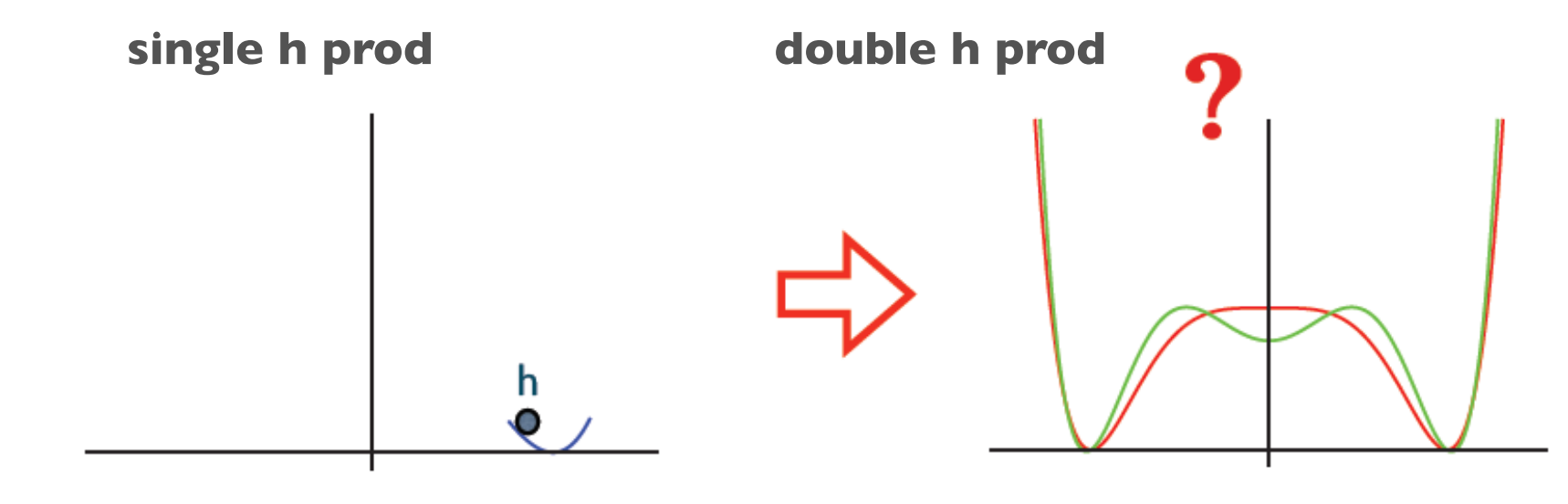
HL-LHC first exploration, ultimate constraints from Higgs factories





Probing Electroweak Symmetry breaking

- **Current measurements** (couplings in single Higgs production) probe **Higgs potential close to minimum**
- Double Higgs production essential to **reconstruct the full Higgs potential** and clarify EWSB mechanism
- Higgs SM potential is *ad-hoc*: not fixed by the SM symmetries, **many other EWSB mechanisms conceivable**



Higgs mechanism

$$V(h) = m_h^2 h^\dagger h + \frac{1}{2}\lambda (h^\dagger h)^2$$

Coleman-Weinberg mechanism

$$V(h) \to \frac{1}{2}\lambda (h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$

Each possibility associated to **completely different EWSB mechanism**, with crucial implications for the **hierarchy problem**, the structure of quantum field theory, and **New Physics at the EW scale**

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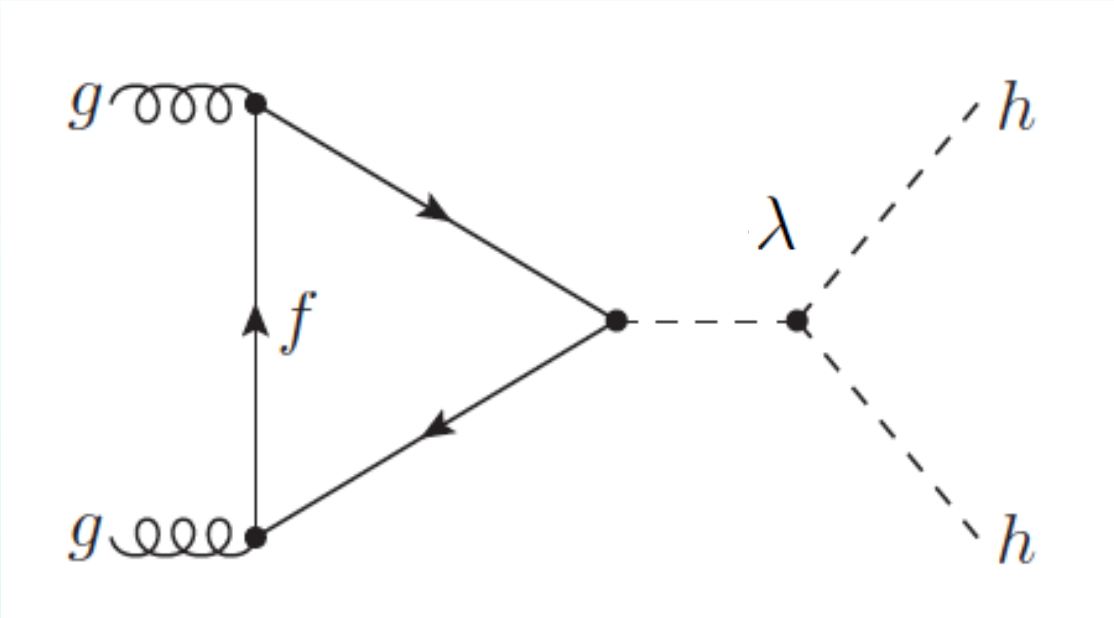

Higgs mechanism **Coleman-Weinberg mechanism**

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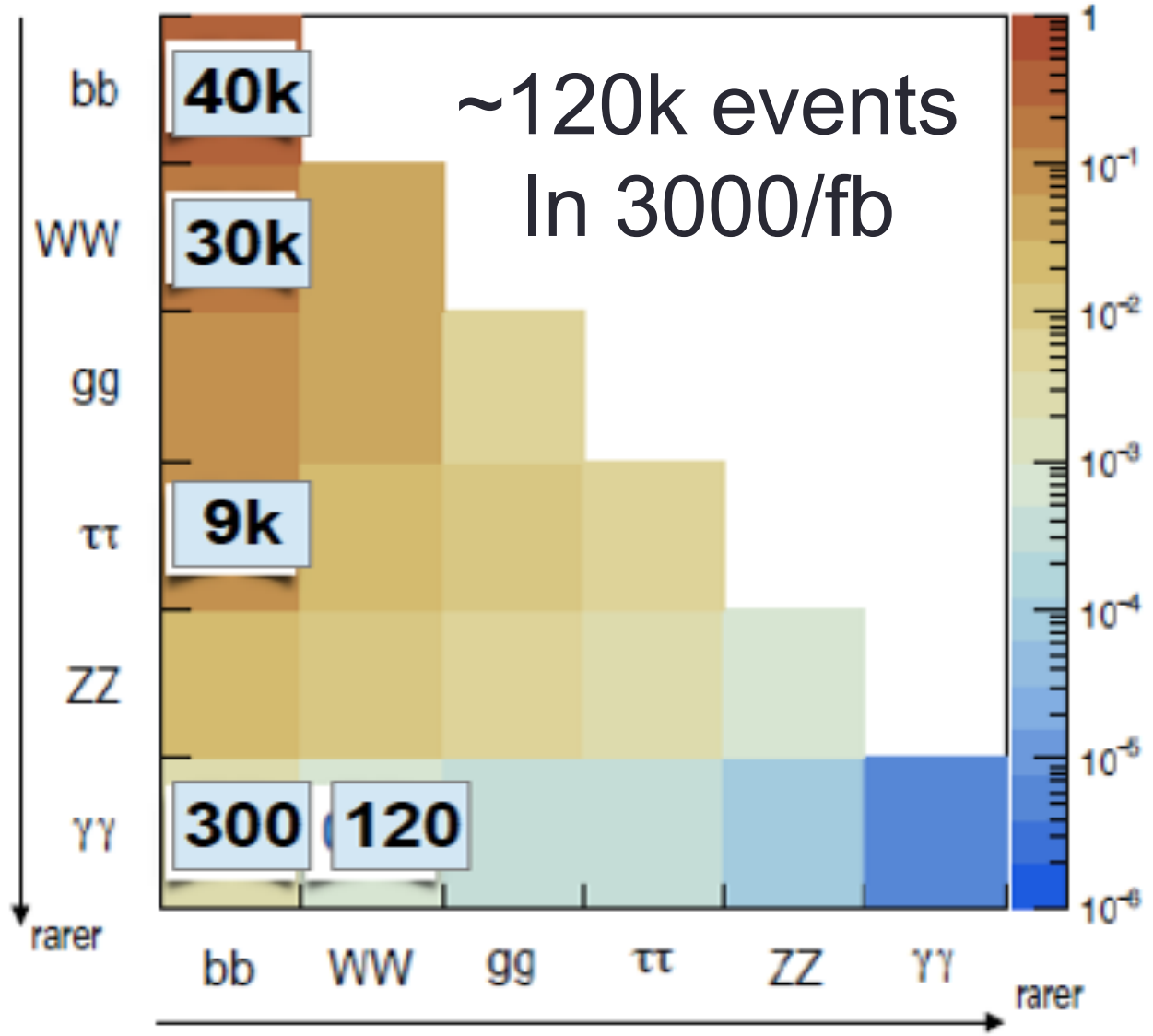
Higgs pair production at the HL-LHC

Expected number of events



- **Low yields** even at the HL-LHC
- Need to have at least a **bb pair** to have sufficient events
- Large background from **QCD and pile-up processes**

Higgs pair production at the HL-LHC

Expected significance

95% CL intervals

Final state	ATLAS	CMS
HH→bbγγ	1.05 σ $-0.8 < \kappa_\lambda < 7.7$	1.43 σ
HH→bbττ	0.6 σ $-4.0 < \kappa_\lambda < 12$	0.39 σ
HH→bbbb	$-3.5 < \kappa_\lambda < 11$	0.39 σ
HH→bbVV		0.45 σ
ttHH, HH→bbbb	0.35 σ	

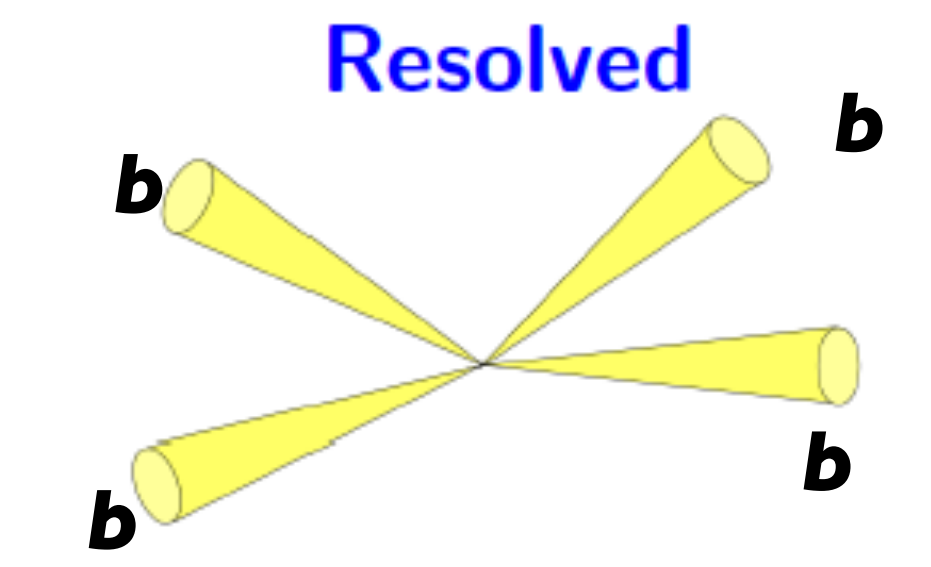
Extremely challenging measurement: **benchmark channel for HL-LHC program**

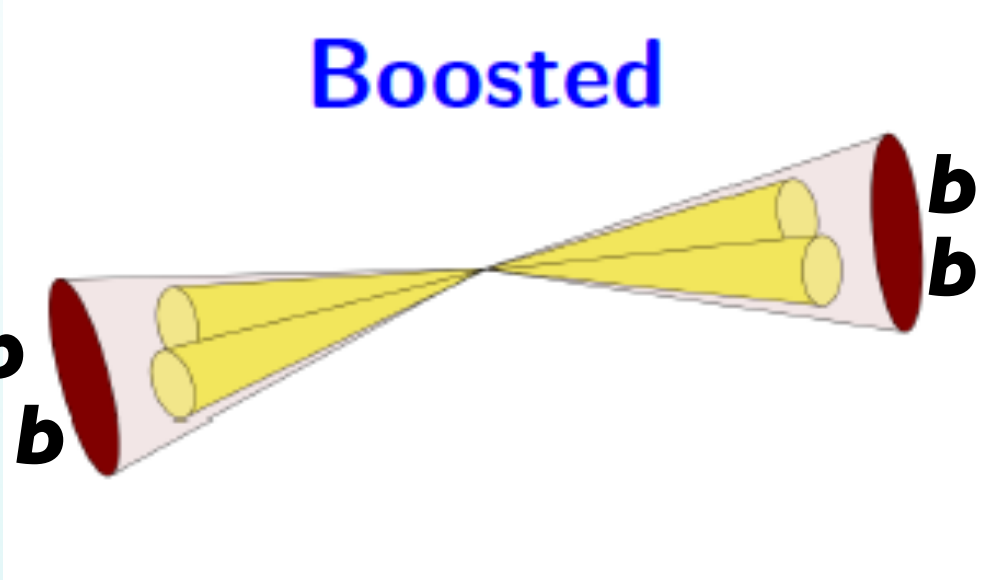
Room for improvement in **analysis algorithm**, **detector optimisation**, **theory calculations**

The 4b channel

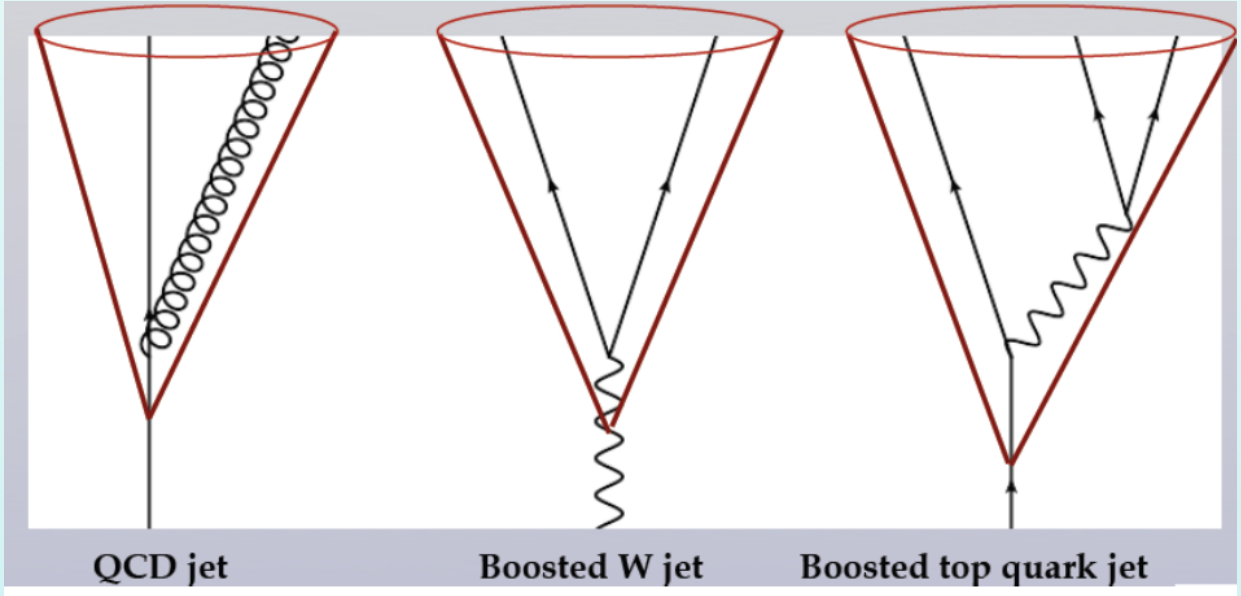
Bortoletto et al 15

- Exploit **4b final state**: highest signal yields, but **overwhelming QCD background** (by orders of magnitude!)
- Carefully chosen selection strategies ensure that **all relevant event topologies can be reconstructed**

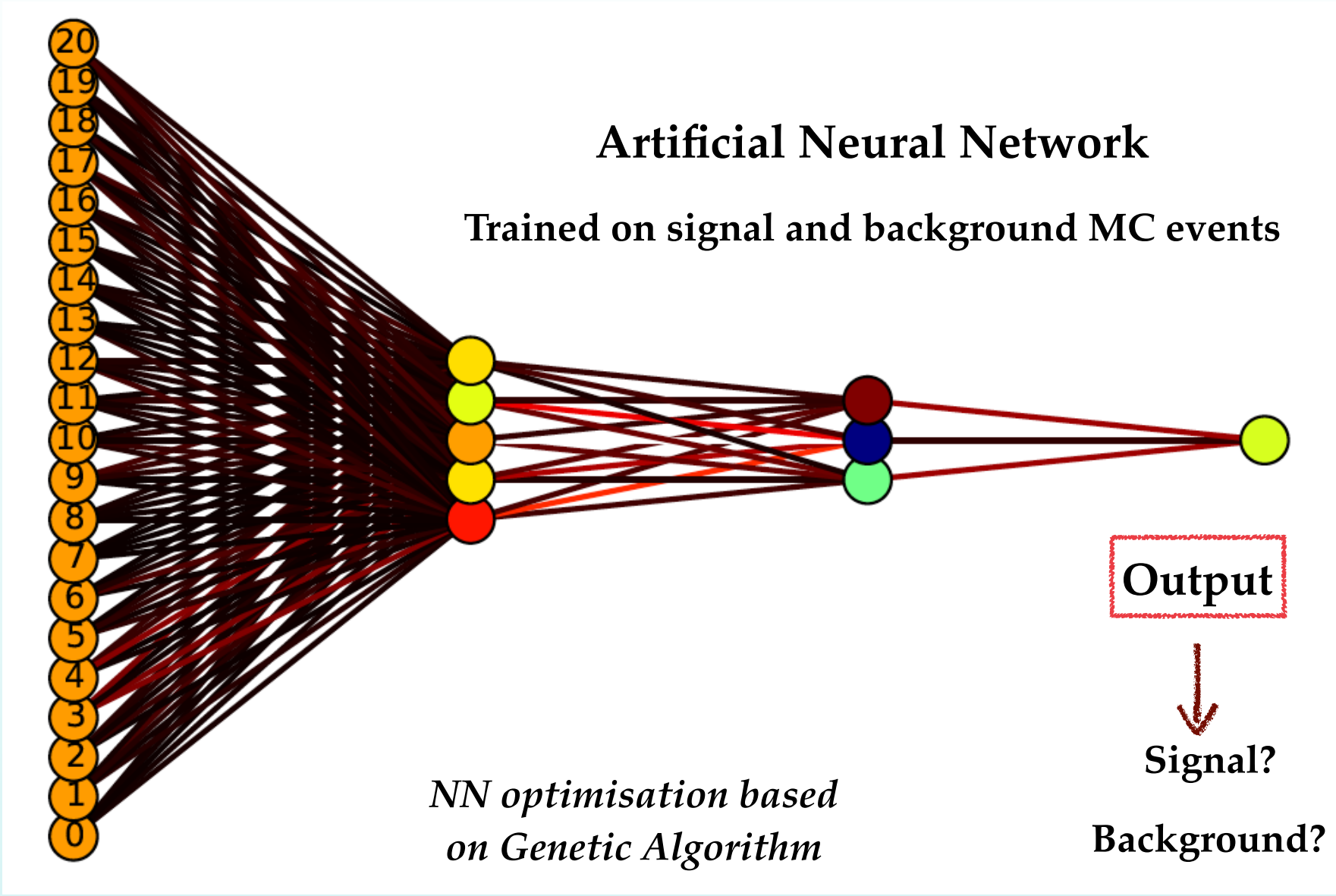




Recent progress in **jet substructure** techniques important to reduced QCD background in the **boosted regime**



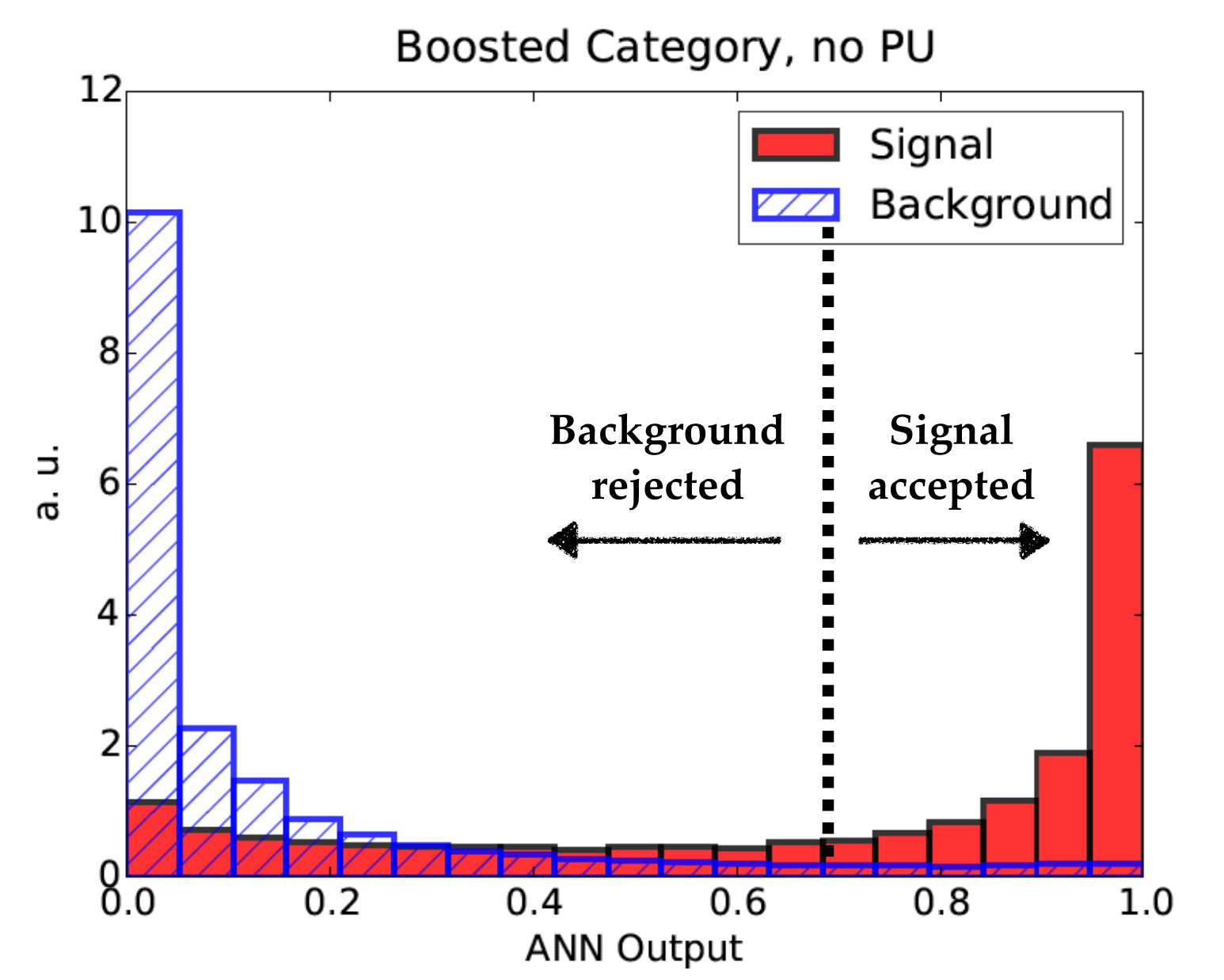
The 4b channel at the HL-LHC



Caveat: in a measurement, training of classifier should be done on ***real data based on control regions***

The 4b channel at the HL-LHC

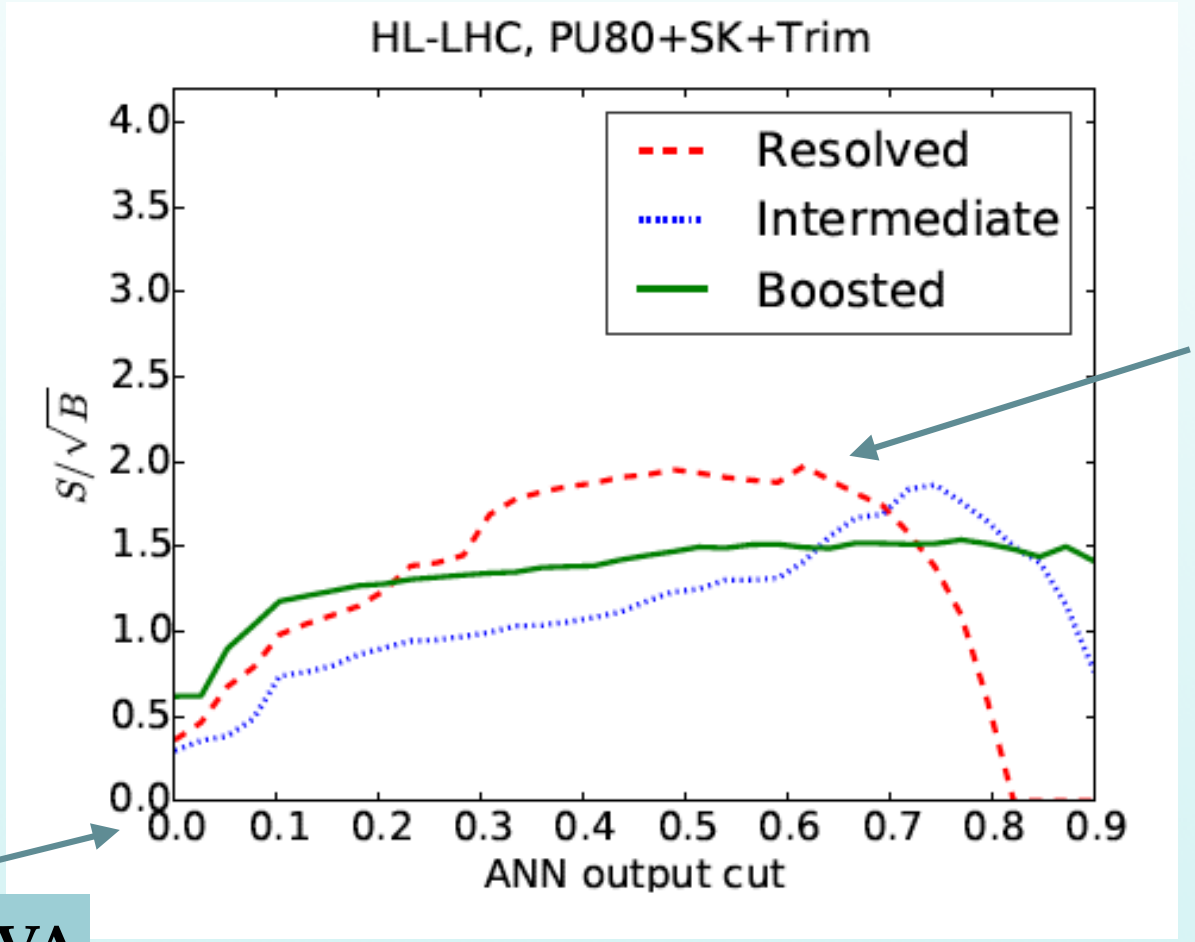
Combining information from all kinematic variables in MVA: **excellent signal/background discrimination**



The 4b channel at the HL-LHC

ML techniques allow to **substantially improve the signal significance** for this process **observe Higgs pair production in the 4b final state** at the HL-LHC. Observation (maybe discovery) within reach!

$$\left(\frac{S}{\sqrt{B_{4b}}}\right)_{\text{tot}} \simeq 4.7\ (1.5)\,, \quad \mathcal{L} = 3000\ (300)\ \text{fb}^{-1}$$



Post MVA

Pre-MVA

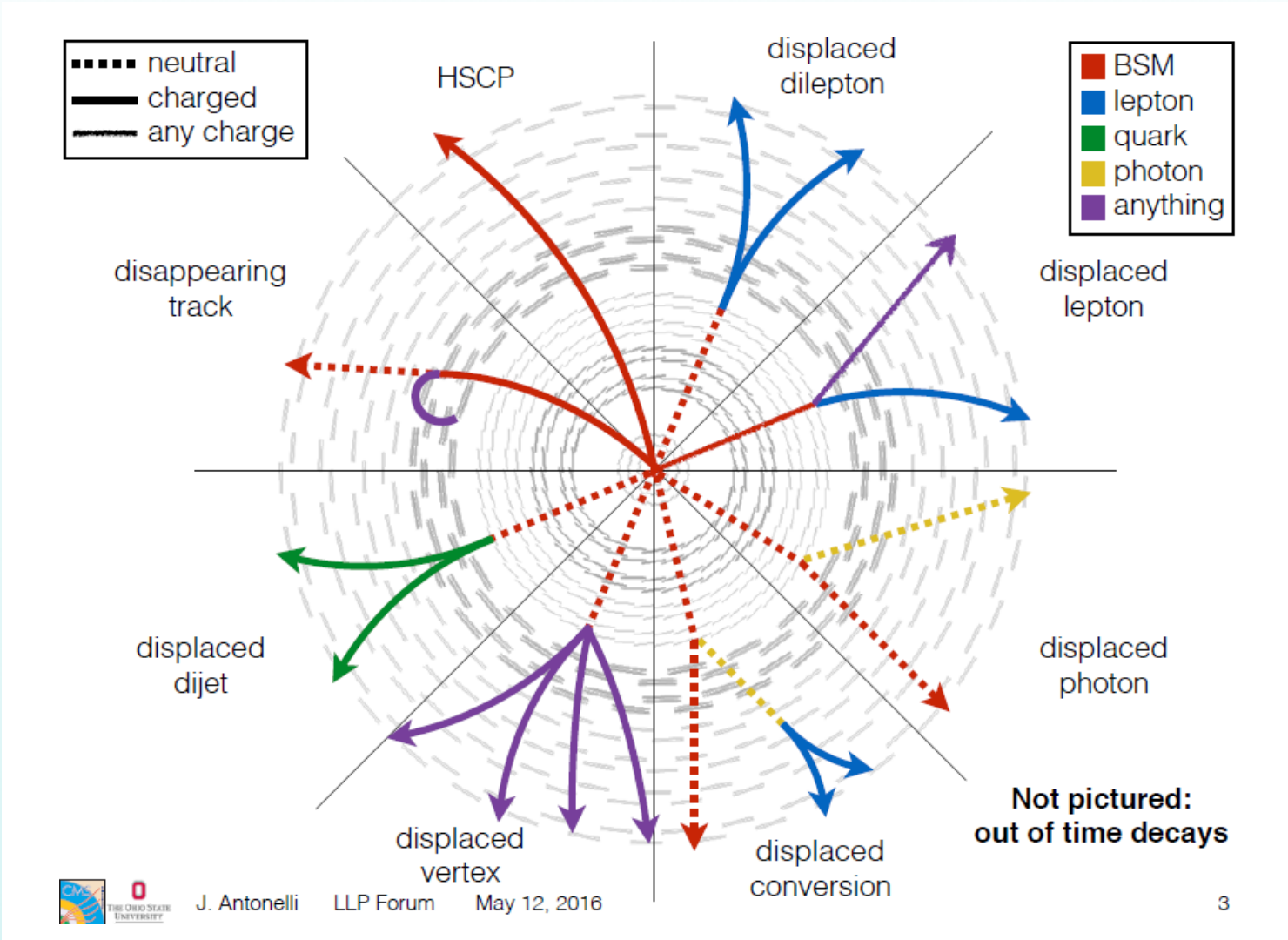
Illustrates powerful interplay of:

- **Advanced analysis algorithms** (Machine Learning)
- **Theory developments** (jet substructure, background suppression)
- **Detector optimisation**

Long-lived particles

LLPs appear in many BSM scenarios involving **Dark Sectors** such as **Hidden Valleys**

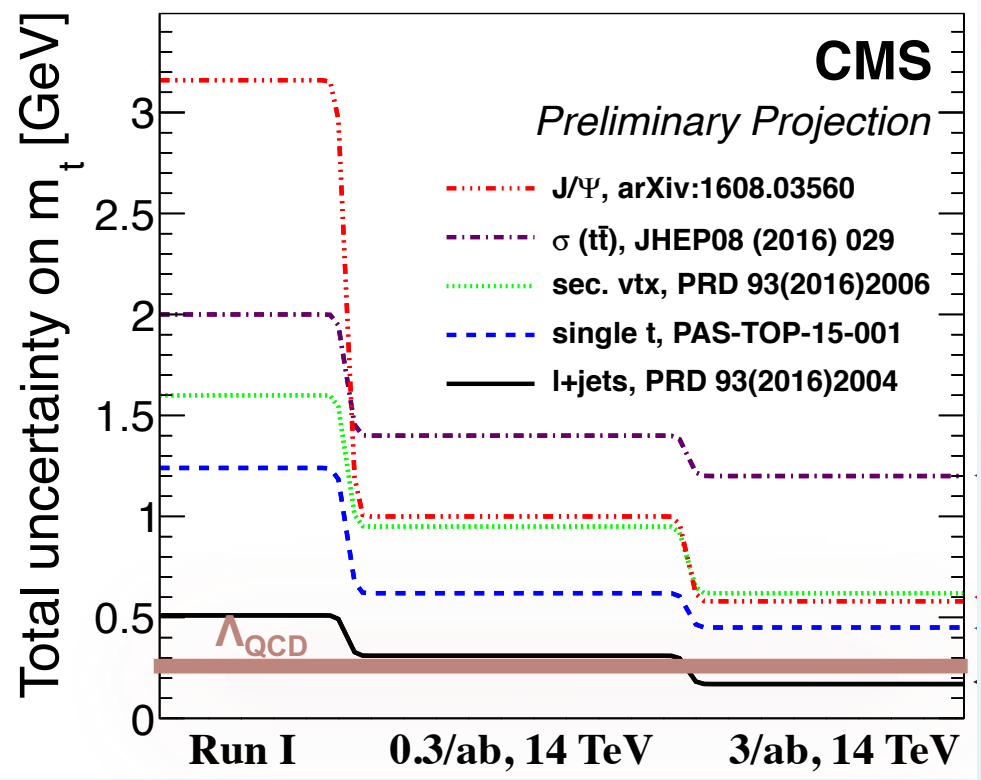
A very **clean signature:** a hidden sector particle decays within the detector volume

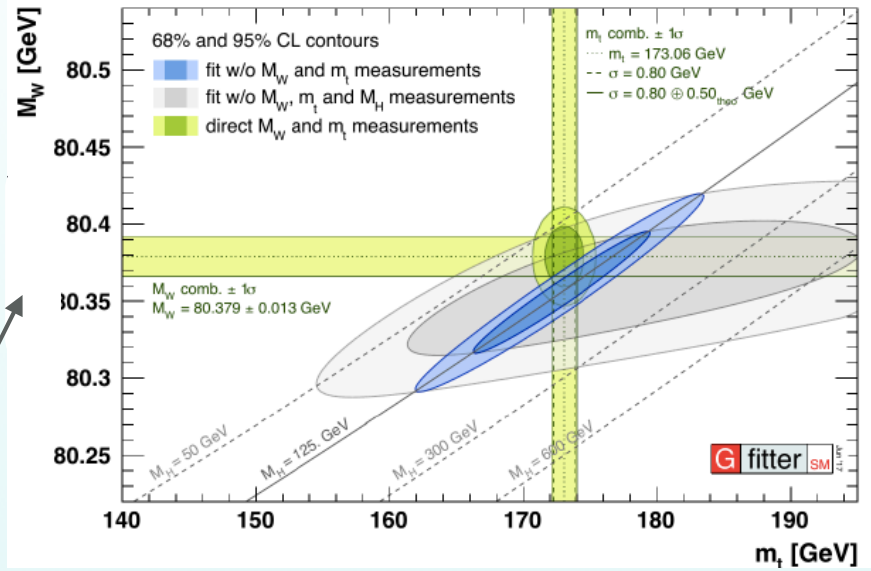


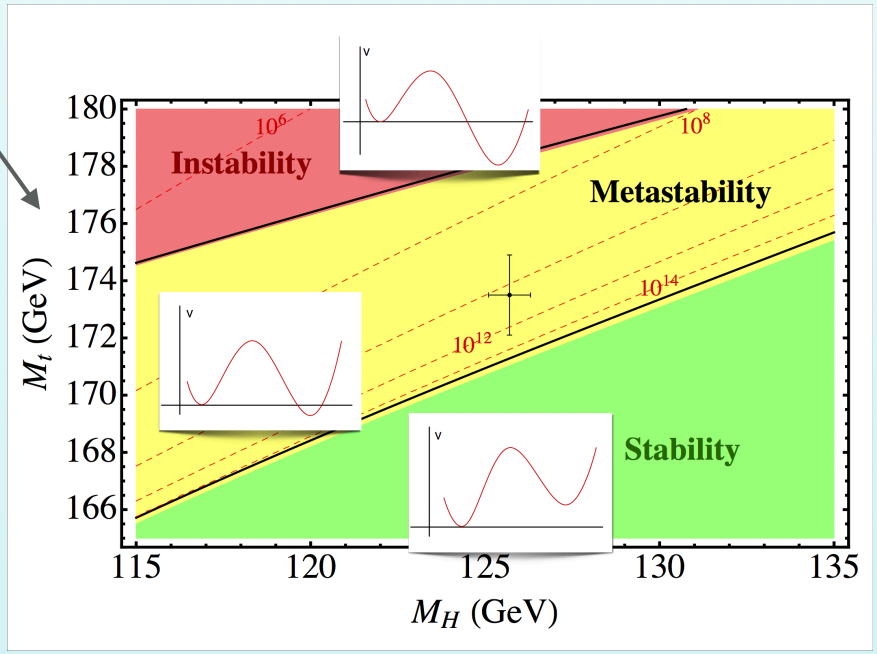
The increased luminosity of the HL-LHC will **strengthen the prospects for LLPs searches**

Precision SM physics

The precision measurement of fundamental SM parameters such as the **W boson** and the **top quark masses** offers a unique opportunity to **stress-test the Standard Model**





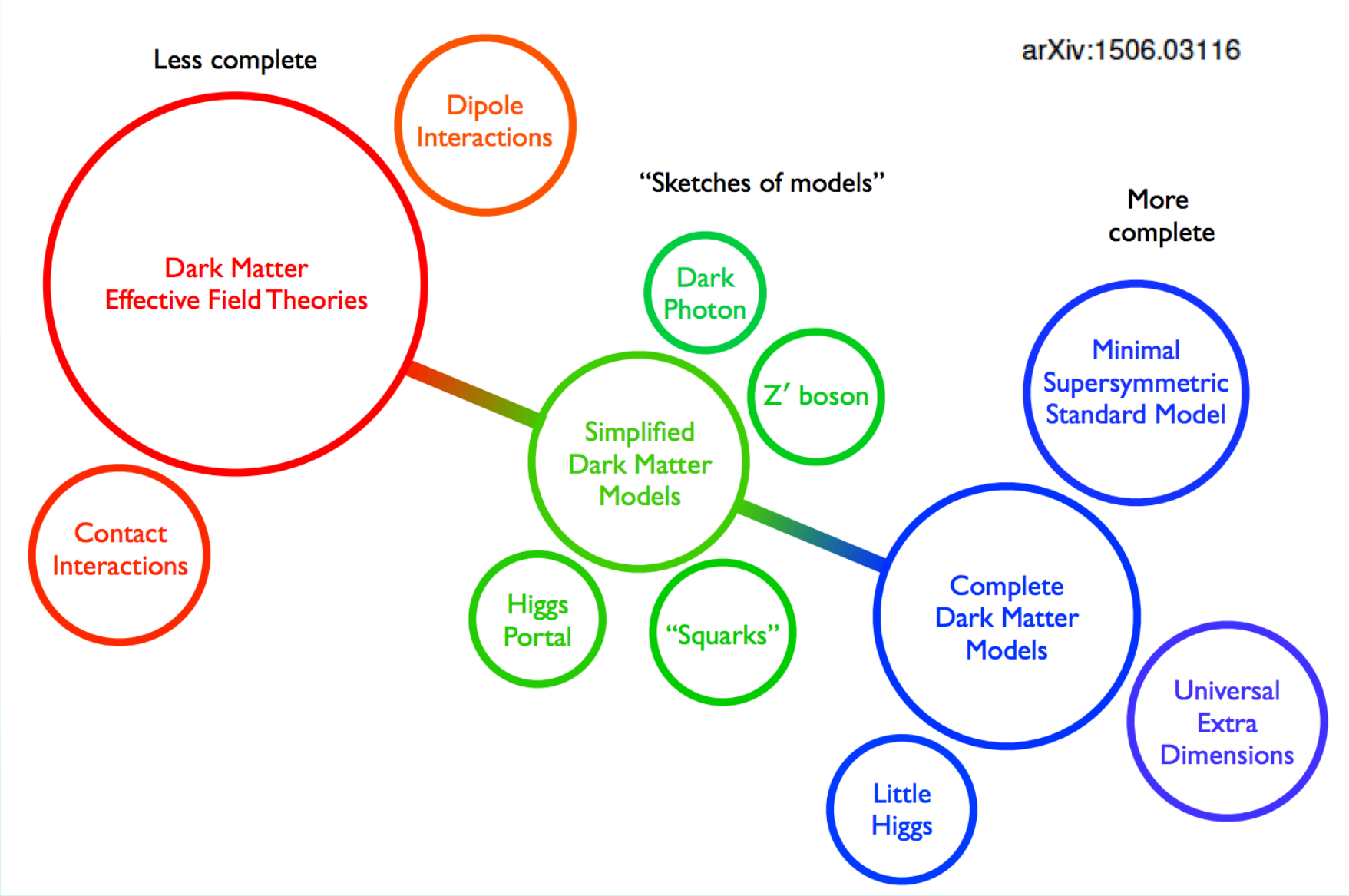


Connection to the apparent **metastability of the electroweak vacuum state** of our Universe

Dark Matter searches

Investigating the possible **production of DM particles** is high on the HL-LHC physics program

Large theory space with still plenty of room for **constraints from colliders**



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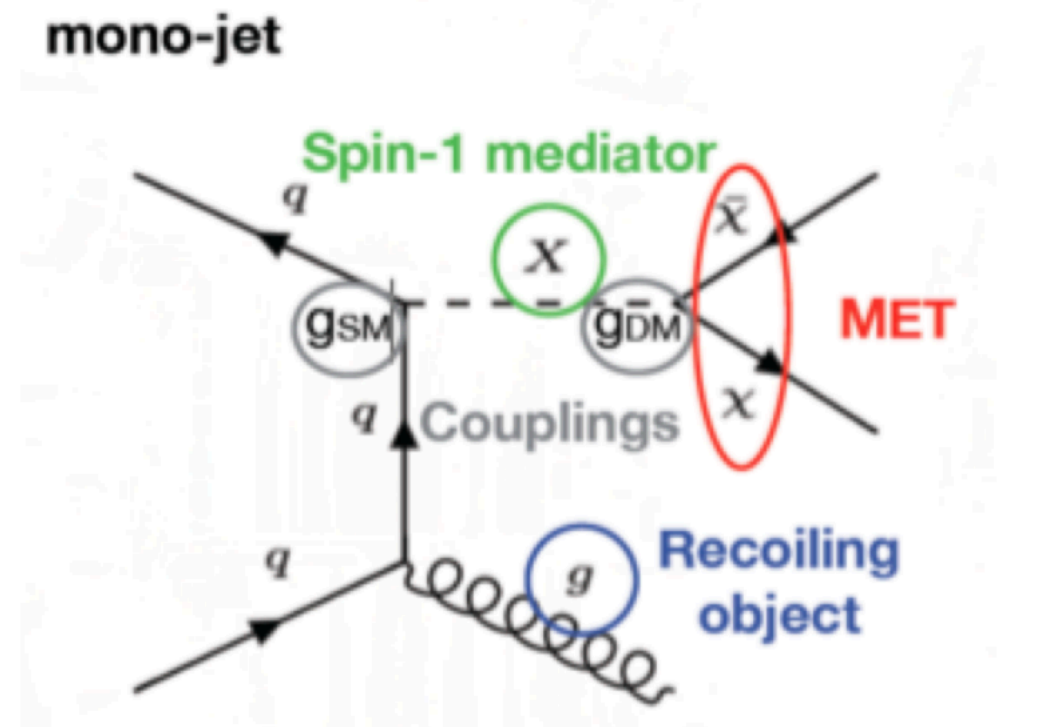
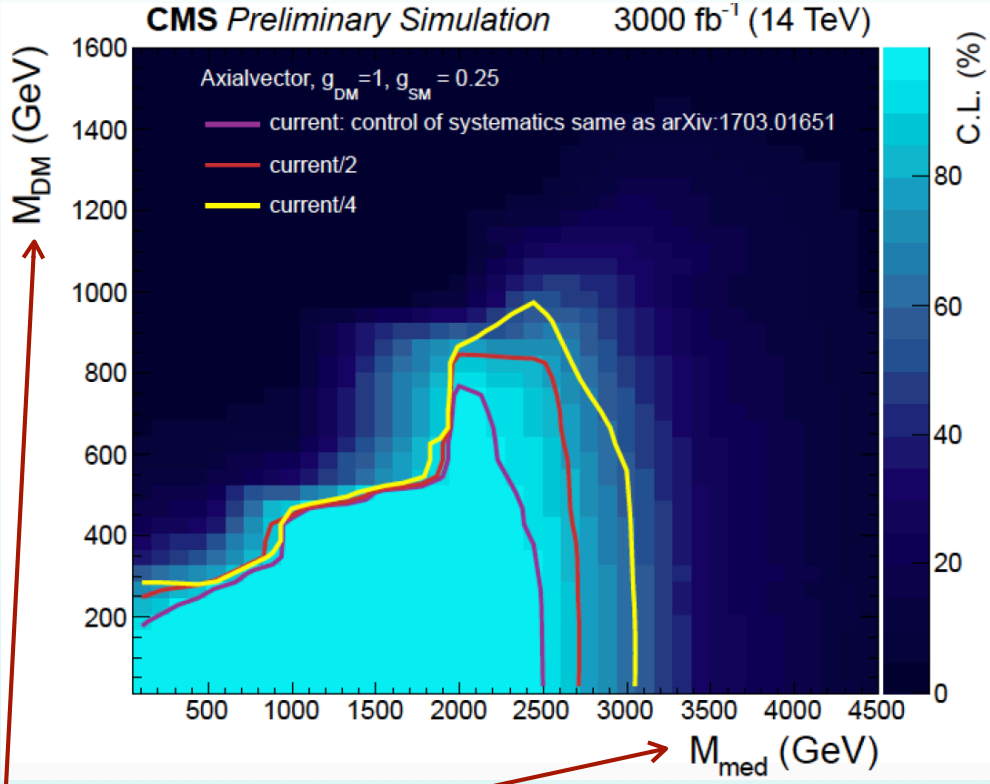




``Monojet signature'':
An unbalanced jet with missing transverse energy

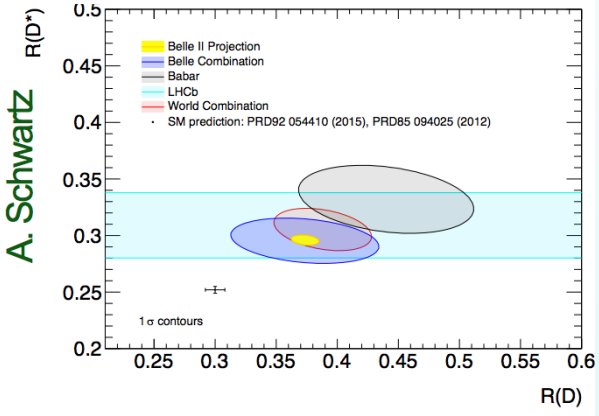
DM particle mass

Mediator particle mass (connects dark and visible sectors)

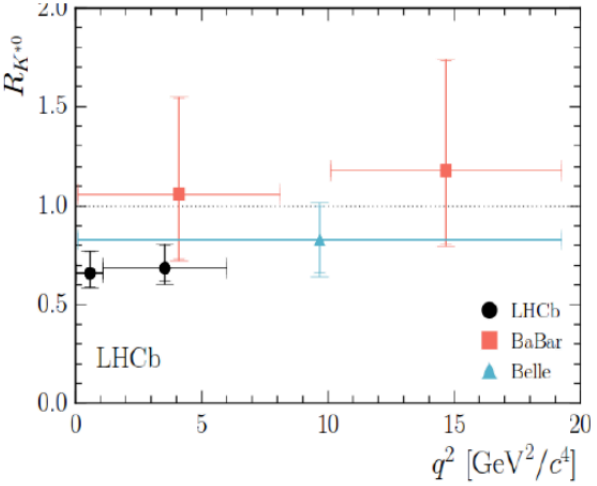
Flavour and the B anomalies

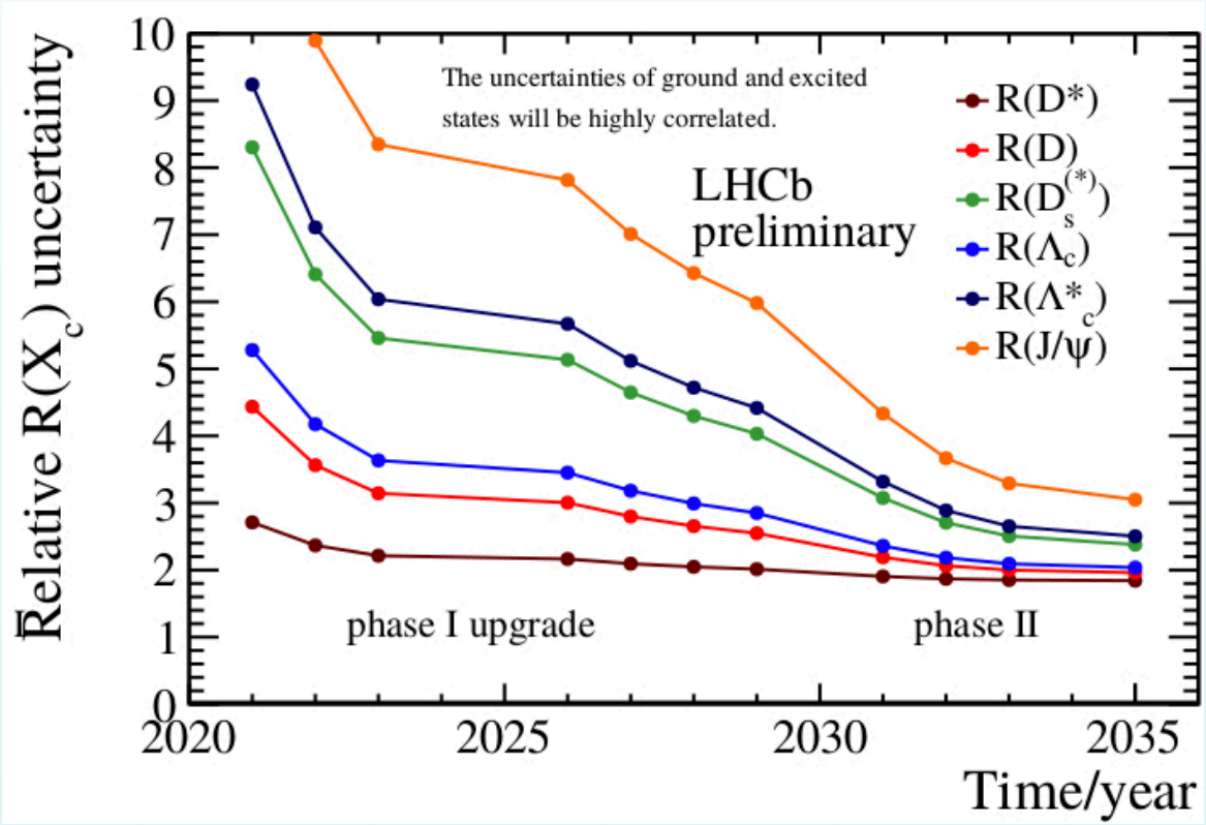
The HL-LHC will improve the **measurements of B-meson decays** where current hints of **violation of Lepton Flavour Universality** (LFU) have been reported

$$R^{\tau/\ell}_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$



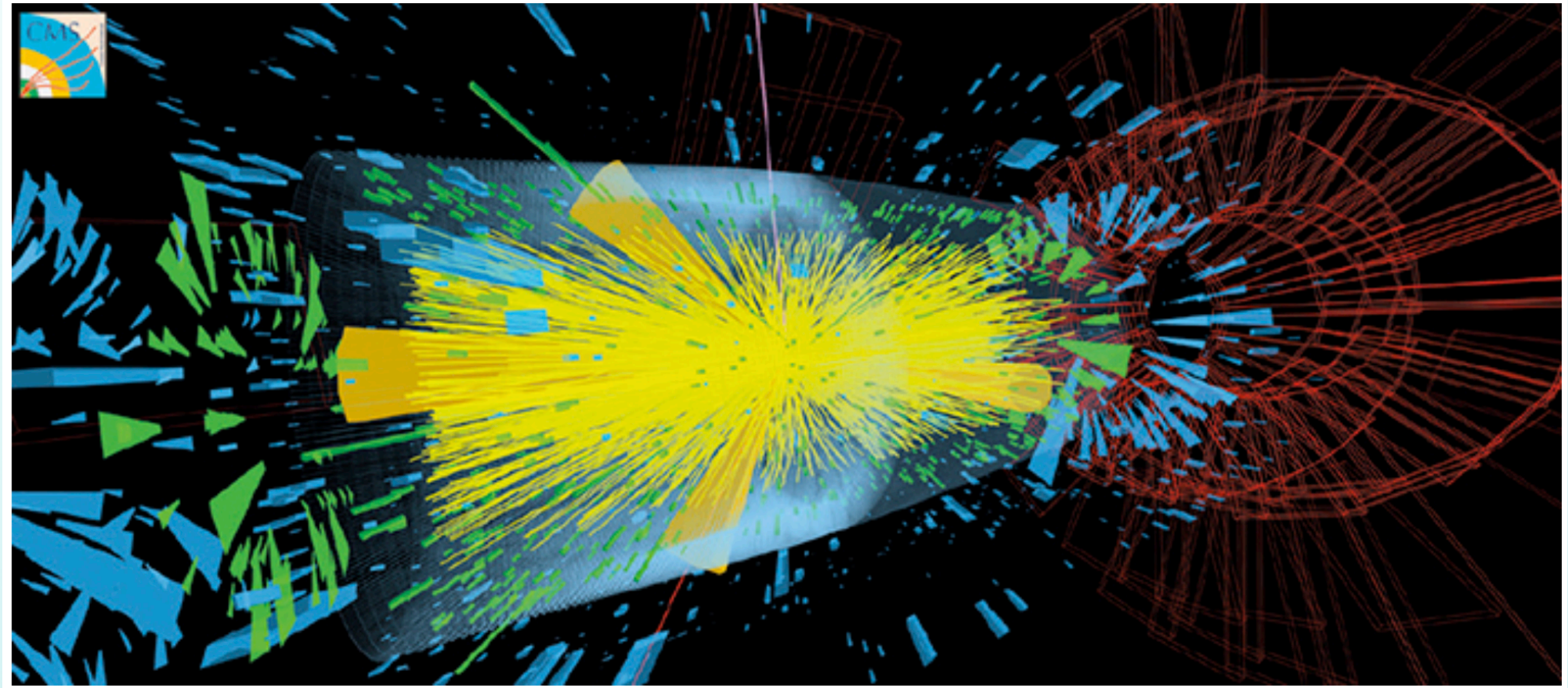
$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

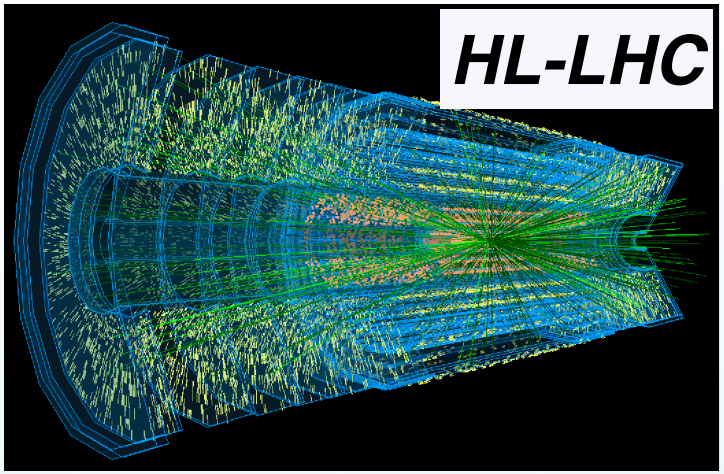




HL-LHC wrap up

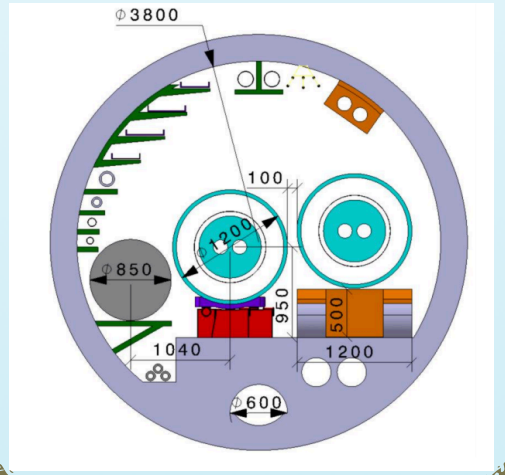
- ☑ HL-LHC is **much more** than ``just'' ten times more LHC data
- ☑ **Extremely broad range of exciting physics topics**, which significantly enhance the overall physics output of the LHC: exotic Higgs decays, Higgs pair production, DM searches, precision SM, flavour physics ….
- ☑ Plenty of exciting physics to **keep us very busy until at least 2035!**



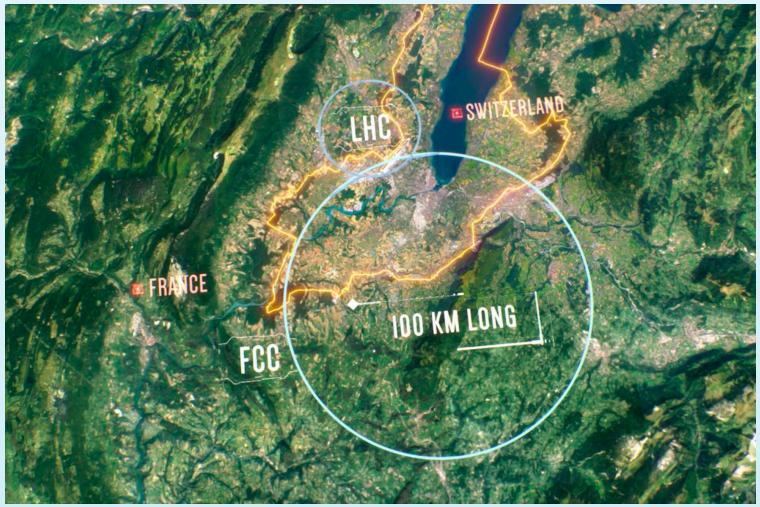


Future High-Energy Hadron Colliders

HE-LHC



FCC-hh

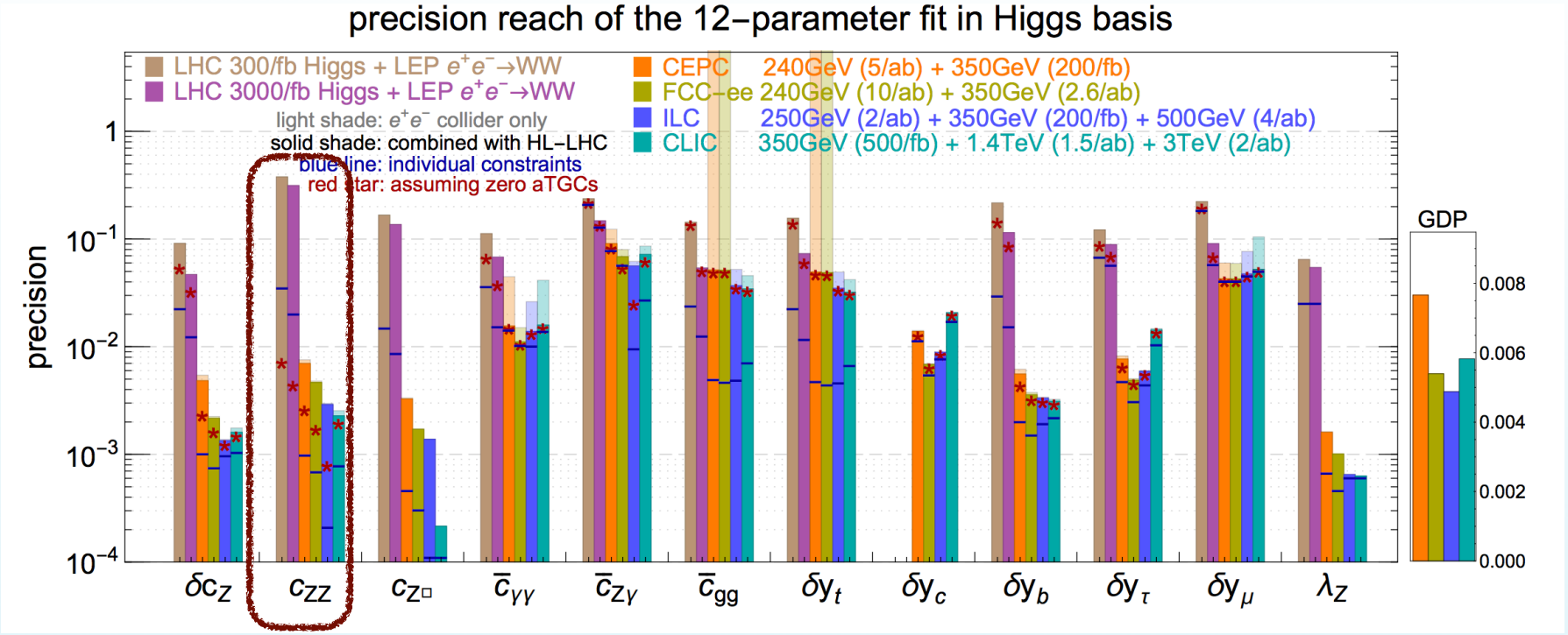


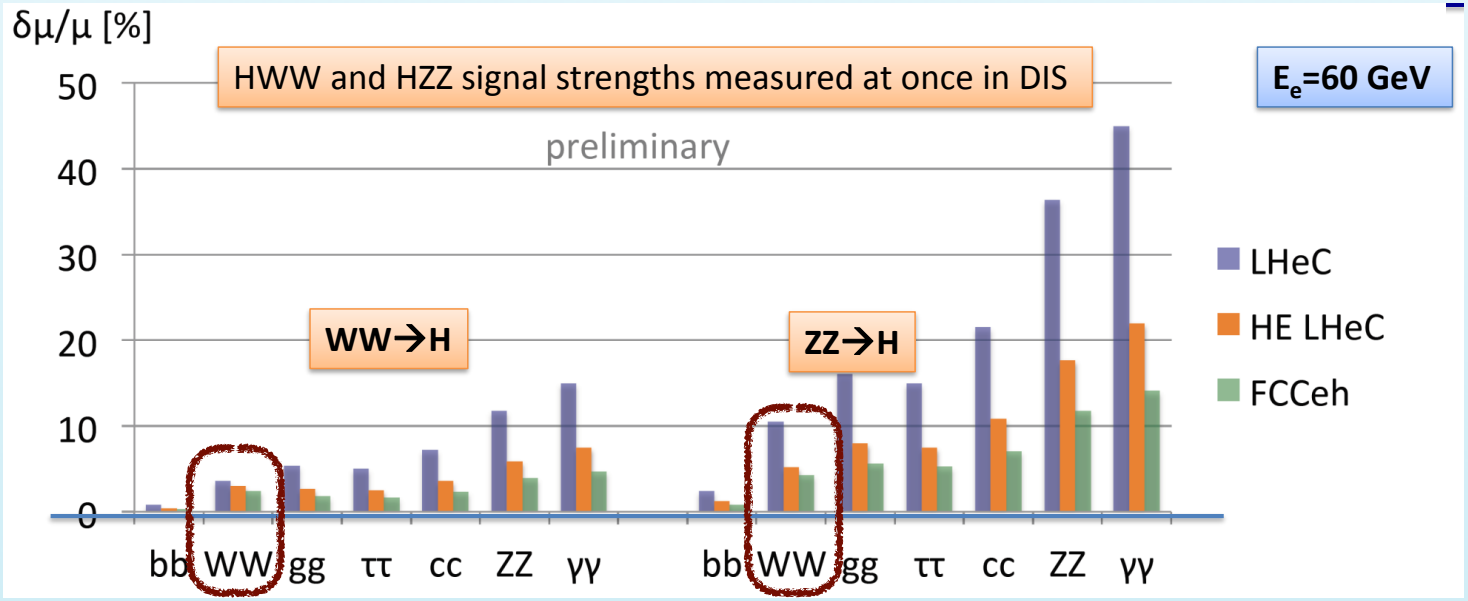
The High-Energy LHC project

- In a nutshell, increase the **CoM energy to 27 TeV** by fitting the FCC-hh magnets in LHC tunnel
- Pros: **doubles LHC energy**, significant **increase of integrated luminosity**, **affordable cost** (within CERN budget)
- Target luminosity: up to **5 times that of HL-LHC**
- Cons: moderate energy increase, **limited exploration potential** at very high energies
- Physics potential being studied now: **Yellow Report** expected by the end of the year

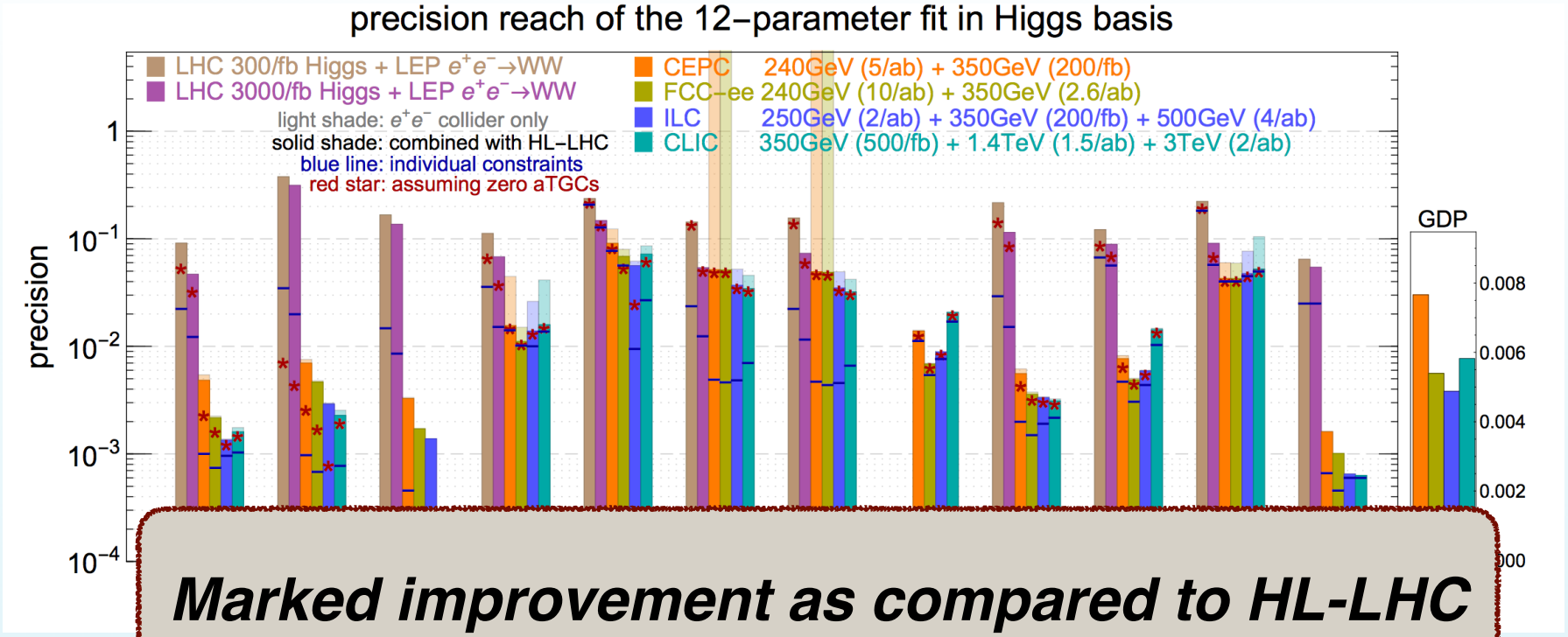
parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1 (0.5)		2.2	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		25 (12.5)	25
norm. emittance $\gamma\varepsilon_{x,y}$ [μm]	2.2 (2.2)		2.5 (1.25)	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	30	25	(5) 1

Higgs Physics at the HE-LHC

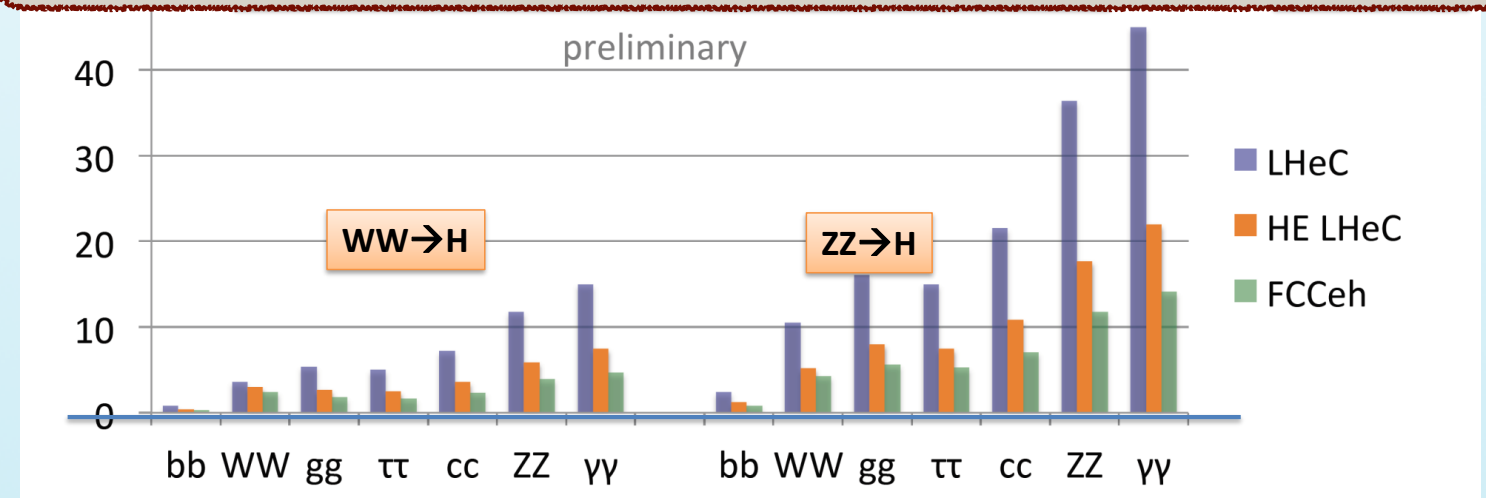




Higgs Physics at the HE-LHC



Marked improvement as compared to HL-LHC
Still not competitive with Higgs factories



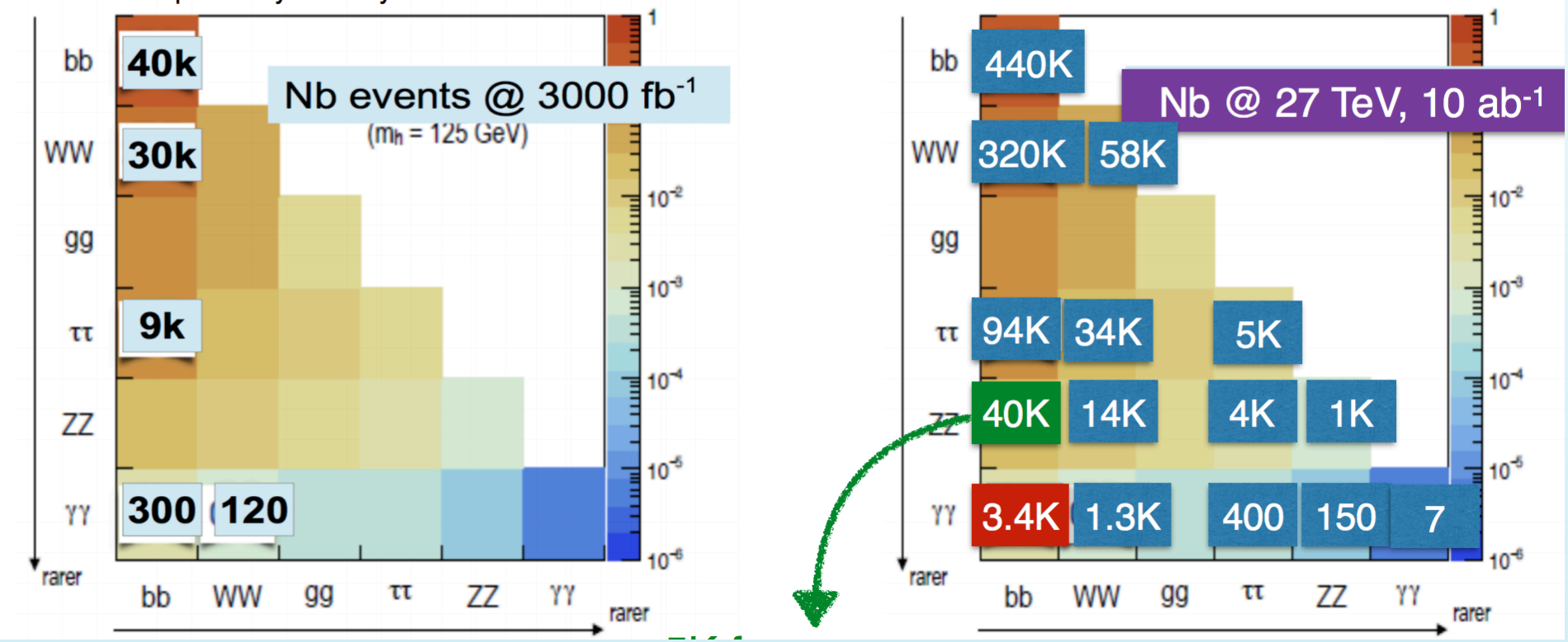
Higgs Physics at the HE-LHC

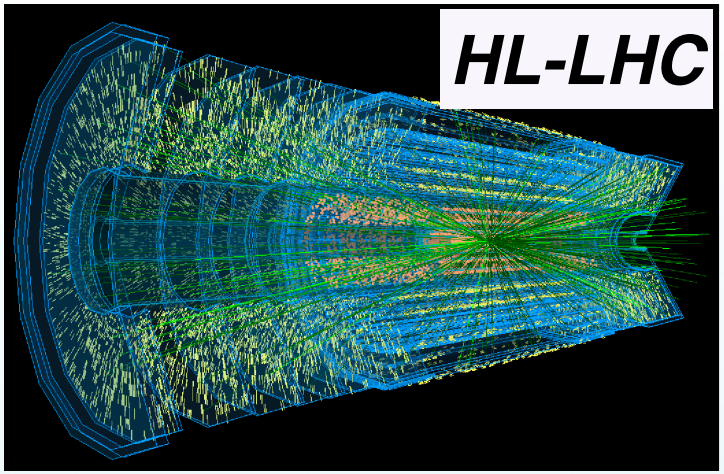
- Double Higgs production **benefits dramatically from the increase in energy**, with a factor 10 increase in events and several new final states opening up

- Channels **without bottom quarks in the final state** become competitive

Double Higgs production @ HE

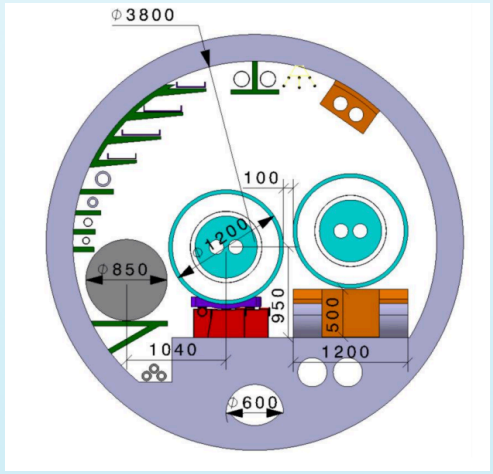
From S. Jezequel talk yesterday



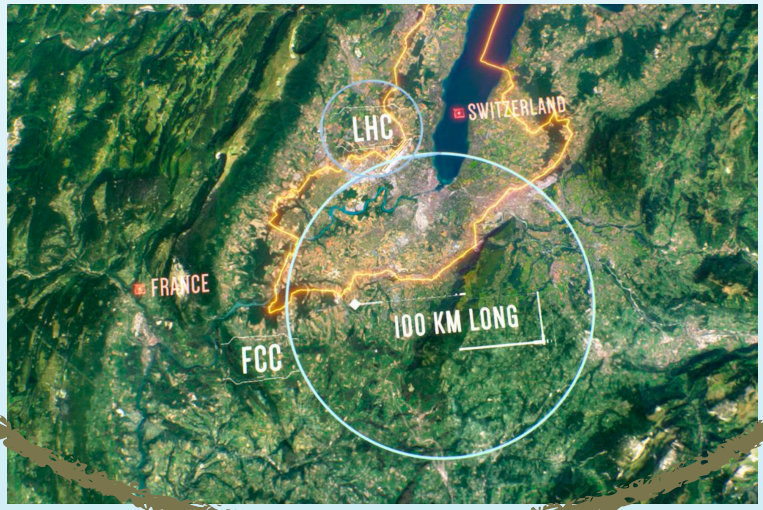


Future High-Energy Hadron Colliders

HE-LHC



FCC-hh

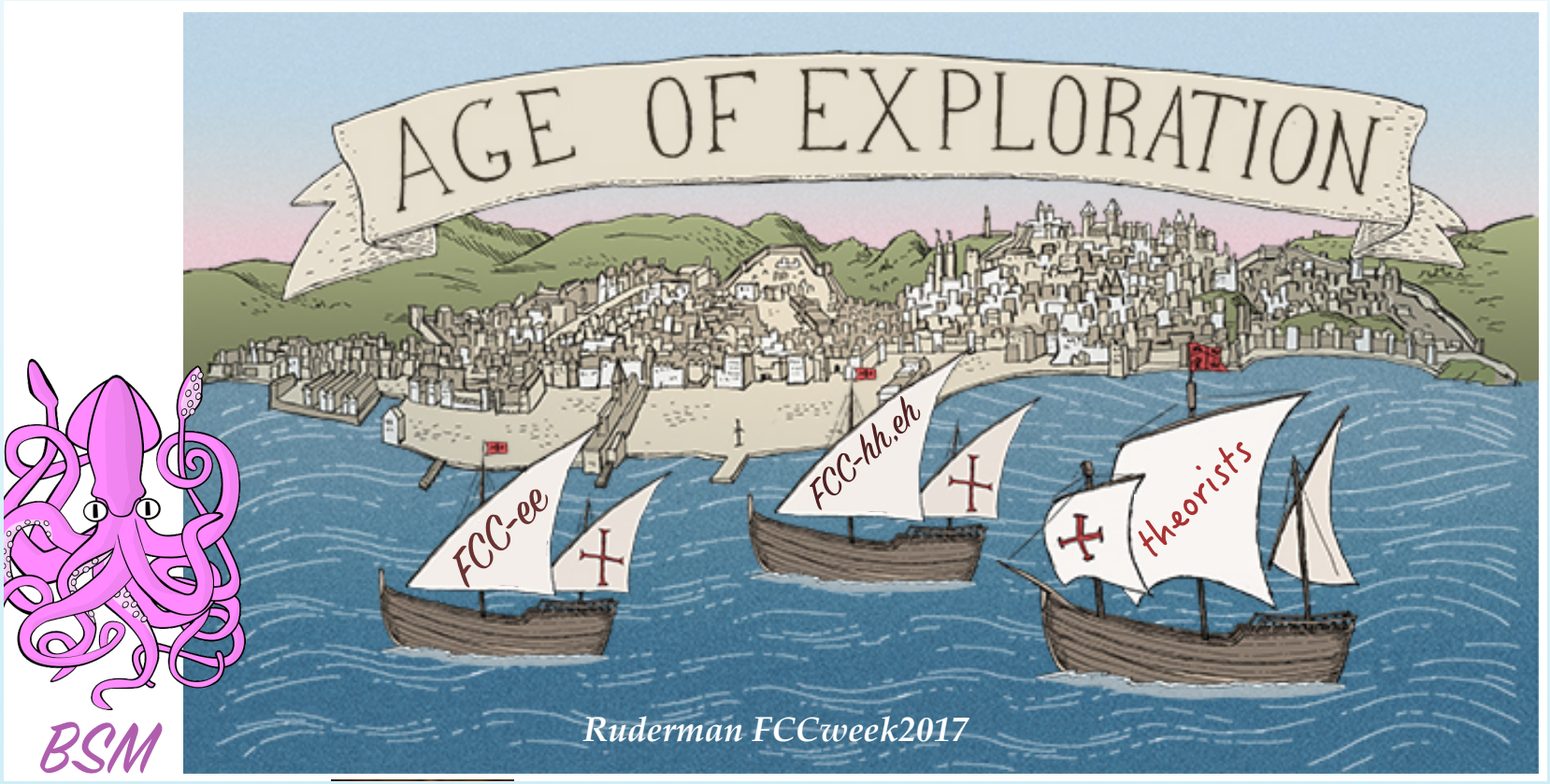


The case for a 100 TeV hadron collider

- ☑ The study of the Standard Model and the Higgs sector cannot be considered as complete until we exhaust the **exploration of phenomena at the TeV scale**

- ☑ No other machine can have a comparable **direct sensitivity to such large mass scales** than a 100 TeV hadron collider

- ☑ **Several guaranteed deliverables**, but scientific case needs to be strengthened by pursuing results in sync at the **future LHC runs**, **dark matter searches**, **flavour physics** …



FCC-hh as a Higgs factory

The **FCC-hh** would be a **Higgs factory**, with huge amounts of Higgs bosons produced

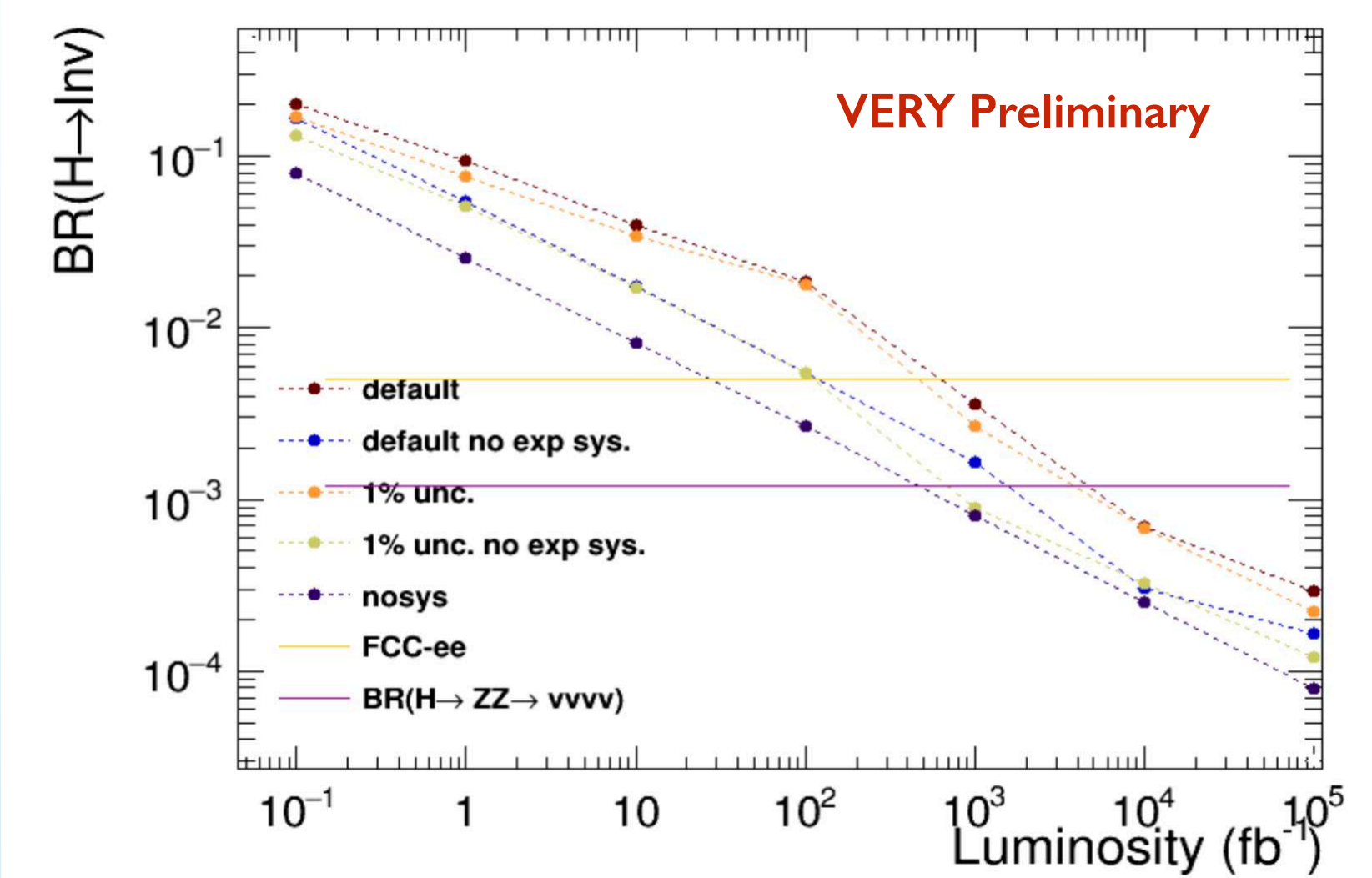
	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

What we can do with these **huge samples of Higgs bosons?**

- Explore tails of **kinematical distributions** more sensitive to BSM, *e.g.* **high pT**
- Reduce stats to place **more stringent selection cuts** to reduce backgrounds and systematics
- Explore **new decay modes, as well as exotic decays** (SM and BSM) with very small branching fractions

Rare and exotic Higgs decays

We can also access rare Higgs decays, such as **Higgs decaying into invisible (DM?) particles**

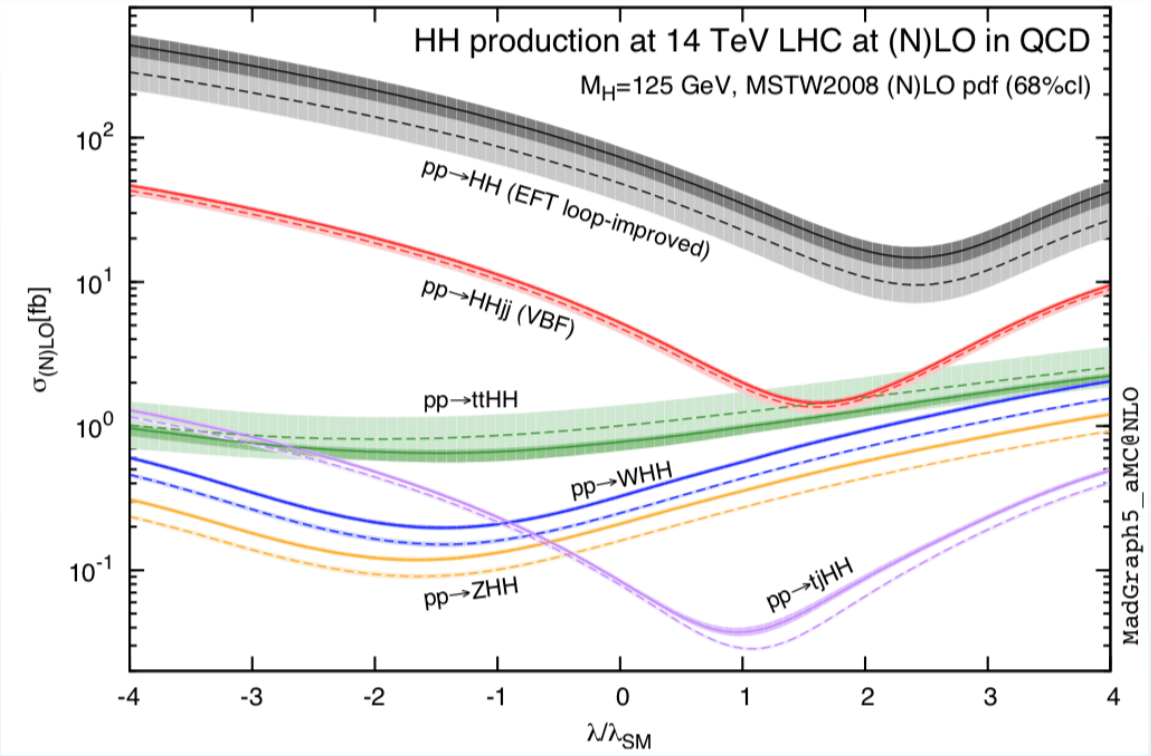


Data-driven background constraints on **ZZ => neutrinos** using **NNLO QCD + NLO EW theory**

With L = 30 ab^{-1} one can **constrain invisible Higgs decays at the O(10^{-4}) level**

The Higgs self-coupling at 100 TeV

- Main advantage over other machines: **energy and statistics**
- But needs to exploit final states which are not background-dominated
- The **bbγγ final state** appears the more competitive due to small backgrounds: **few-percent determination of the Higgs self-coupling** within reach
- The fully hadronic final state (4b) is not competitive due to **huge backgrounds**



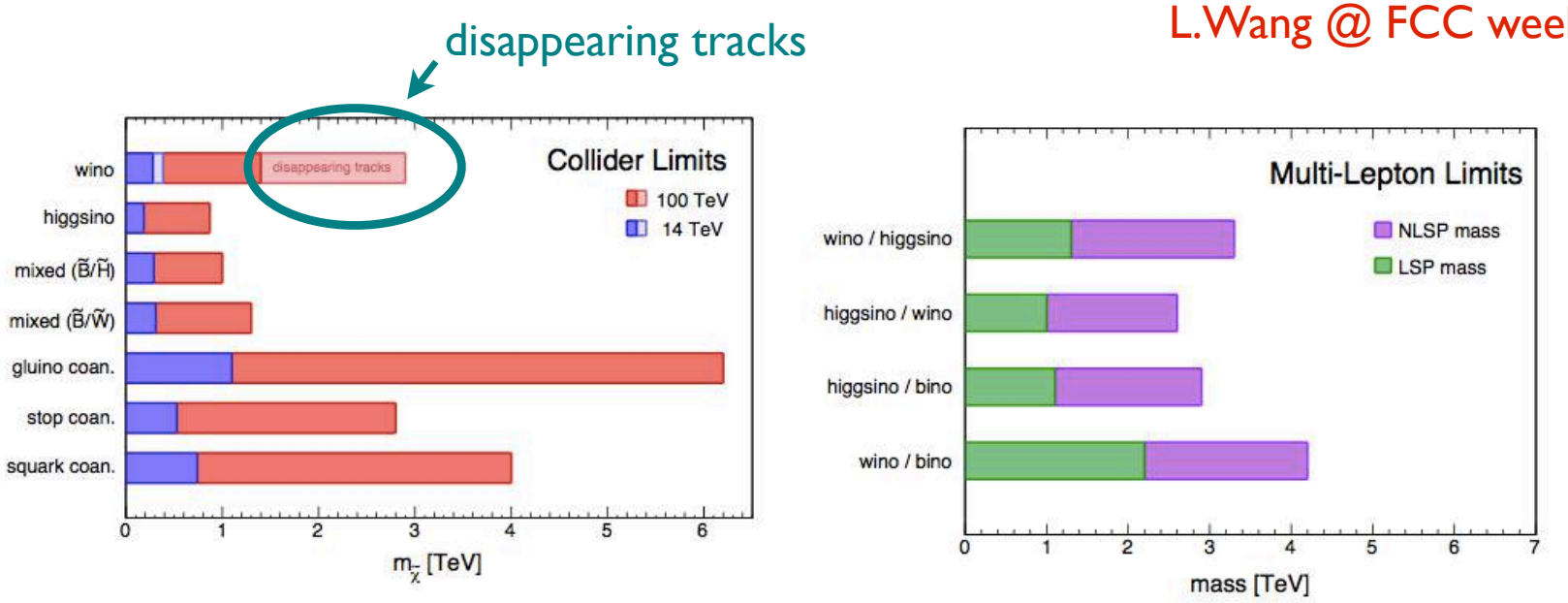
process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

Dark Matter at 100 TeV

A 100 TeV hadron collider would provide ``**no-lose theorems**'' for specific scenarios of WIMP dark matter, in particular **upper bounds of the WIMP mass**

WIMP searches at colliders

L.Wang @ FCC week



$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

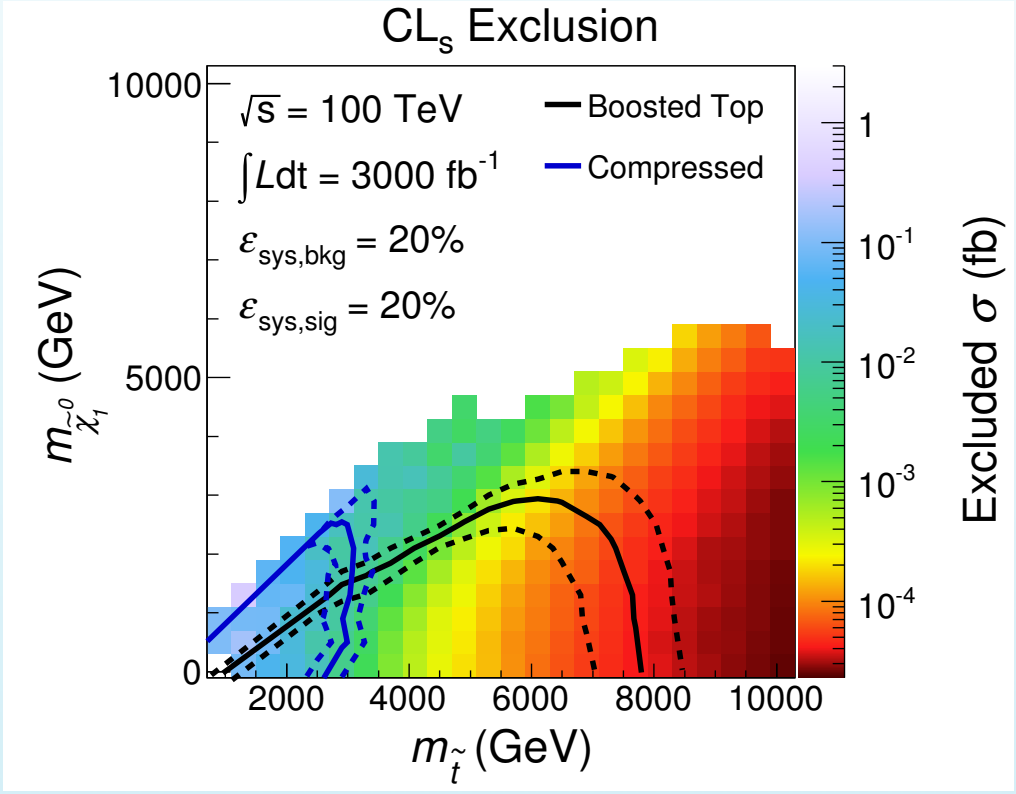
100 TeV pp collider will probe TeV WIMP very well.

Direct searches for heavy particles

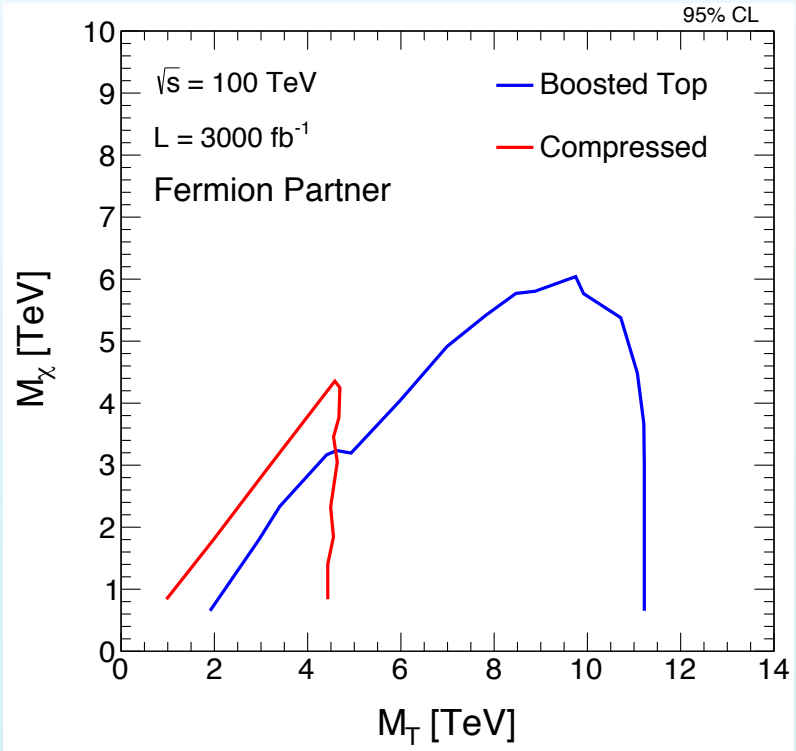
A 100 TeV hadron collider can extend the **reach for new BSM particles** above **the 10 TeV scale**

No other machine can compete with this **direct reach**

Scalar top partners



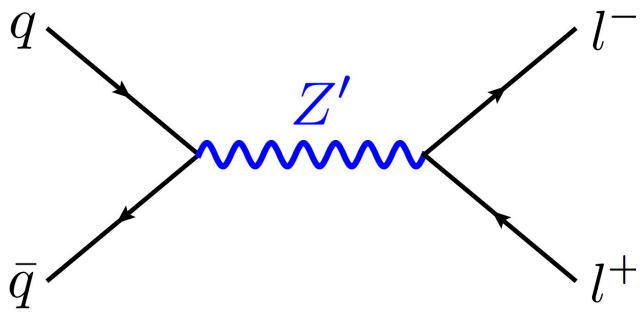
Fermionic top partners



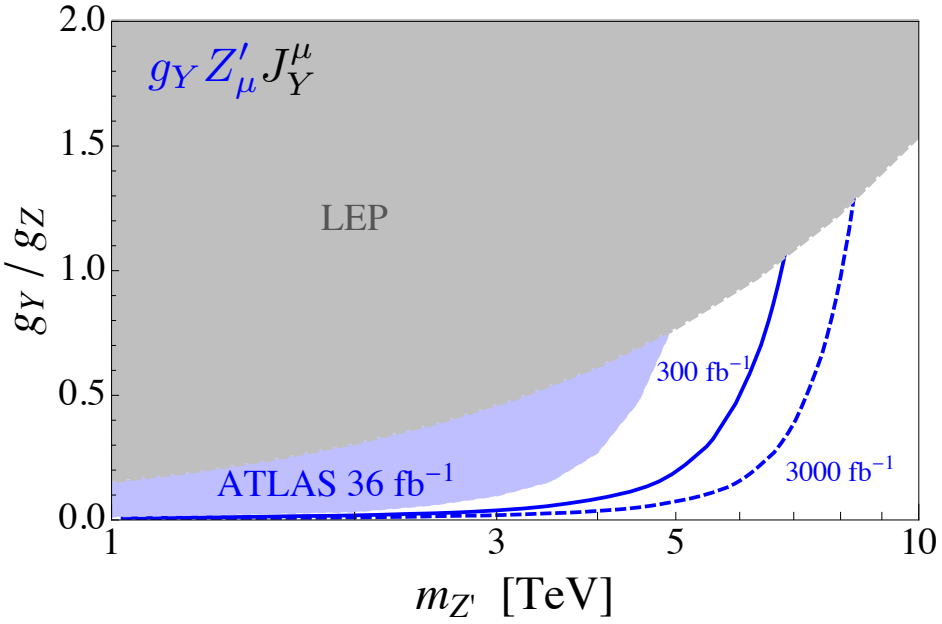
New fundamental interactions

If **new fundamental interactions** arise at high energies, then the FCC-pp could pin them down

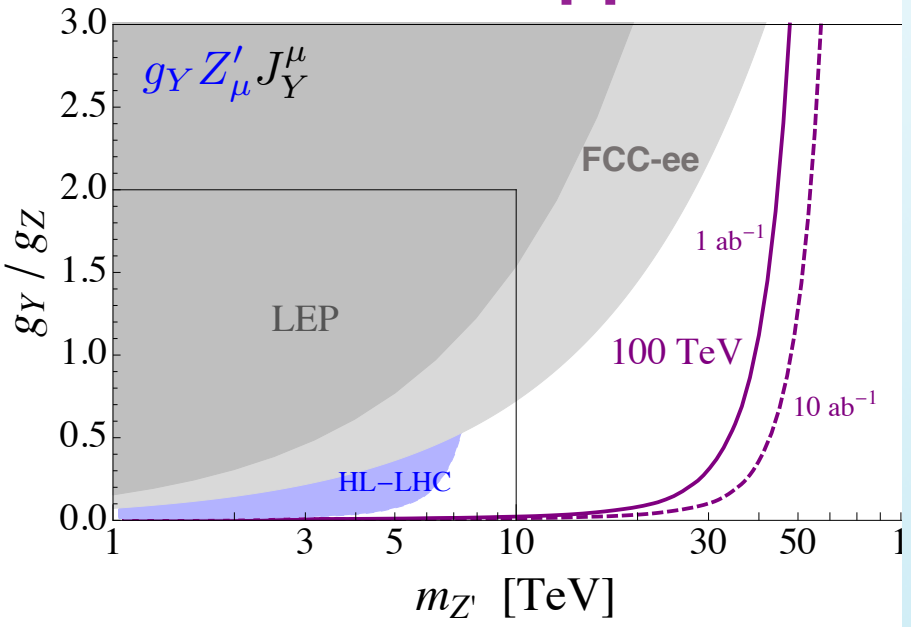
Depending on the interaction strength, sensitivity to a **new Z' boson of up to 50 TeV**

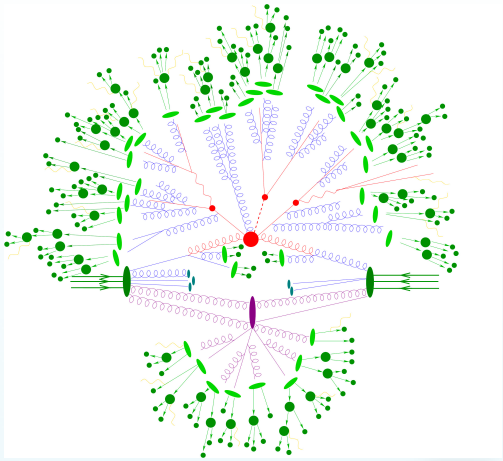


LHC

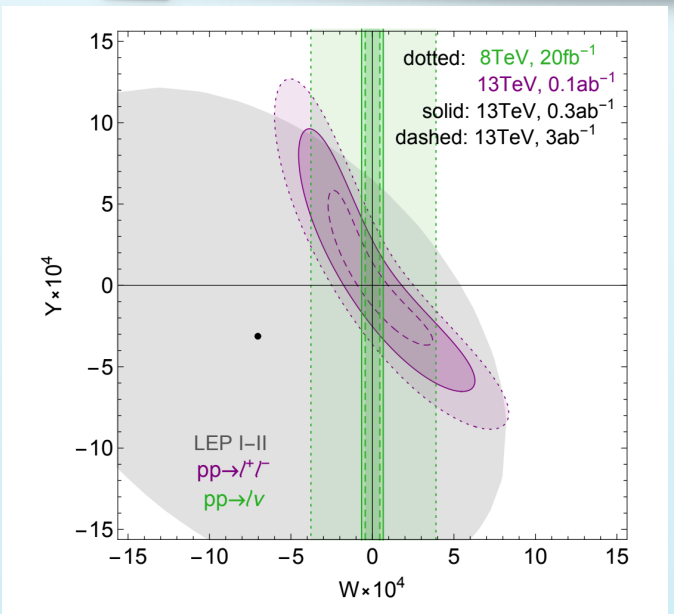


FCC-pp





The cosmic connection: neutrino telescopes, cosmic rays, gravitational waves



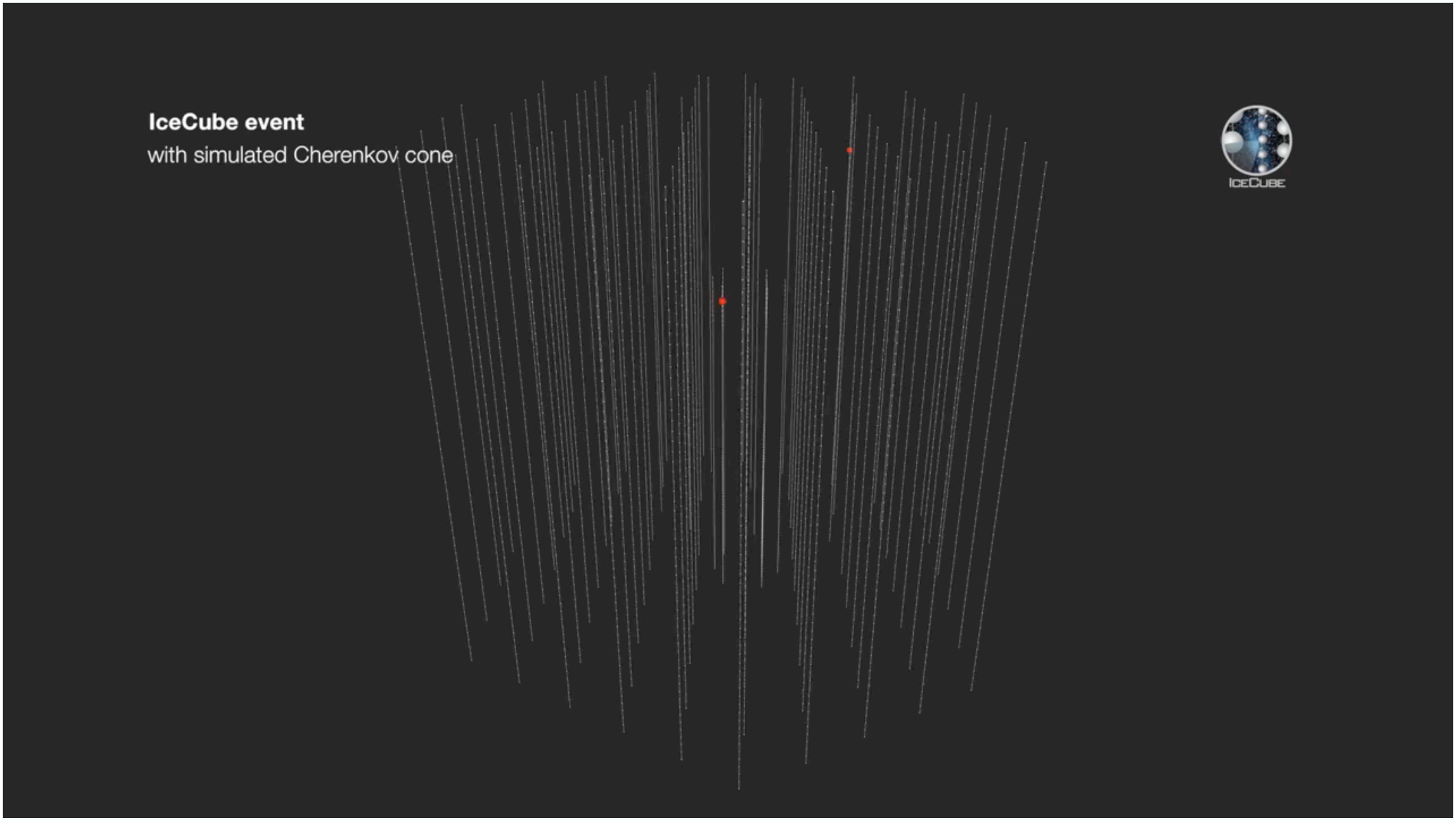
the neutrino universe

Observation of ultra-high energy (UHE) neutrino events at **IceCube** heralds start of **neutrino astronomy**

*Neutrinos are not **deflected or attenuated**: unique probes of extreme astrophysical events*

the neutrino universe

Observation of ultra-high energy (UHE) neutrino events at **IceCube** heralds start of **neutrino astronomy**



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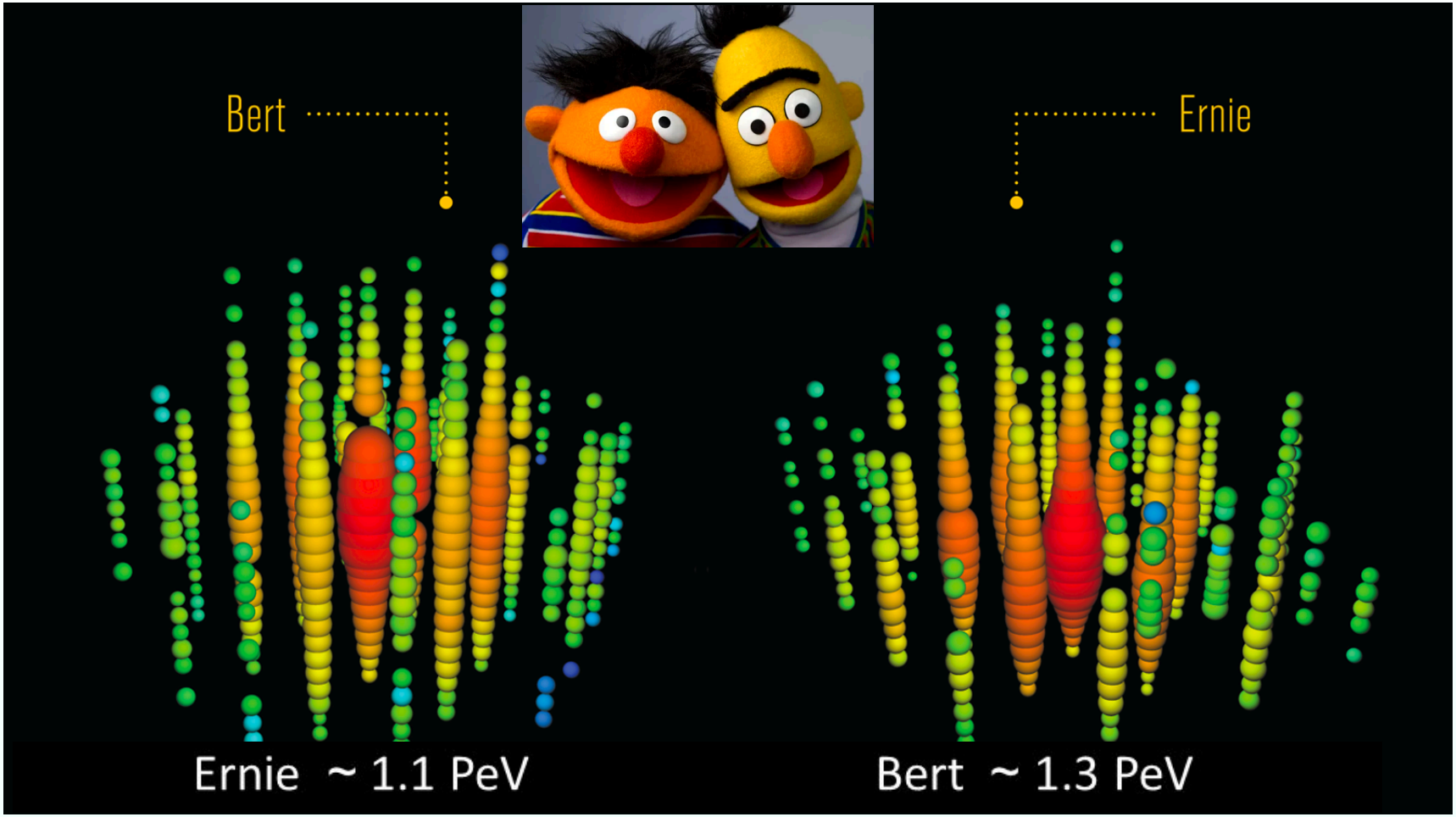
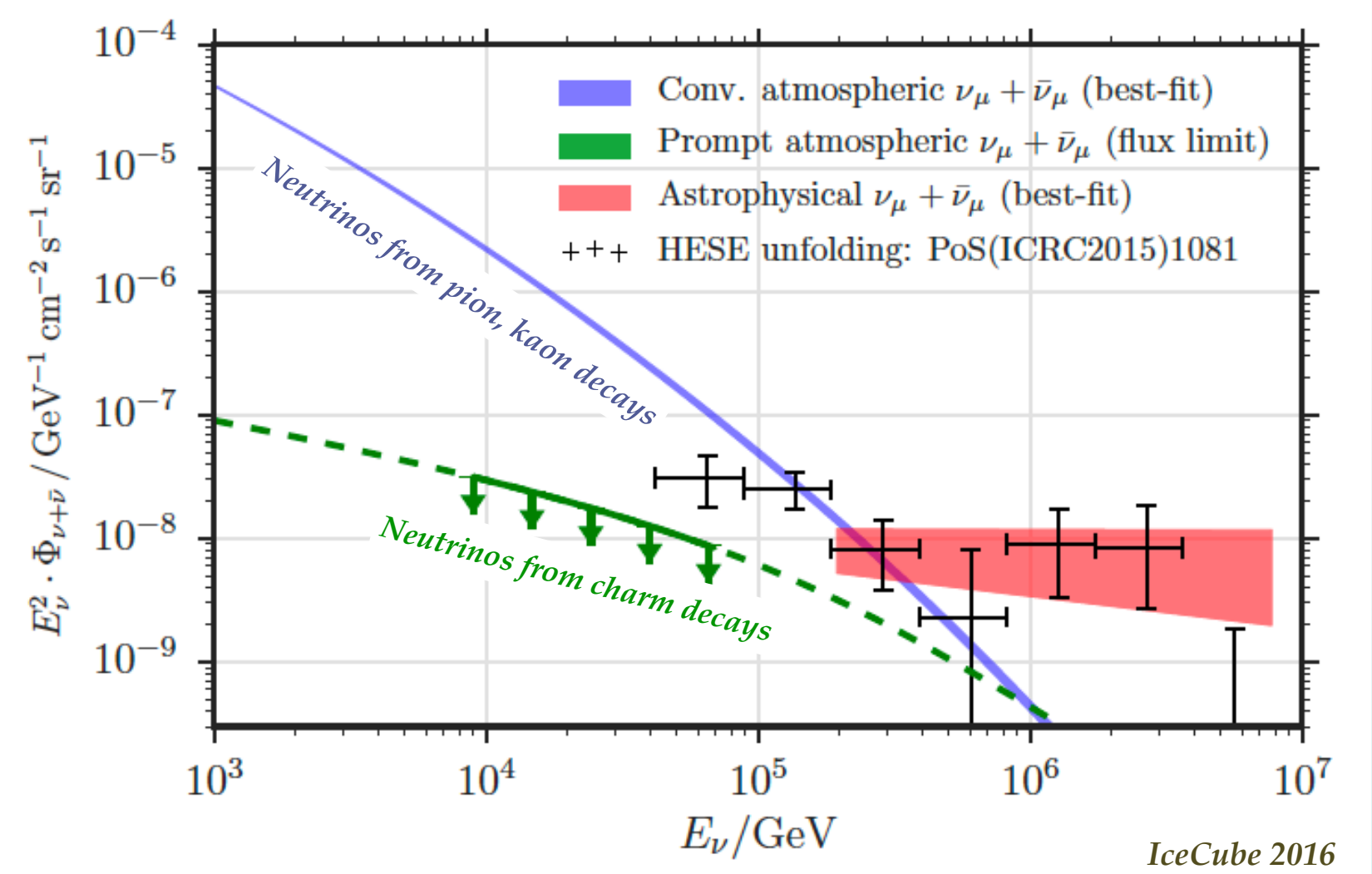


Same centre-of-mass energy than in proton-proton collisions at the TeV!

Precision QCD and … neutrino astronomy?

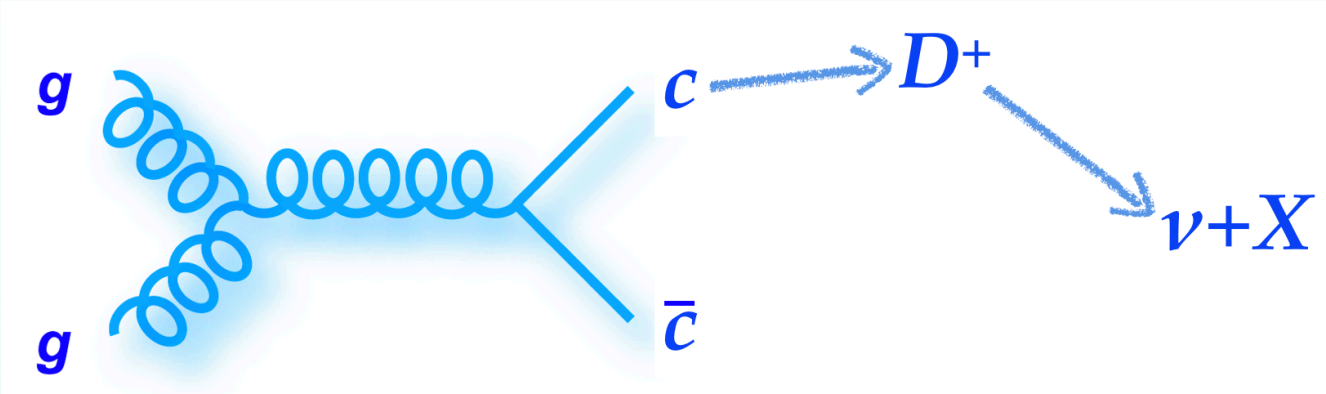


Detection of ultra-high energy neutrinos represents the beginning of **neutrino astronomy**: new window to the Universe!

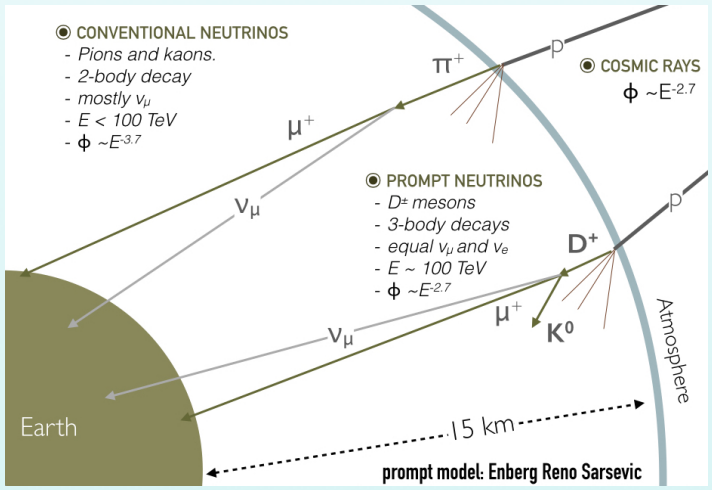
However, the dominant background, **prompt neutrinos from charm decays**, never been detected…

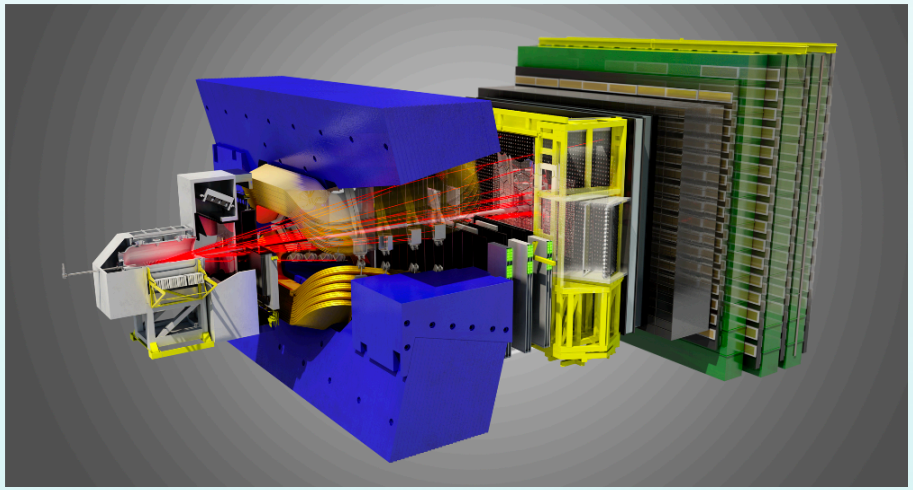
Precision QCD and … neutrino astronomy?

QCD (and the LHC) to the rescue! Include ***D* meson production data from LHCb** into PDF fit to constrain **small-*x* gluon**: precise predictions for **signal and background events at neutrino telescopes**



IceCube $E_{CR} = 100$ *PeV* → *Lorentz boost* → *LHCb* $E_{lab} \approx 14$ *TeV*





Direct overlap kinematics between charm production in UHE cosmic rays and at the LHC

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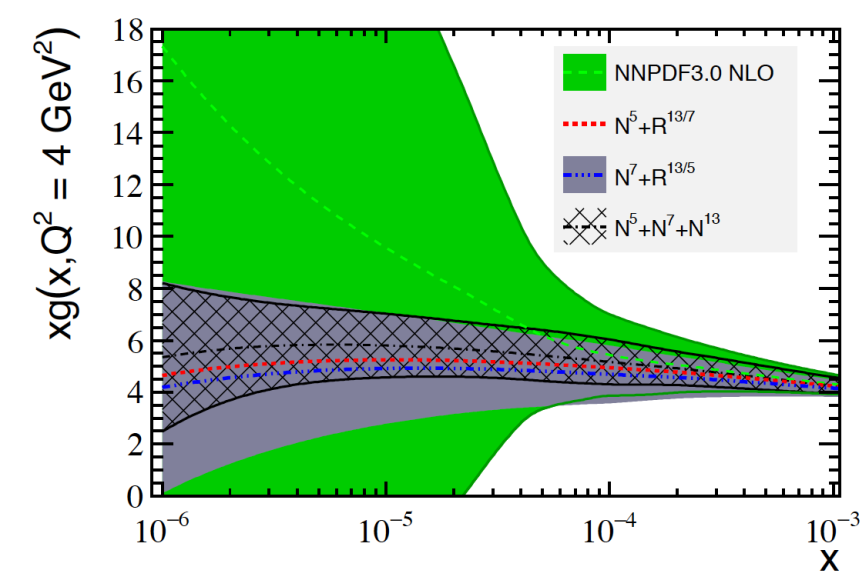
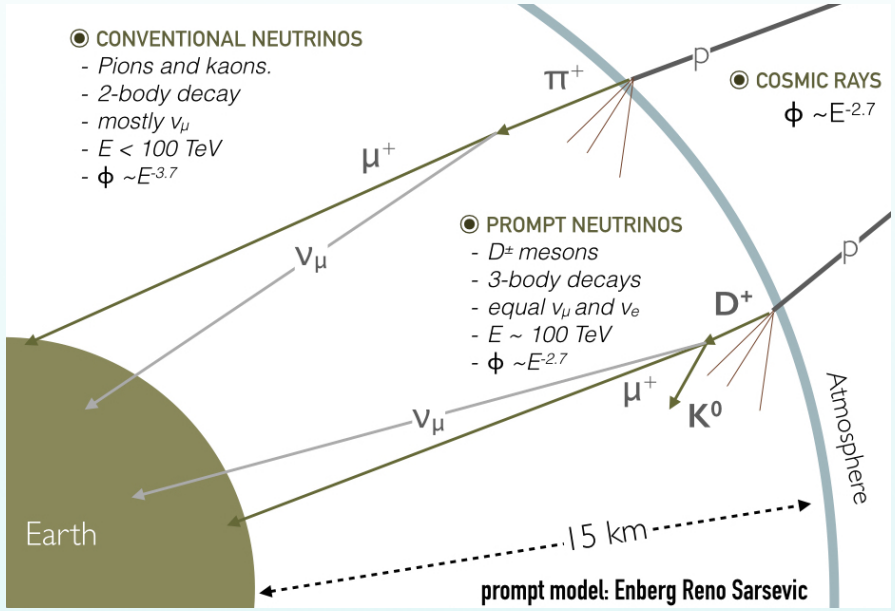
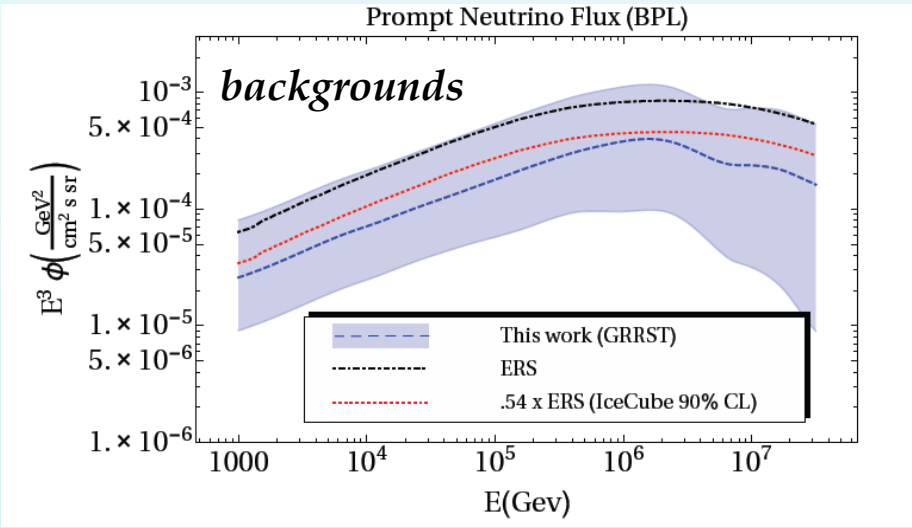
Precision determination of small-x gluon from charm production art LHCb



Gauld, JR 16





Progress in precision QCD benefits other fields beyond collider physics (i.e. also nuclear physics)

Gauld, JR, Rottoli, Sarkar, Talbert 15

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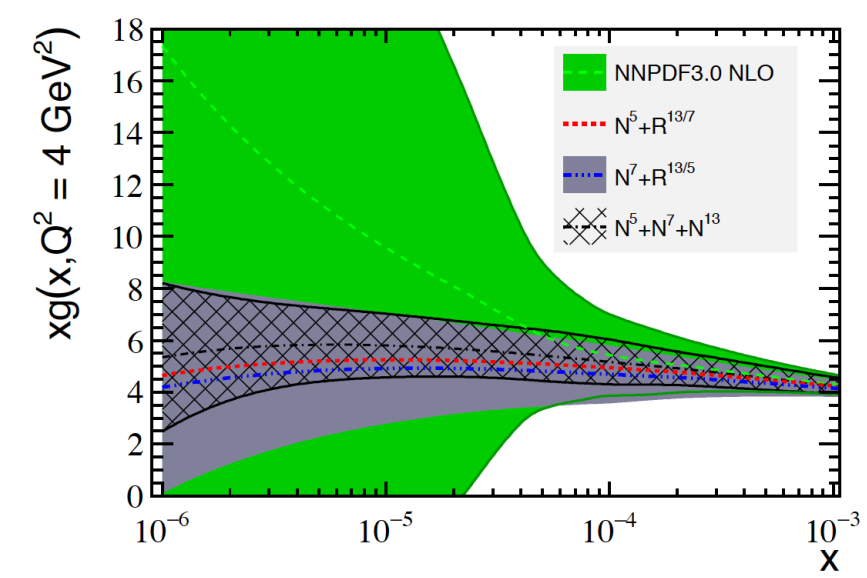

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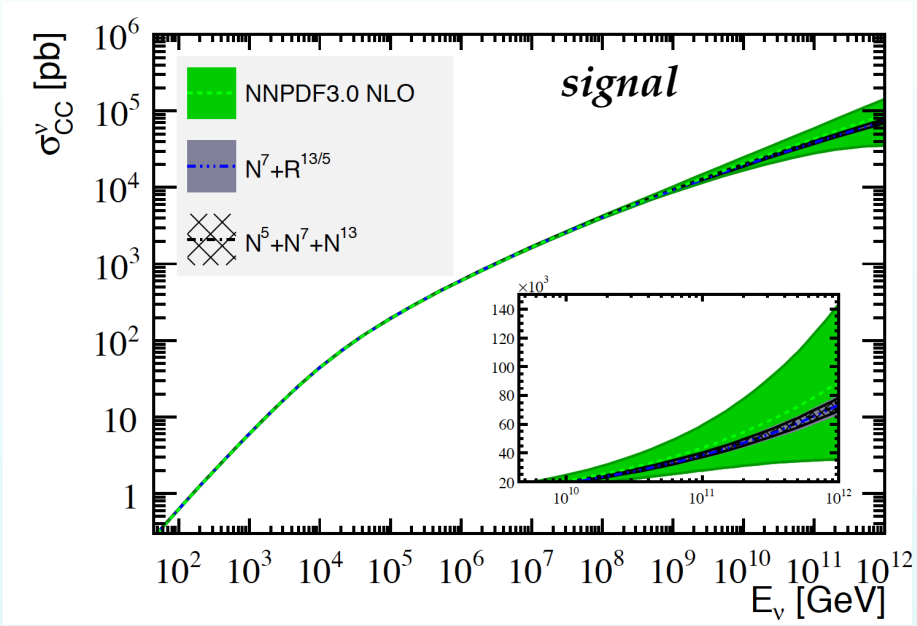
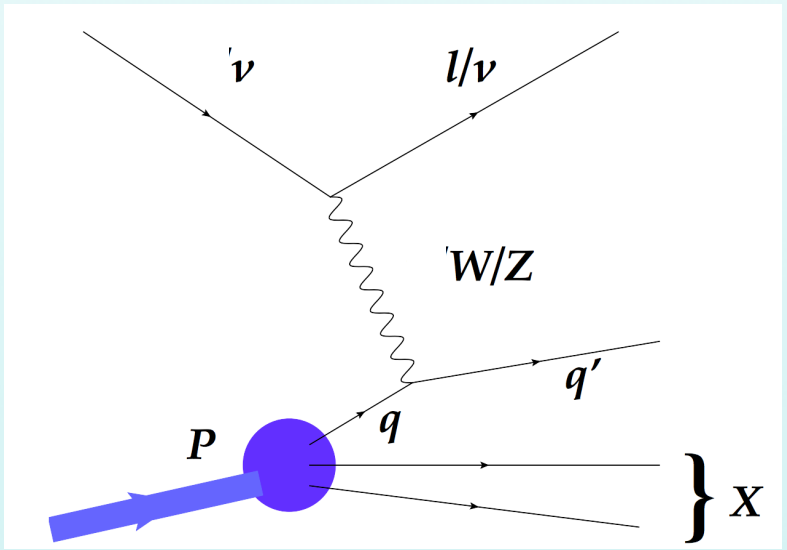




Progress in precision QCD benefits other fields beyond collider physics (i.e. also nuclear physics)

Physics at Future Colliders

☑ The discovery of the Higgs boson opens a **new era for Particle Physics**

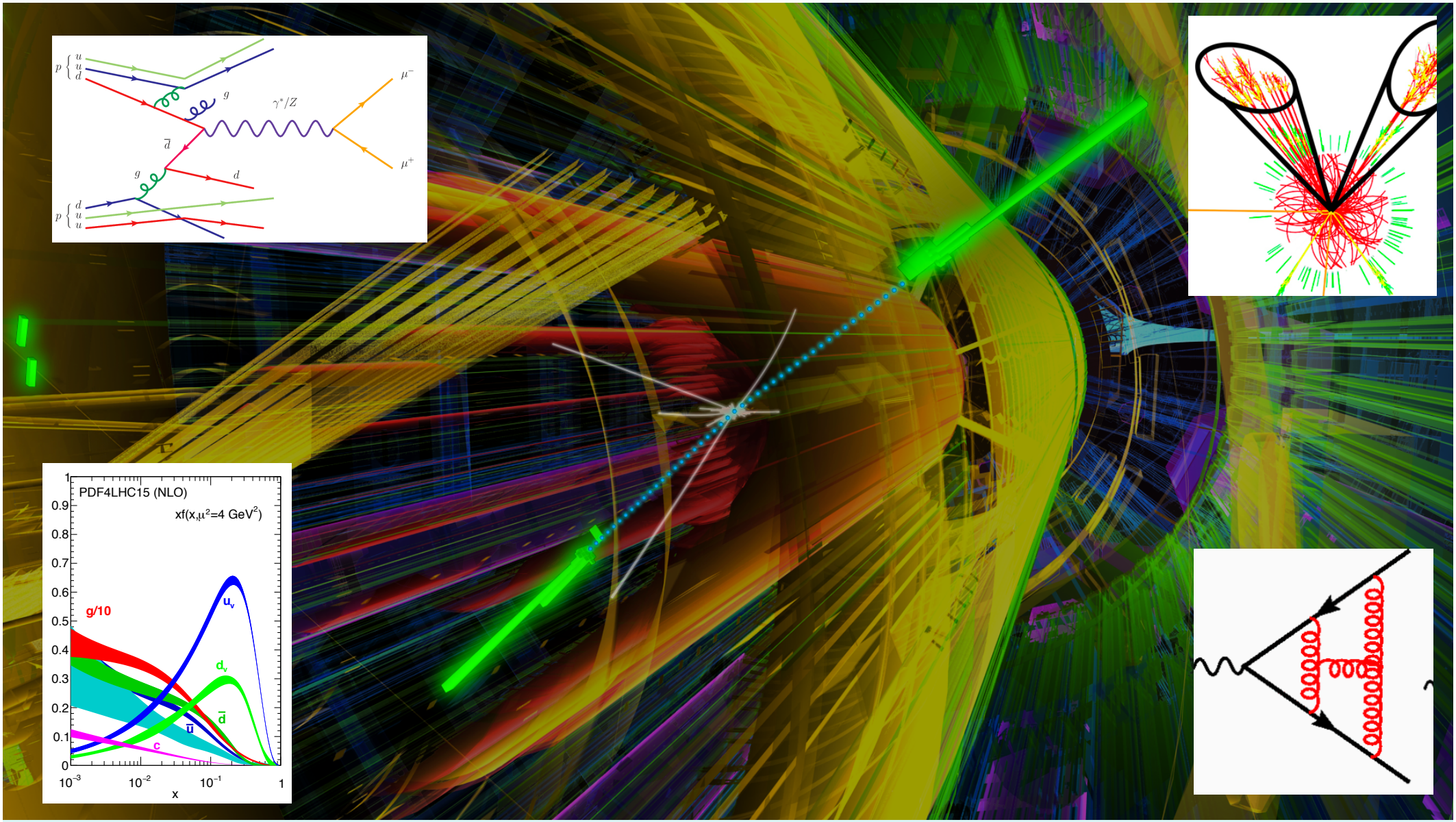
☑ The results from the present and future runs of the LHC, as well as from other experiments (DM, flavour, low energies) will determine **the future of field for next decades**

☑ No machine has **guaranteed discoveries,** but they have each very strong physics deliverables in the study of the **Higgs, top, and electroweak sectors**

☑ **Lepton colliders** offer **unprecedented precision for Higgs measurements** and strong indirect sensitivity to bSM via loop effects, but limited coverage of high-energy region

☑ **Future high-energy hadron colliders** would continue the **exploration of the high-energy frontier** while providing many opportunities for precision Higgs and SM measurements

Fascinating times to explore the high-energy frontier!



Stay tuned for news!

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