



KEK Theory Meeting on Particle Physics Phenomenology (KEK-PH2018)

February 13-16 2018

Beyond the LHC: physics goals and CERN's plans for future colliders

or, as Mihoko put it:

***All you need to know about the “bright” future of
CERN high energy projects***

Michelangelo L. Mangano
Theory Department, CERN, Geneva



What are we talking about when we're talking about CERN's future plans ...

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**✓ Approved
2026-37**

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update '16**

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CDR (end '18)

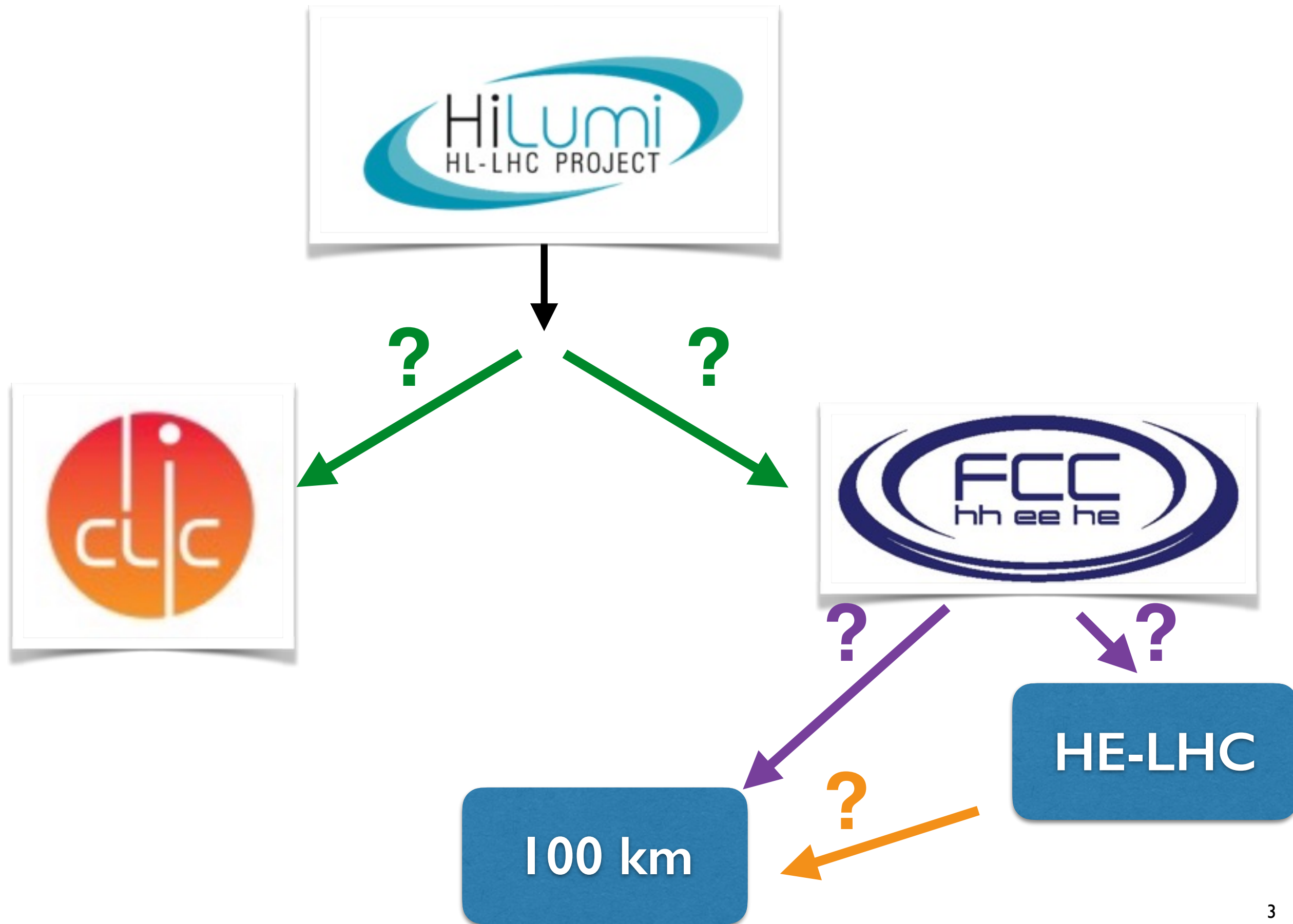
100km tunnel

- **e⁺e⁻ @ 91, 160, 240, 365 GeV**
- **pp @ 100 TeV**
- **e_{60GeV} p_{50TeV} @ 3.5 TeV**

LHC tunnel: HE-LHC

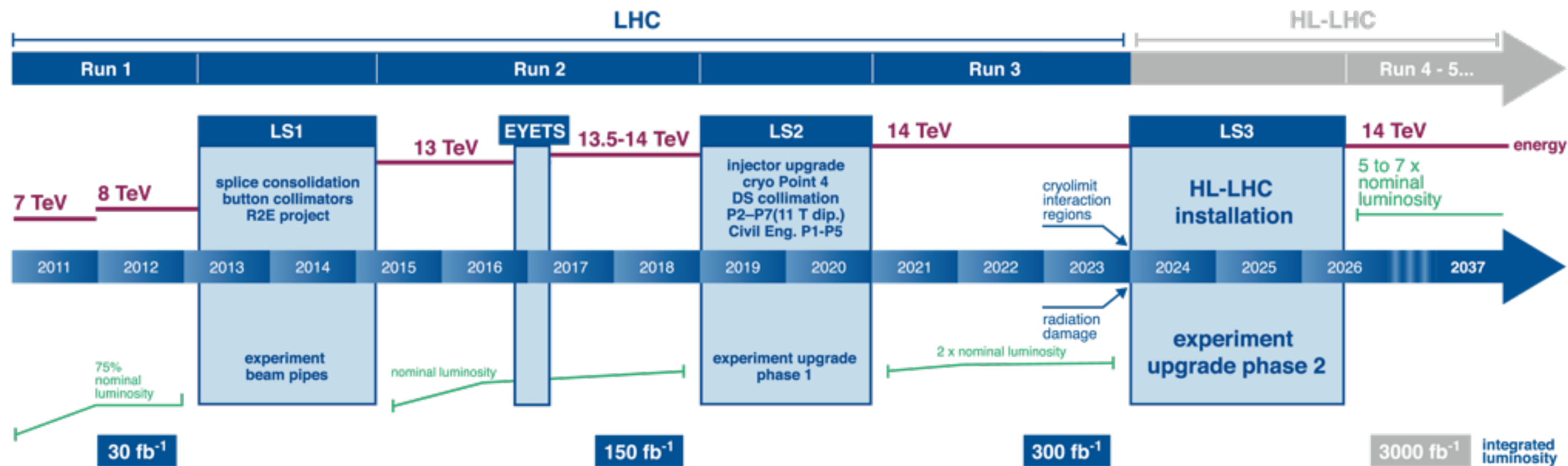
- **pp @ 27 TeV, 15ab⁻¹**

Possible paths



Long-term LHC plan

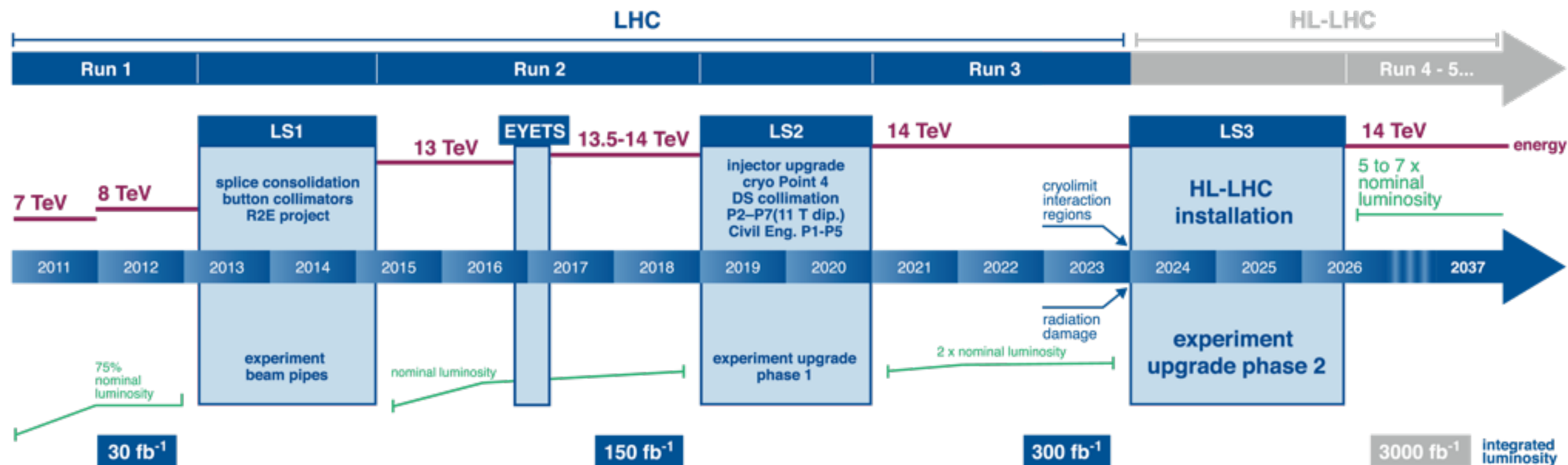
LHC / HL-LHC Plan



The 35fb⁻¹ of 13 TeV data analyzed so far are just 1% of the final statistics

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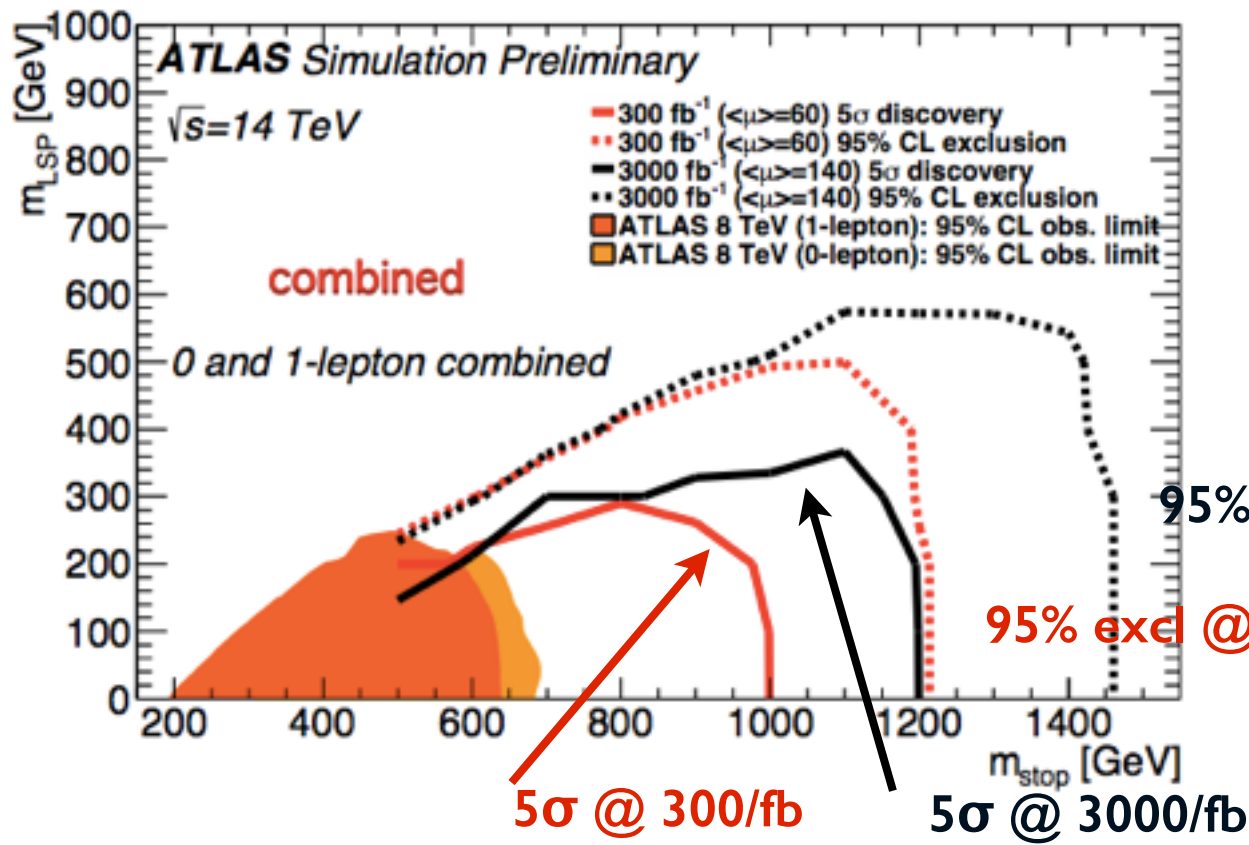
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==>> the LHC physics programme has barely started! <<==

LHC vs HL-LHC: examples of prospects for direct searches

Direct stop searches (ATLAS Snowmass doc)

$Z' \rightarrow e^+e^-$



ATLAS/CMS HL docs	300/fb	3000/fb
95% excl (ATLAS)	6.5 TeV	7.8 TeV
5 σ (CMS)	5.1 TeV	6.2 TeV

Message:

- What's been excluded at 300 fb⁻¹ may not be discovered at 3000 fb⁻¹

Question:

- If LHC sees nothing new after 300 fb⁻¹, why would we keep going all the way to 3000 fb⁻¹

Key question for the future developments of HEP:
**Why don't we see the new physics we expected to
be present around the TeV scale ?**

- Is the mass scale beyond the LHC reach ?
- Is the mass scale within LHC's reach, but final states are elusive to the direct search ?

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities

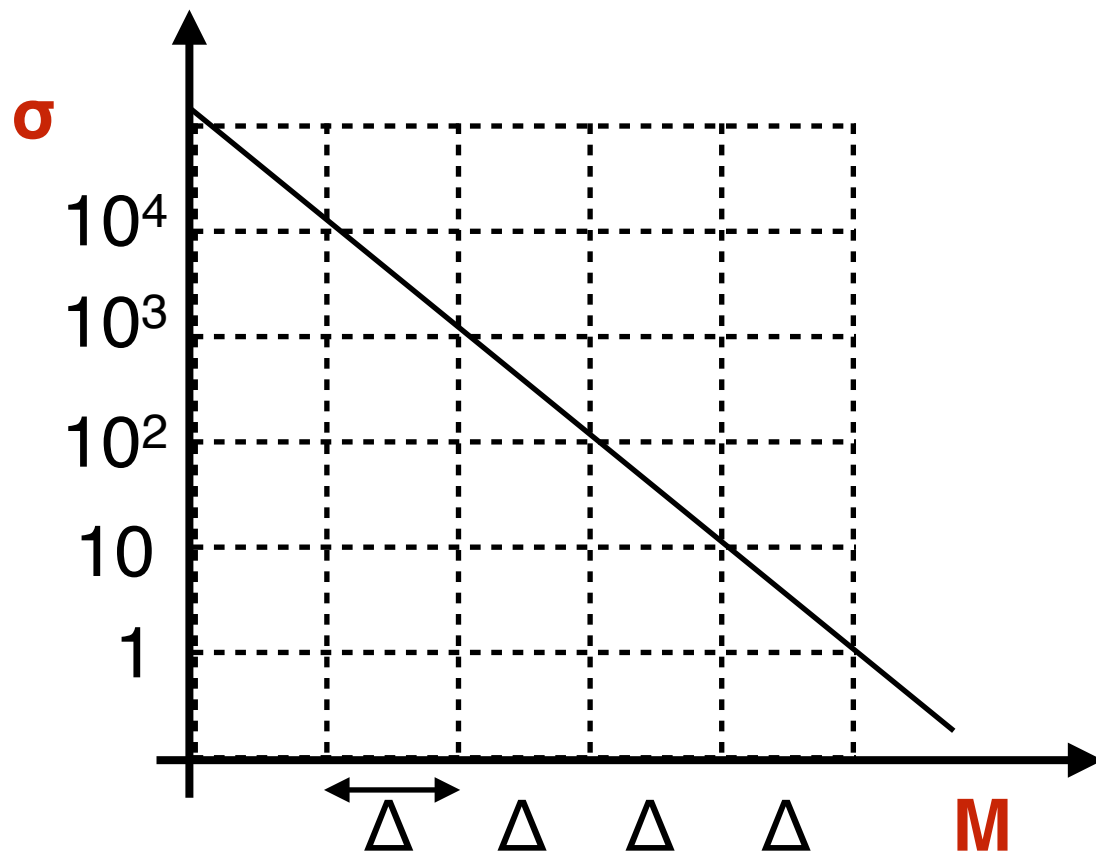
Readiness to address both scenarios is the best hedge for the field:

- *precision*
- *sensitivity (to elusive signatures)*
- *extended energy/mass reach*

Mass reach vs reach for rare/elusive proc's

(assume 0 bg's, key points don't change in presence of bg)

At large M , $\sigma \sim \sigma_0 \exp(-cM)$



$L \rightarrow 10 \times L \Rightarrow M \rightarrow M + \Delta$ ↗ mass reach

$$\delta M/M = \Delta/M \Rightarrow$$

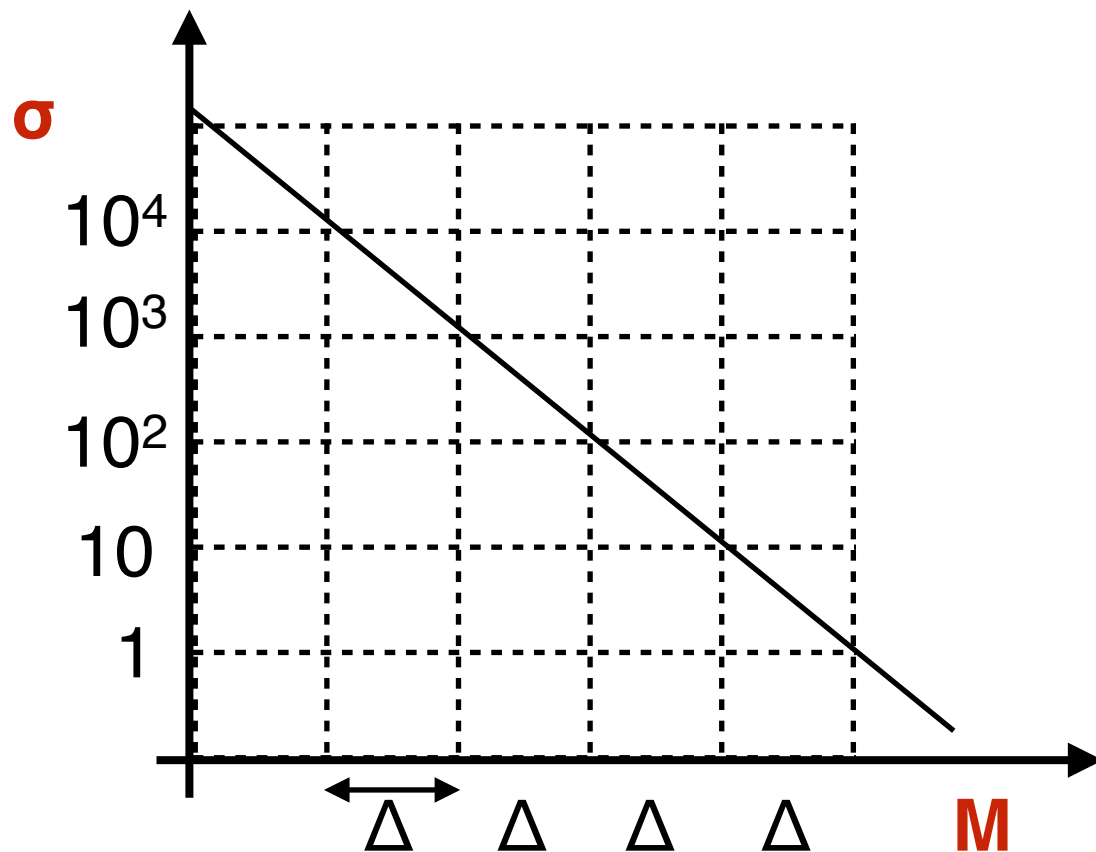
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At fixed M : “coupling strength” reach

$$L \rightarrow 10 \times L \Rightarrow \sigma_0 \rightarrow \sigma_0 / 10$$

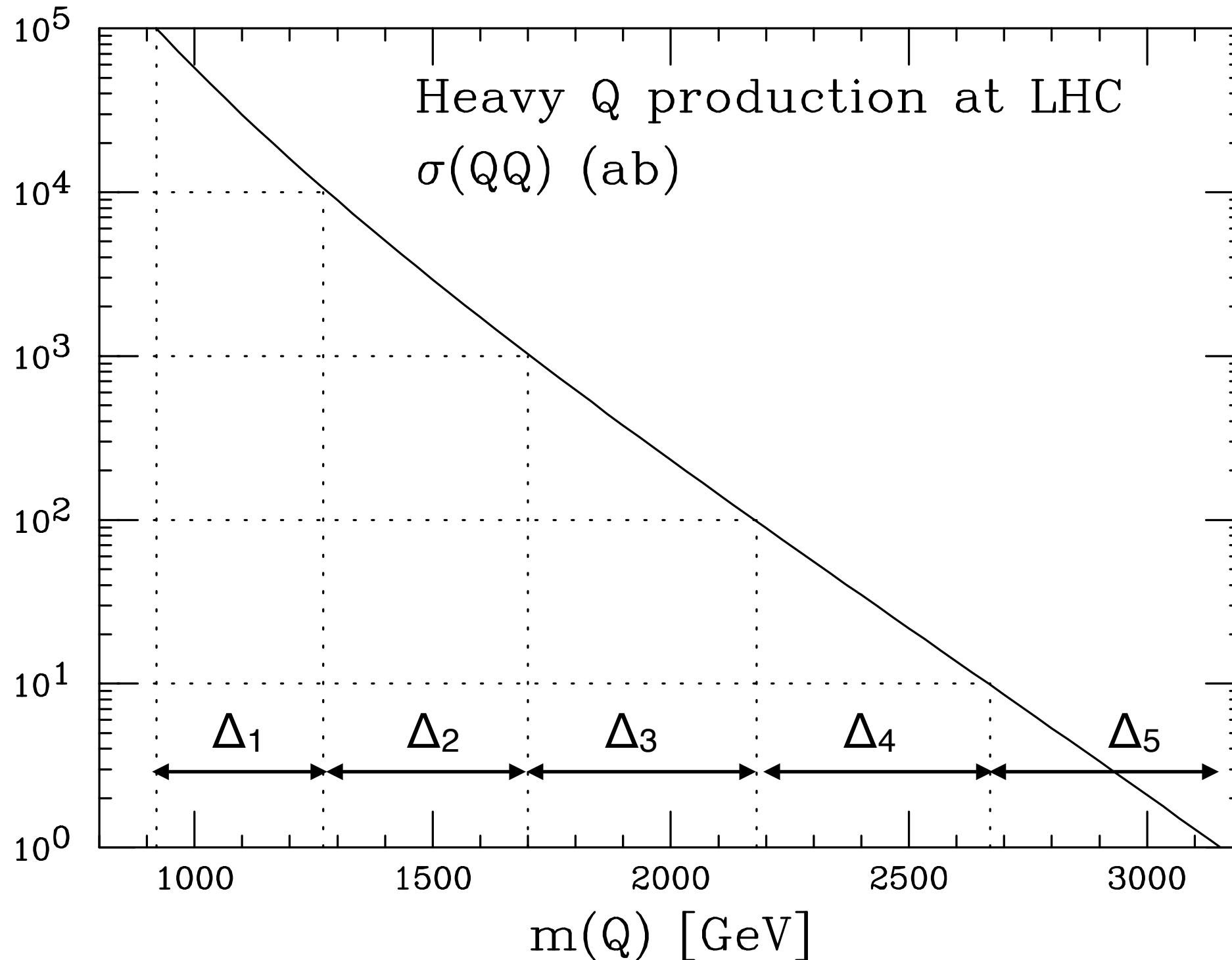
$$\text{If } \sigma_0 \sim 1/\Lambda^n \Rightarrow$$

$$L \rightarrow 10 \times L \Rightarrow \Lambda \rightarrow 10^{1/n} \Lambda$$



the reach for smaller and smaller couplings, BRs or for larger scales of new physics, Λ , keeps improving at higher L !

Example: heavy Q reach in $pp \rightarrow QQ$



$$\Delta_{a=1,\dots,5} \text{ (GeV)} \sim 350, 430, 480, 480, 480$$

\Rightarrow Below $\sigma=O(\text{fb})$, $\sigma \sim \exp(-M/M_0)$ and $\Delta \rightarrow \text{const}$

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 - higher luminosity continues to benefit the search for rare or elusive phenomena, which is where new physics at the LHC might be hiding

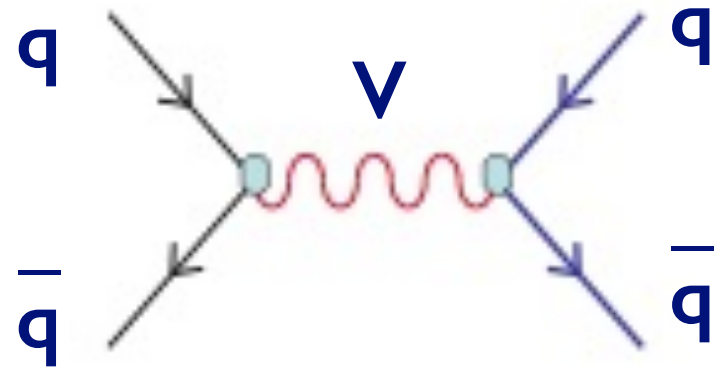
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- Examples, from the Tevatron, of the role of high Luminosity:
 - B_s oscillations
 - Higgs search
 - m_W and m_{top}

**other smart ways to exploit
larger statistics:**

Larger statistics, giving access to more secluded kinematical regions, allow to exploit new powerful analysis tools, and gain sensitivity to otherwise elusive signatures

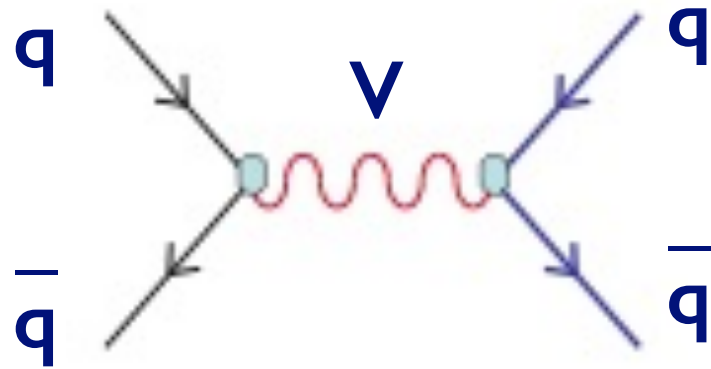
Example: search for low-mass resonances $V \rightarrow 2$ jets



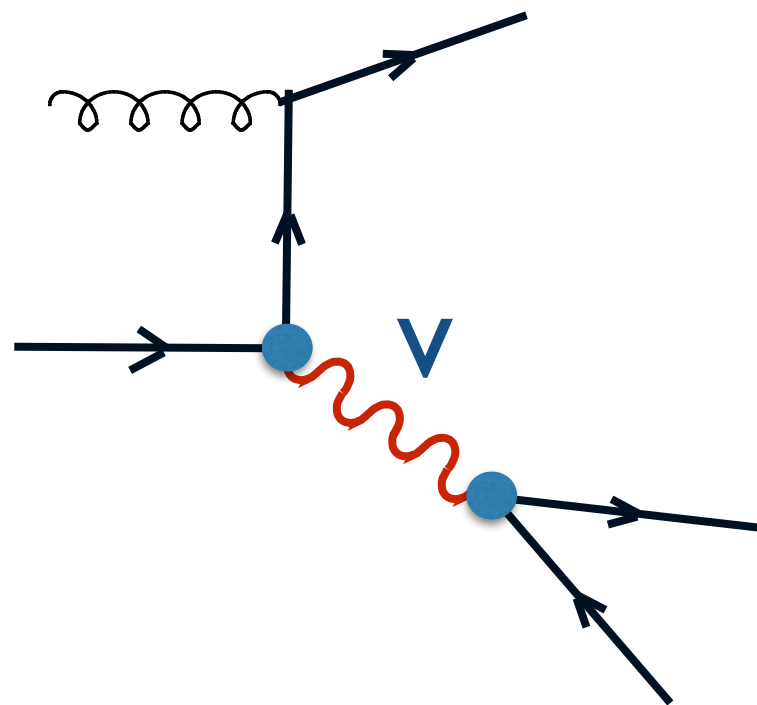
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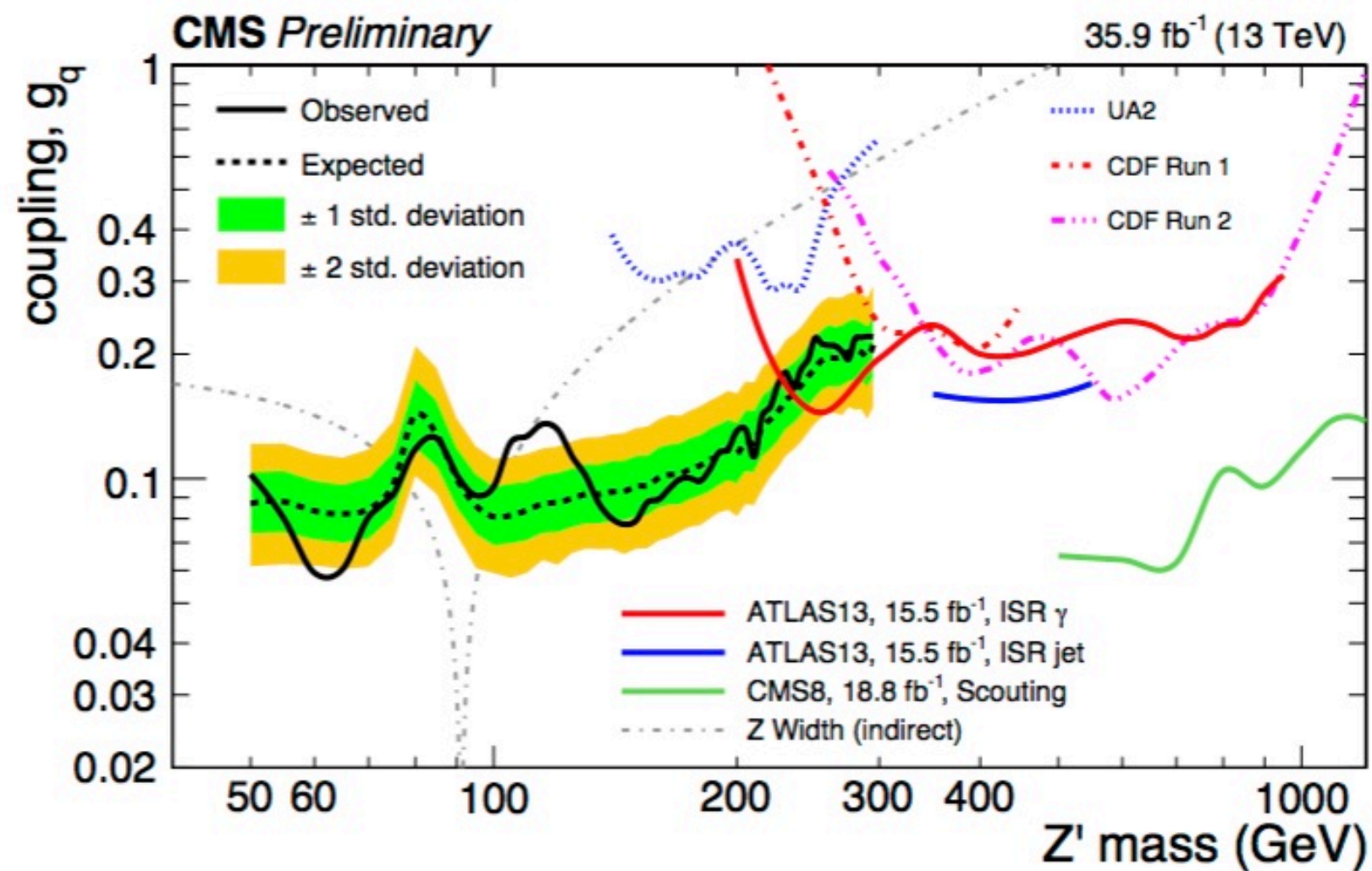
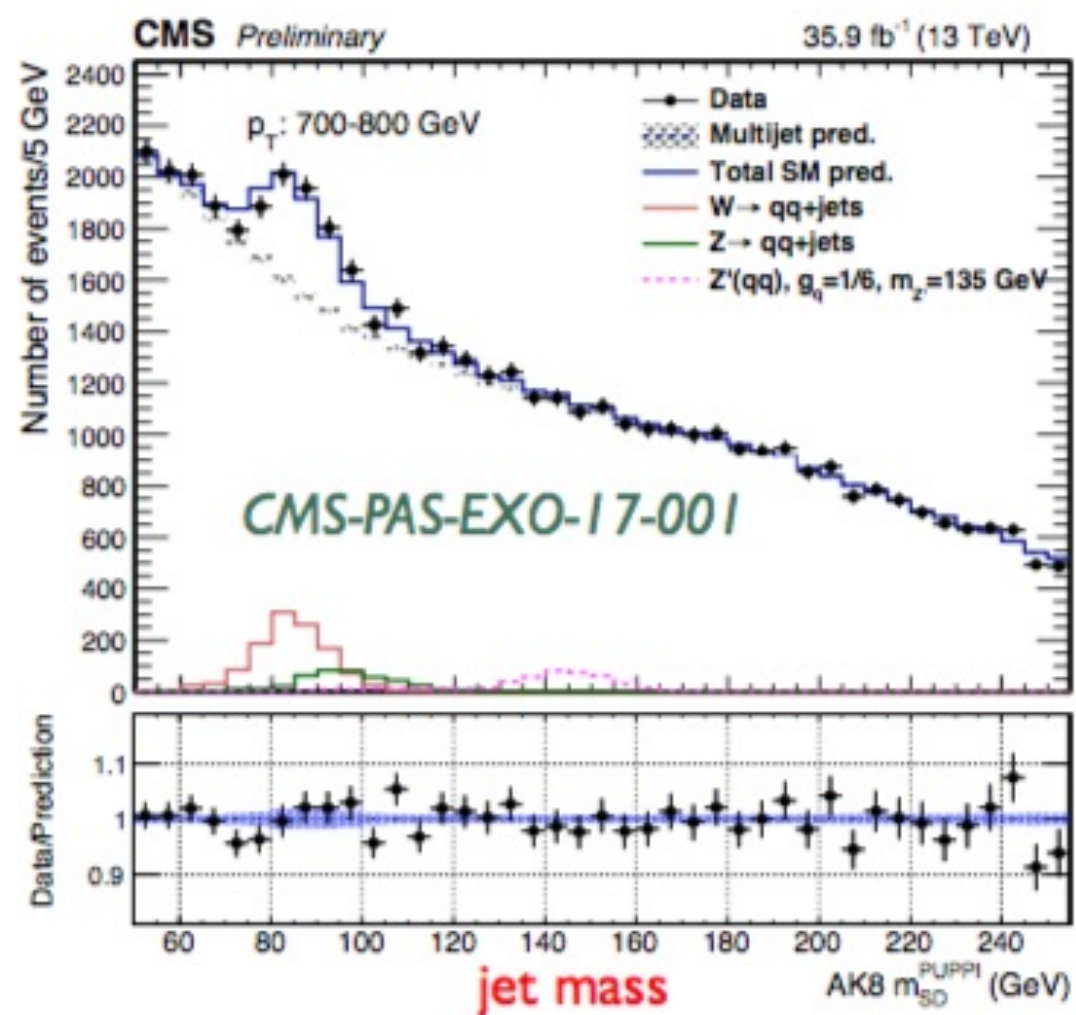
search impossible at masses below few hundred GeV, due to large $gg \rightarrow gg$ bg's and trigger thresholds



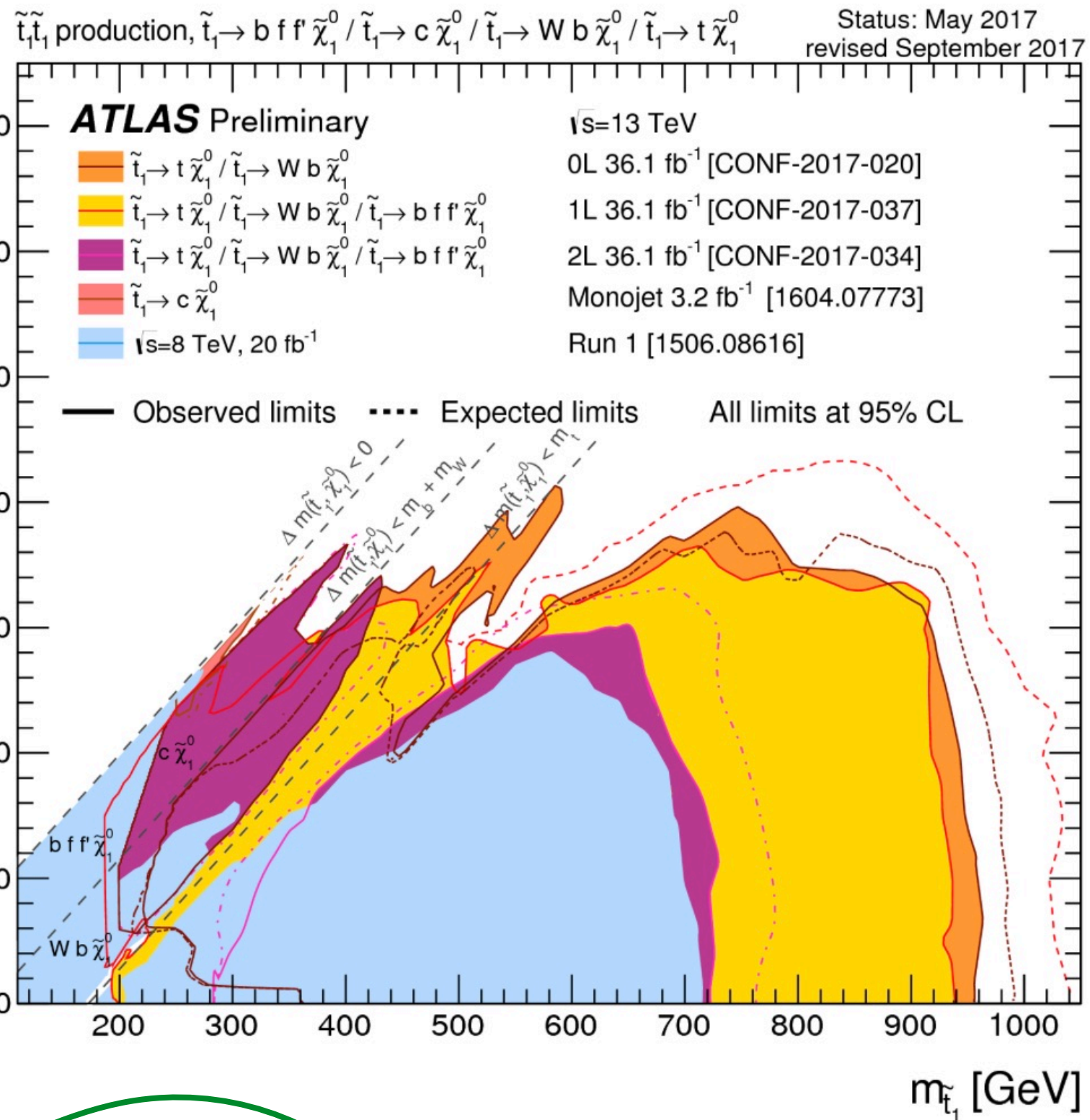
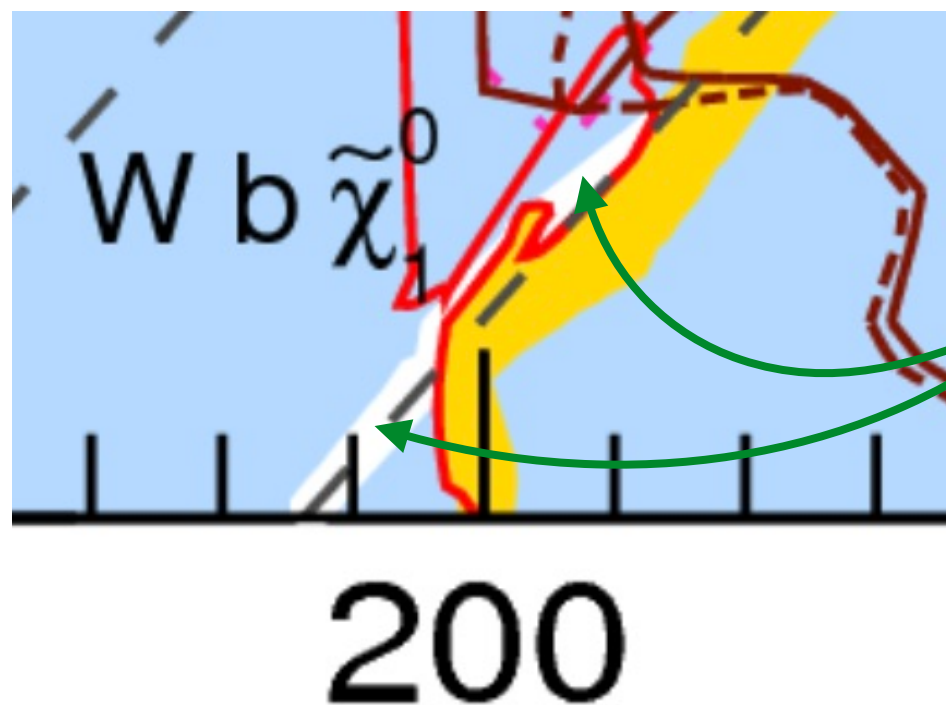
At large p_T

- S/B improves (qg initial state dominates both S and B)
- use boosted techniques to differentiate $V \rightarrow qq$ vs QCD dijets
- $\epsilon_{\text{trig}} \sim 100\%$

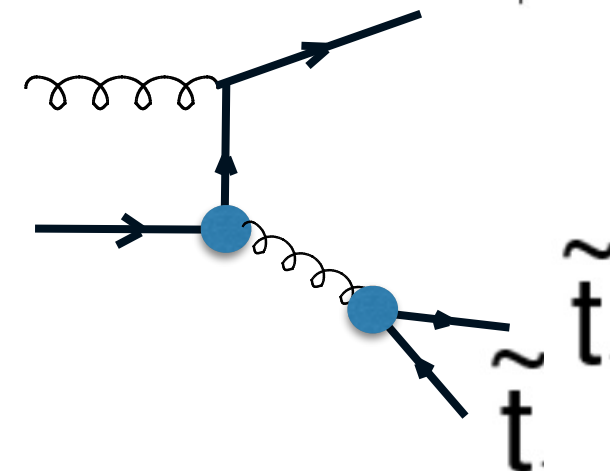
Sensitivity to potential mediators in low-mass regions so-far unexplored



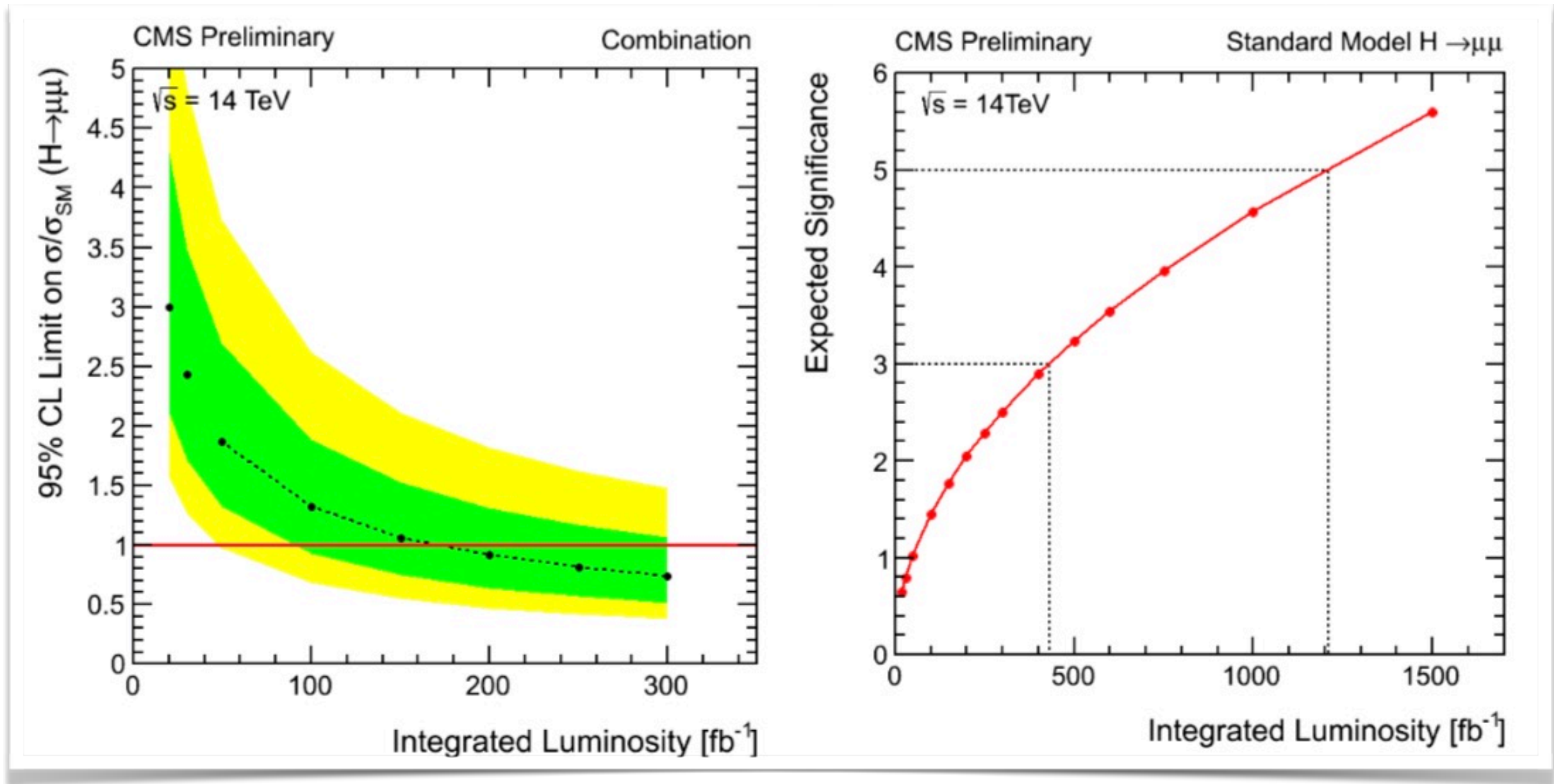
other possible applications



can one fill these small gaps with high-pt stop pairs?



H couplings to 2nd generation: the role of HL-LHC



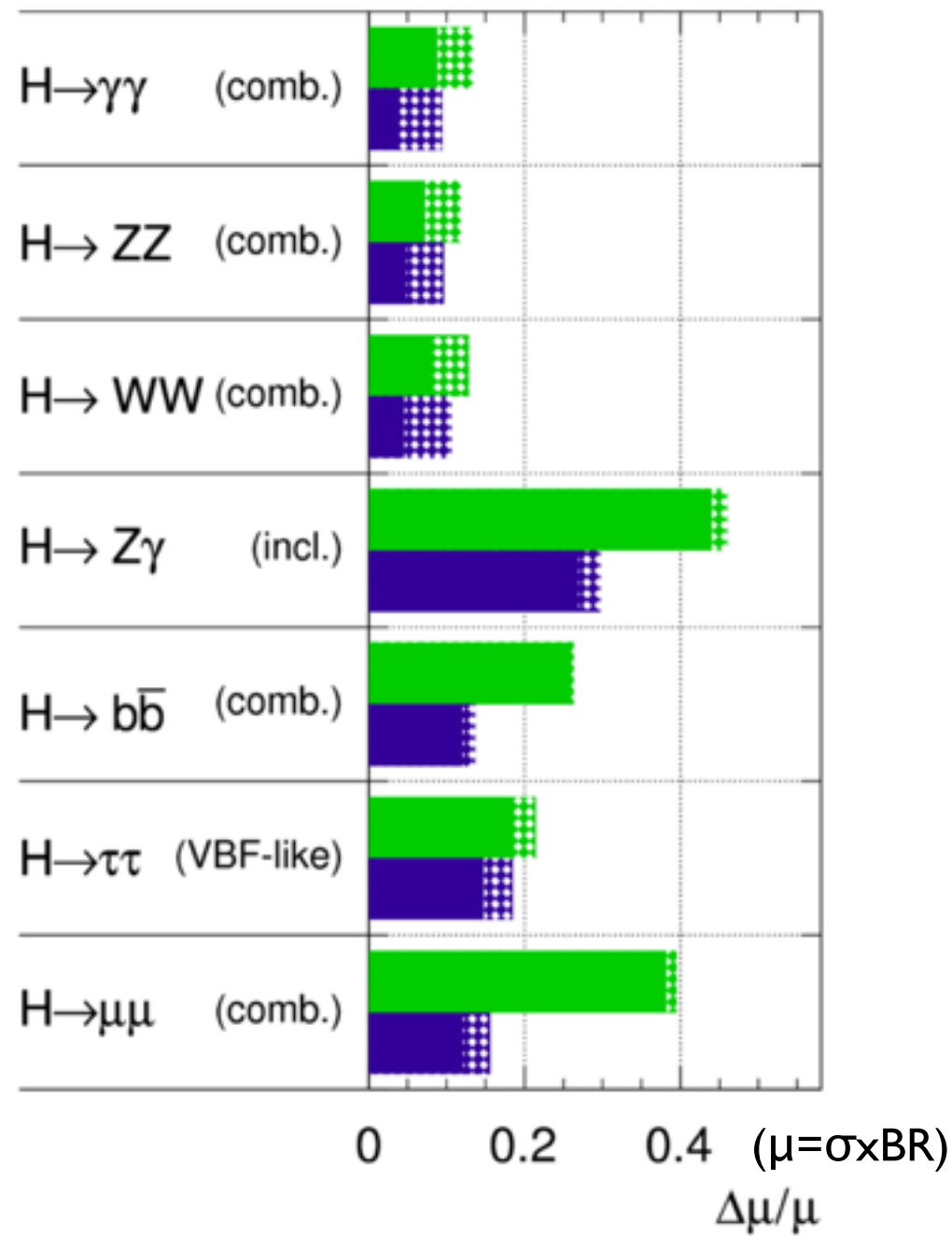
Projections from CMS-HIG-13-007

Projected precision on H couplings at HL-LHC

ATL-PHYS-PUB-2014-016

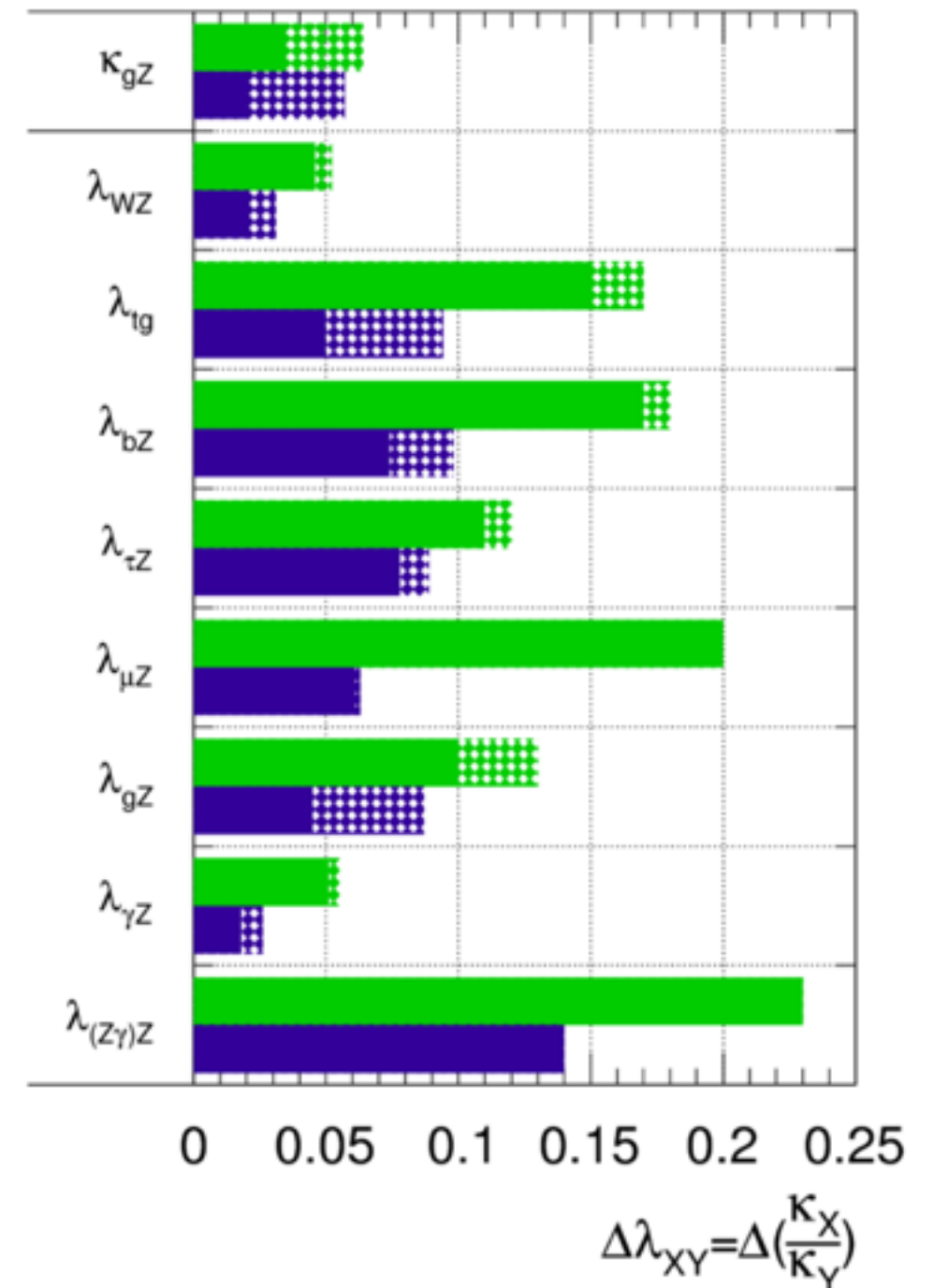
ATLAS Simulation Preliminary

$\sqrt{s} = 14 \text{ TeV}$: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$



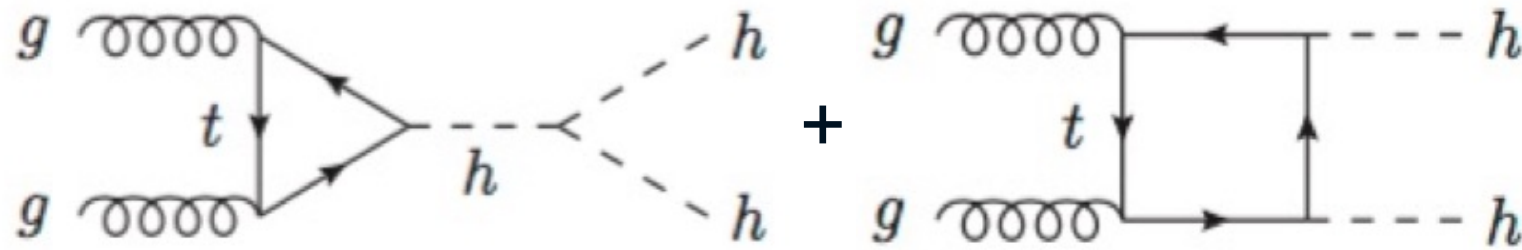
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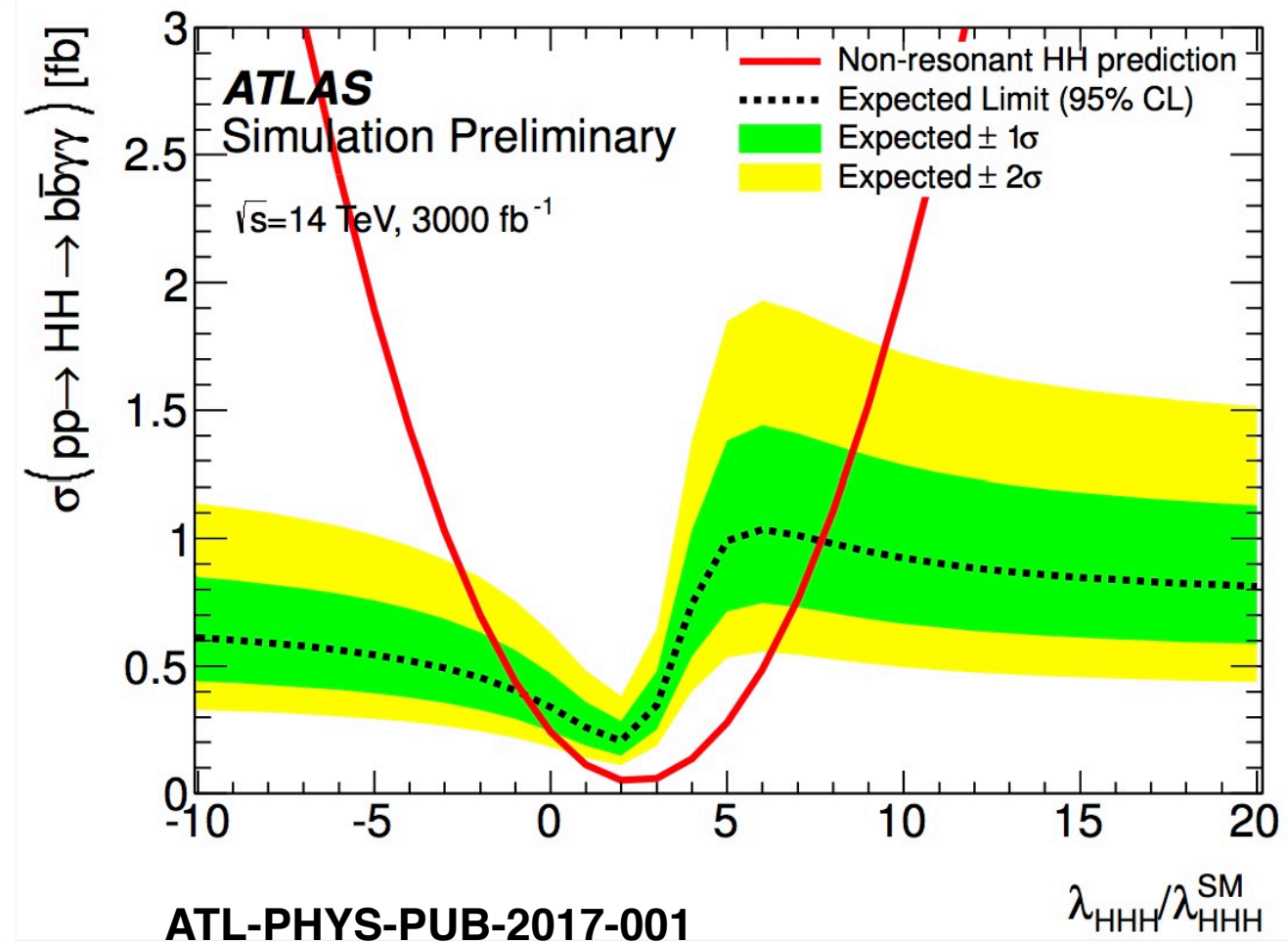
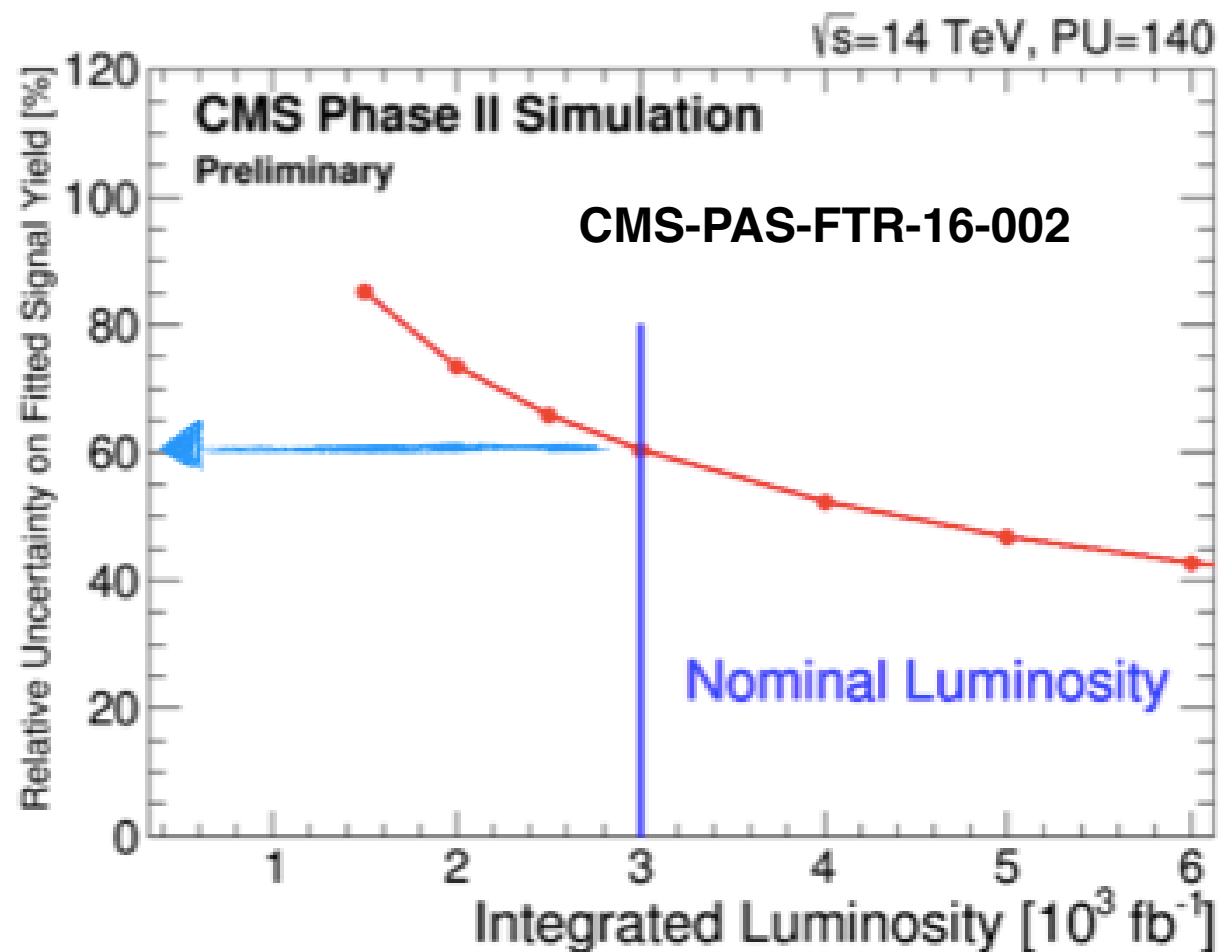


solid areas: no TH systematics
shaded areas: with TH systematics

What will HL-LHC tell us about the Higgs potential?



- Strong negative interference between the two diagrams near threshold
- Selfcoupling diagram suppressed well above threshold, due to 1/S behaviour
- => it's hard!!



Barely $1-2\sigma$ evidence for Higgs pair production, but no quantitatively significant determination of λ : $-0.8 < \lambda/\lambda_{\text{SM}} < 7.7$ @95%CL

$-0.2 < \lambda/\lambda_{\text{SM}} < 2.6$
 w. kinematical analysis

Colliders beyond the LHC

The potential of a Future Circular Collider

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 - **mass reach enhanced** by factor $\sim E / 14 \text{ TeV}$ (will be 5–7 at 100 TeV, depending on integrated luminosity)
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- Provide firm Yes/No answers to questions like:
 - is the SM dynamics all there is at the TeV scale?
 - is there a TeV-scale solution to the hierarchy problem?
 - is DM a thermal WIMP?
 - did baryogenesis take place during the EW phase transition?

Examples: precision Higgs physics

Higgs couplings @ FCC

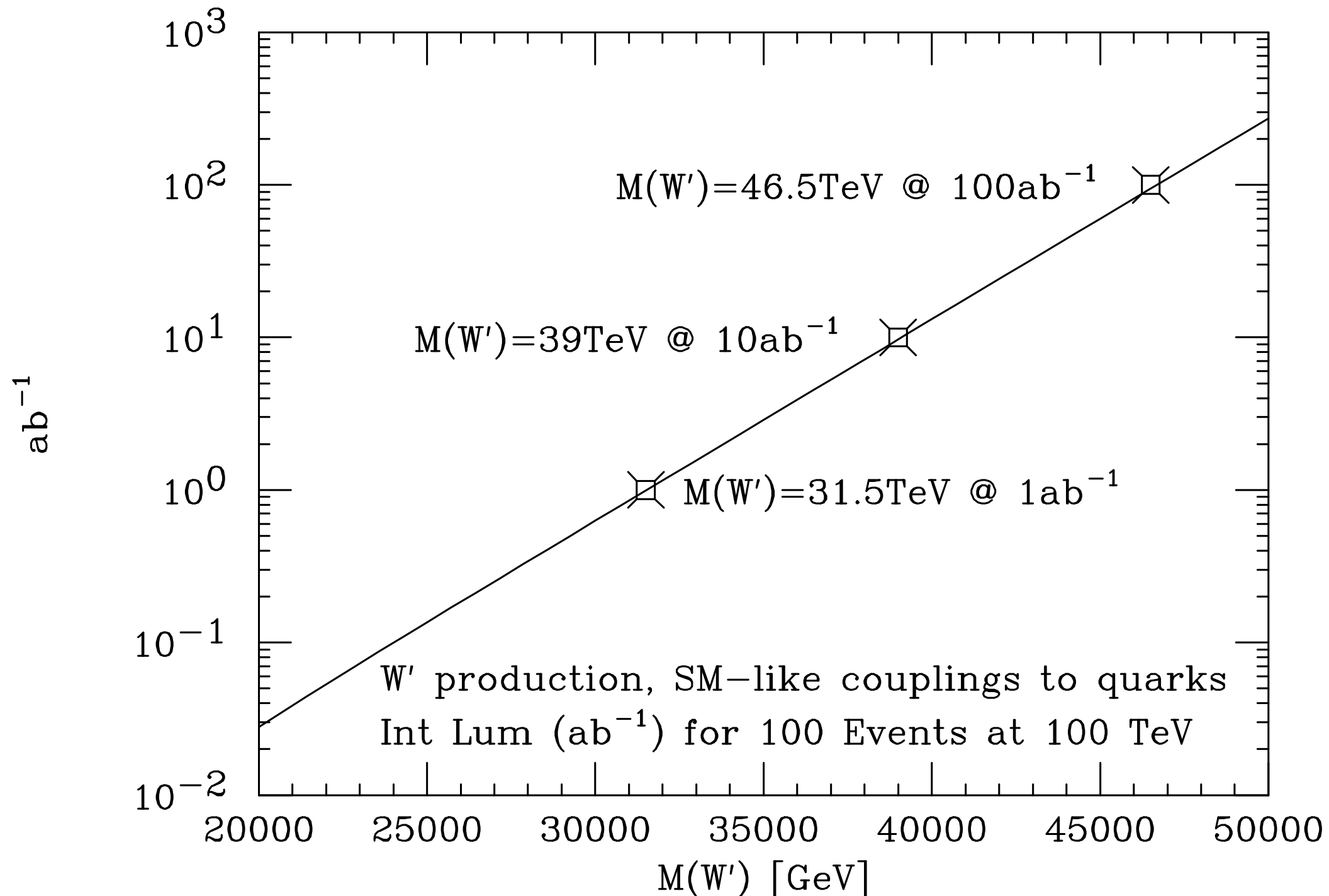
g_{HXY}	ee [240+350 (4IP)]	pp [100 TeV] 30ab ⁻¹	ep [60GeV/50TeV], 1ab ⁻¹
ZZ	0.15%	<1%	
WW	0.19%		
bb	0.42%		0.2%
cc	0.71%		1.8%
gg	0.80%		
$\tau\tau$	0.54%		
$\mu\mu$	6.2%	<1%	
$\gamma\gamma$	1.5%	<0.5%	
Z γ		<1%	
tt	~13%	1%	
HH	~30%	3.5%	under study
uu,dd	H-> $\rho\gamma$, under study		
ss	H-> $\phi\gamma$, under study		
BR _{inv}	< 0.45%	few 10 ⁻⁴	
Γ_{tot}	1%		

Examples: direct discovery reach

New gauge bosons discovery reach

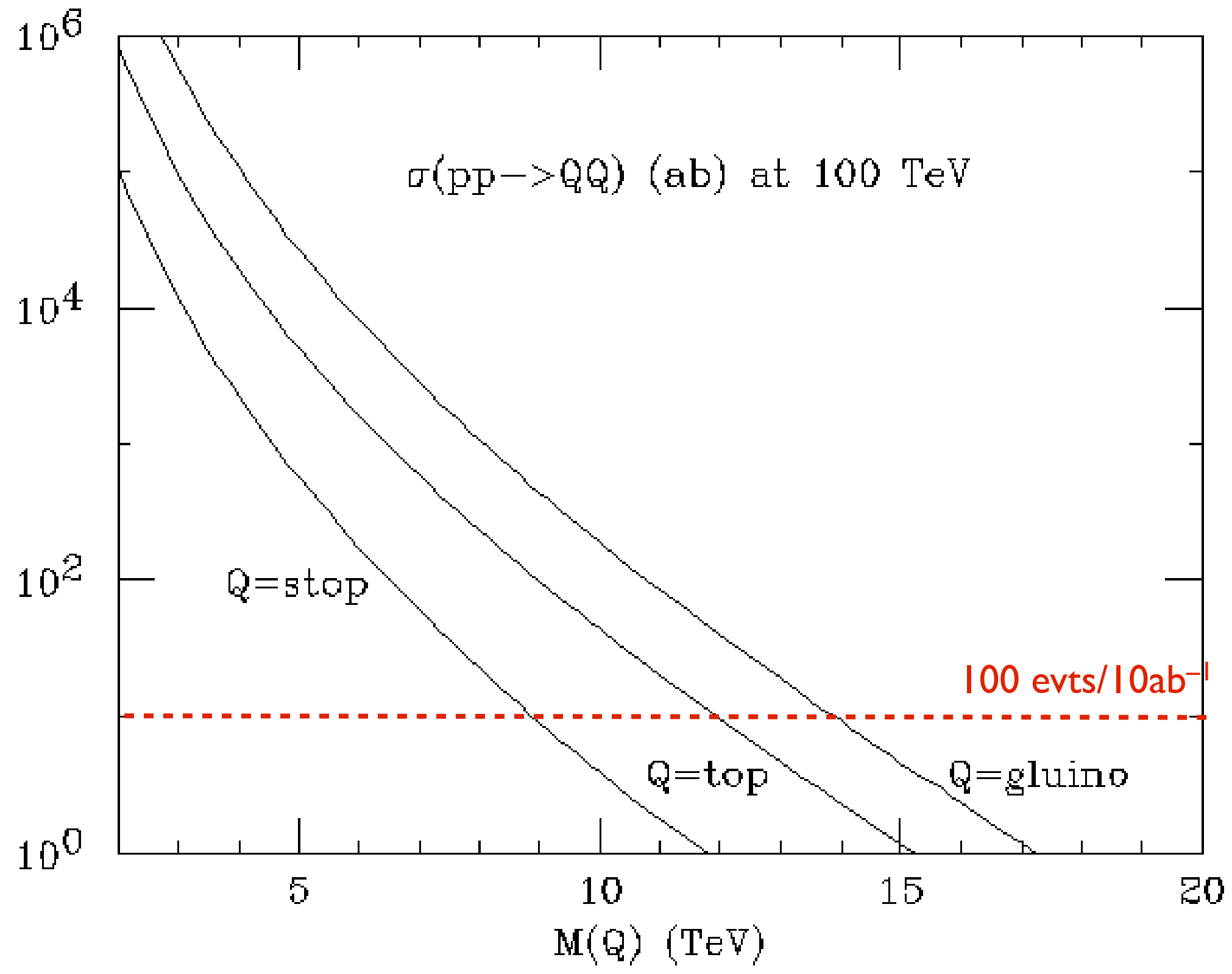
Example: W' with SM-like couplings

NB For SM-like Z' , $\sigma_{Z'} BR_{lept} \sim 0.1 \times \sigma_{W'} BR_{lept}$, \Rightarrow rescale lum by ~ 10

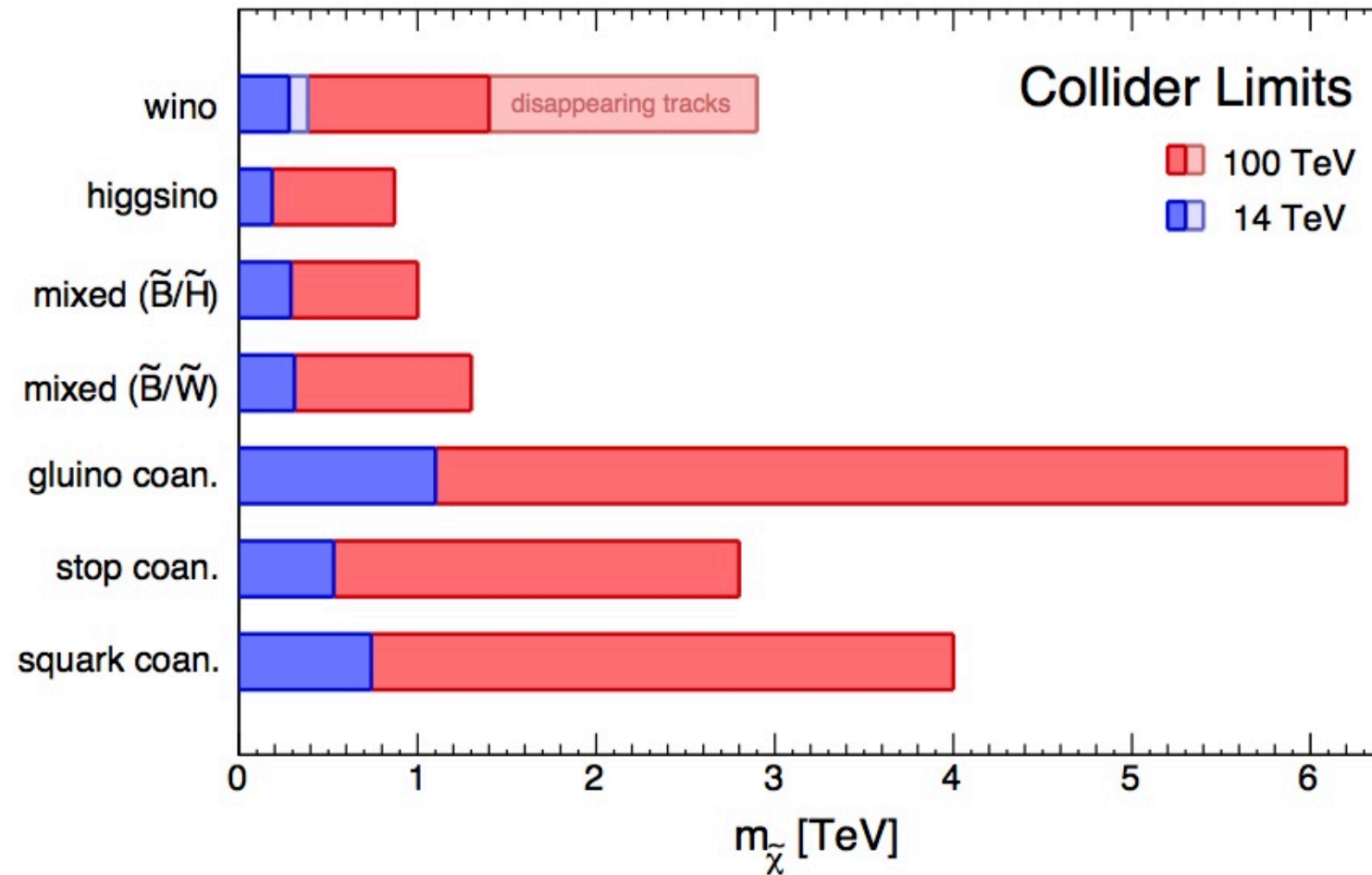
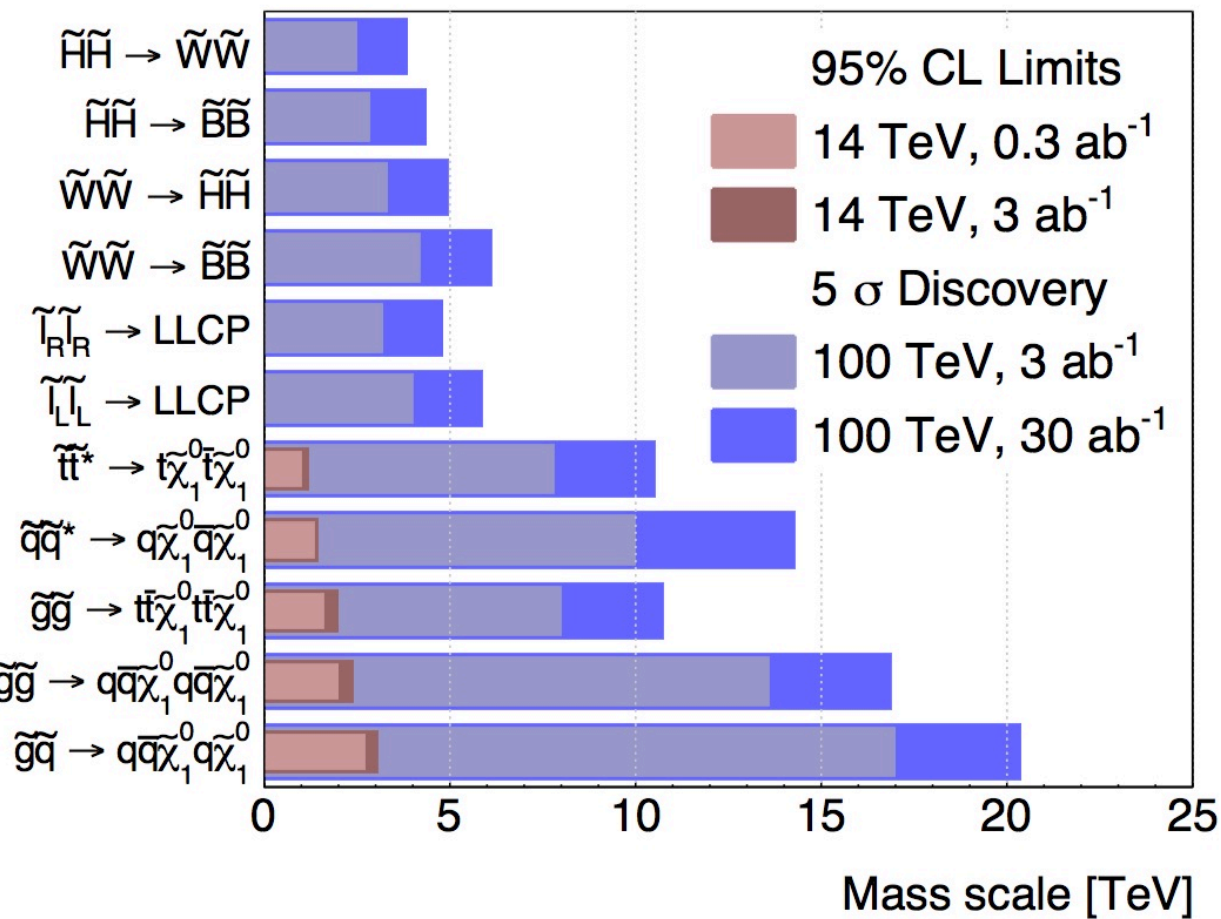


At $L=O(\text{ab}^{-1})$, $\text{Lum} \times 10 \Rightarrow \sim M + 7 \text{ TeV}$

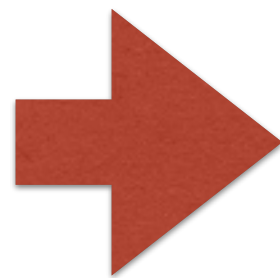
Discovery reach for pair production of strongly-interacting particles



SUSY and DM reach at 100 TeV



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



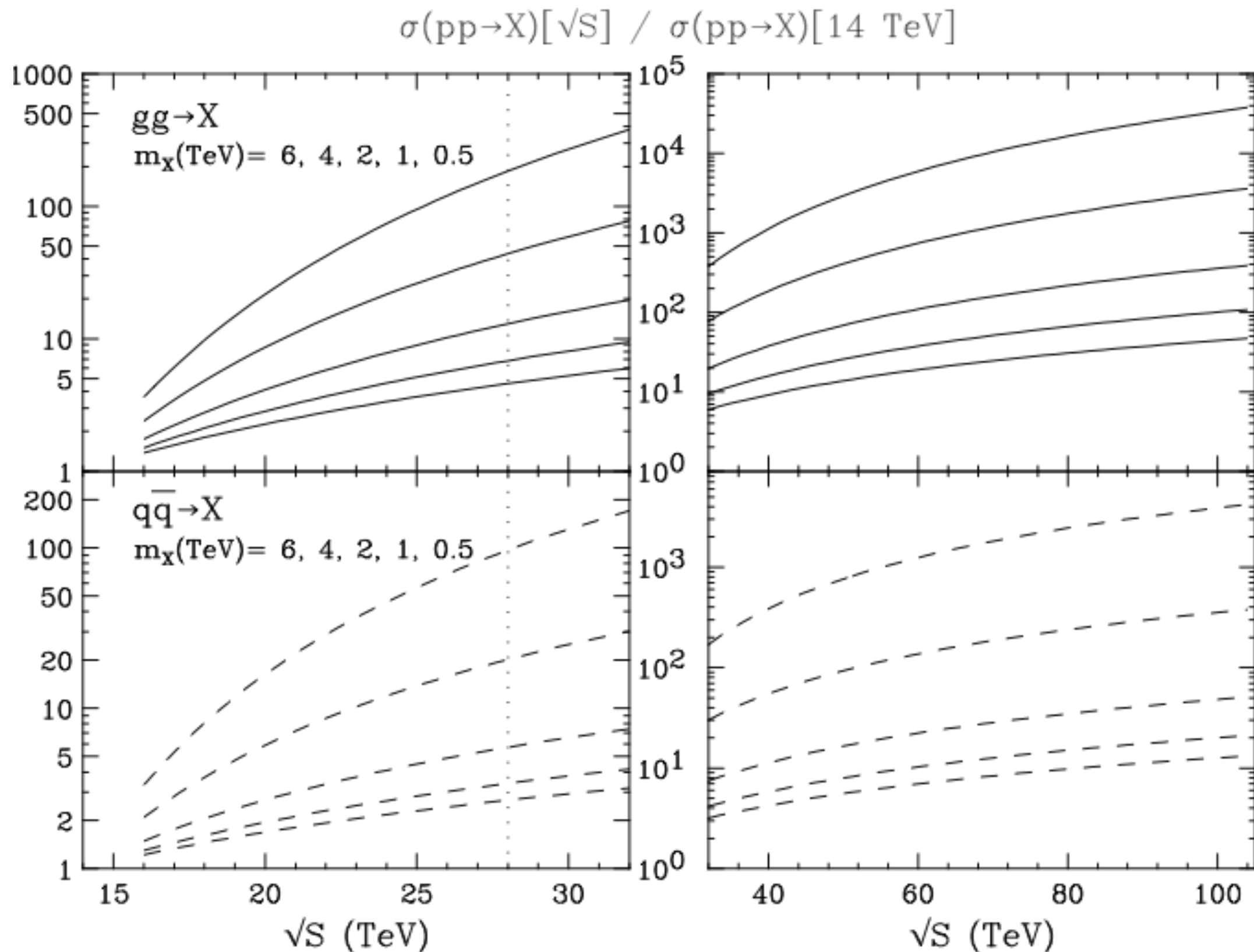
possibility to find (or rule out) thermal WIMP DM candidates

100 TeV ?

200 TeV ?

27 TeV in the LHC tunnel, replacing current magnets with those developed for FCC ?

Evolution, with beam energy, of scenarios with the discovery of a new particle at the LHC



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- All of this to be explored during the running CERN Workshop on HL/HE-LHC physics

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

30 October 2017 to 1 November 2017

CERN

Europe/Zurich timezone

Search...



<https://indico.cern.ch/event/647676/>

Next mtg of Higgs, BSM and flavour WGs: April 4-6 at FNAL, <https://indico.fnal.gov/event/16151/>

Next general mtg: June 18-20, CERN, <https://indico.cern.ch/event/686494/>

Workshop twiki pages: <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop>

To join the mailing list, click [here](#)

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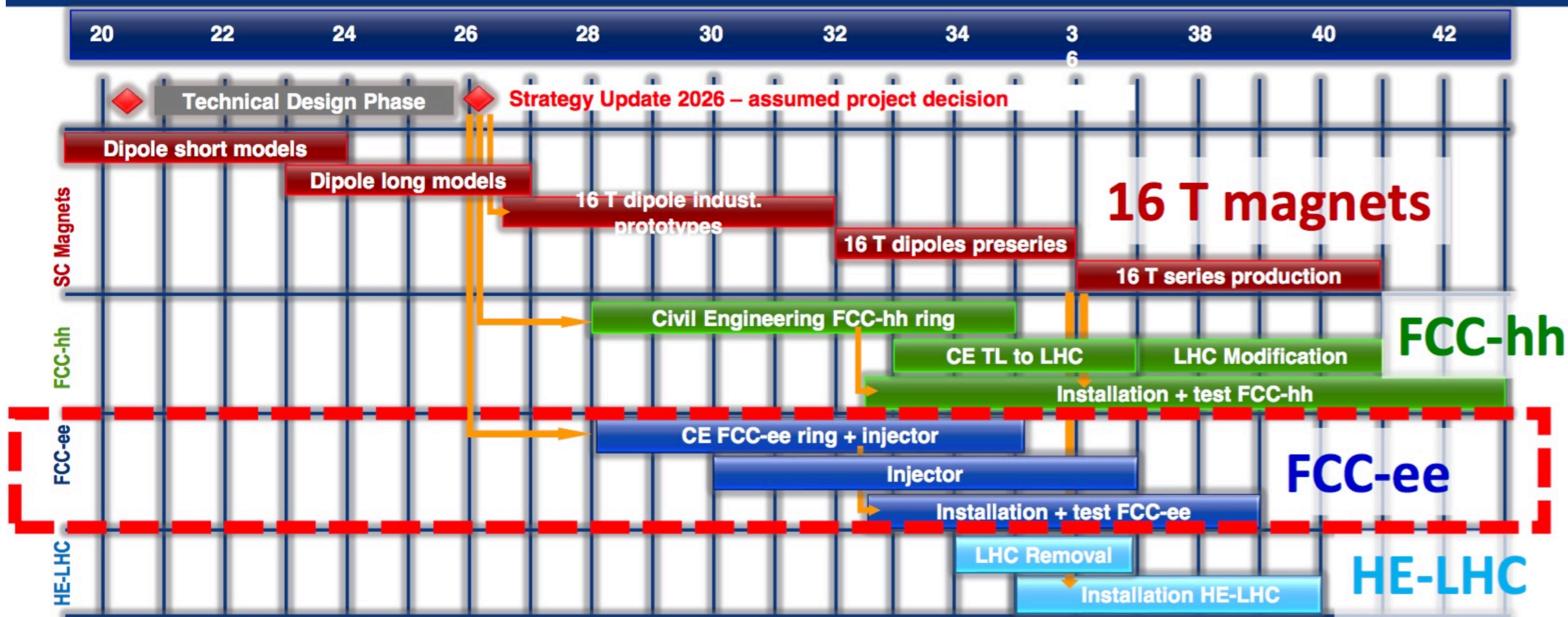
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=> it's like building the LHC ex-novo, and more

- very unlikely to be cheaper ...
- ... but not incompatible with a \sim constant CERN budget
- nevertheless feasibility to be proven (eg magnets bigger than LHC's: will they fit in the tunnel ??)



Technical Schedule for each the 3 Options



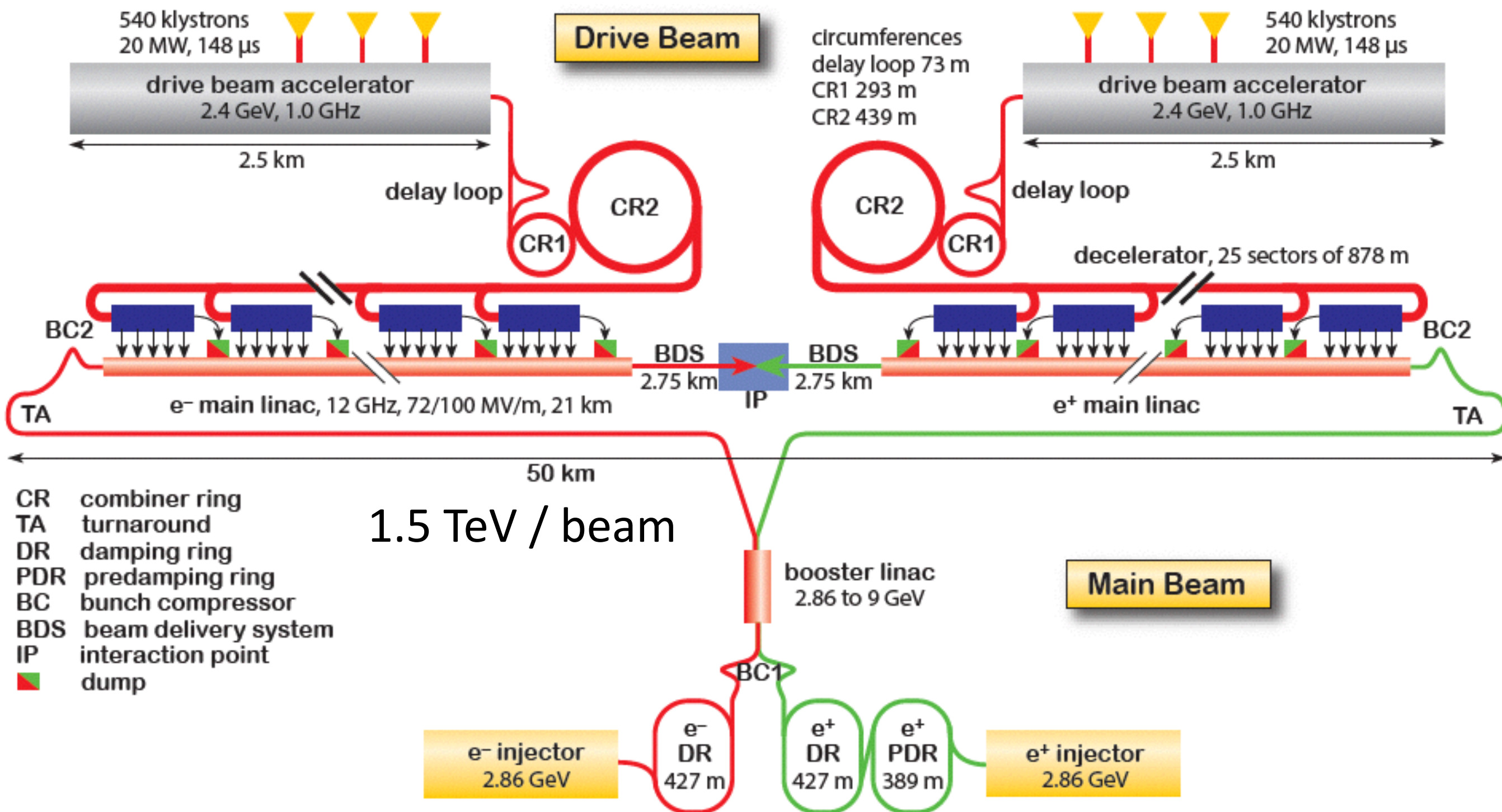
schedule constrained by 16 T magnets & CE

→ earliest possible physics starting dates

- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)

M. Benedikt

CLIC layout (3 TeV)



Project staging

Optimize machine design w.r.t. cost and power for a staged approach to reach multi-TeV scales:

- ~ 380 GeV (optimised for Higgs + top physics)
- ~ 1500 GeV
- ~ 3000 GeV

Adapting appropriately to LHC + other physics findings

Possibility for first physics no later than 2035

Project Plan to include accelerator, detector, physics

CLIC roadmap

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion



Final remarks

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- Nevertheless, the precise route followed to get there (via CLIC? via HE-LHC? via FCC-ee? ...) must take account of the fuller picture, to emerge from the LHC as well as other current and future experiments in areas ranging from flavour physics to dark matter searches. The right time scale for this assessment is ~ 10 yrs from now

Material and infos



Physics at the FCC-hh

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider>

Now available as a **CERN Yellow Report**

<https://e-publishing.cern.ch/index.php/CYRM/issue/view/35/showToc>

- **Volume 1: SM processes** (238 pages) arXiv:1607.01831
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages) arXiv:1606.09408
- **Volume 3: beyond the Standard Model phenomena** (189 pages) arXiv:1606.00947
- **Volume 4: physics with heavy ions** (56 pages) arXiv:1605.01389
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)

- **FCC-ee:**

- “First Look at the Physics Case of TLEP”, JHEP 1401 (2014) 164
- “High-precision α_s measurements from LHC to FCC-ee”, arXiv:1512.05194

- **FCC-eh:** no document as yet, see however

- “A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector”, J.Phys. G39 (2012) 075001

Recent Workshops



2nd FCC Physics Workshop

15-19 January 2018

CERN

Europe/Zurich timezone

<https://indico.cern.ch/event/618254/>



Mini workshop: Precision EW and QCD calculations for the FCC studies: methods and techniques

12-13 January 2018


CERN


Europe/Zurich timezone

<https://indico.cern.ch/event/669224/>



Ions at the Future Circular Collider

 Friday 29 Sep 2017, 09:00 → 12:30 Europe/Zurich

 160-1-009 (CERN)

<https://indico.cern.ch/event/664479/>

Andrea Dainese (INFN - Padova (IT)) , Carlos Albert Salgado Lopez (Universidade de Santiago de Compostela (ES)) ,

 Nestor Armesto Perez (Universidade de Santiago de Compostela (ES)) ,

Silvia Masciocchi (GSI - Helmholtzzentrum für Schwerionenforschung GmbH (DE)) , Urs Wiedemann (CERN)