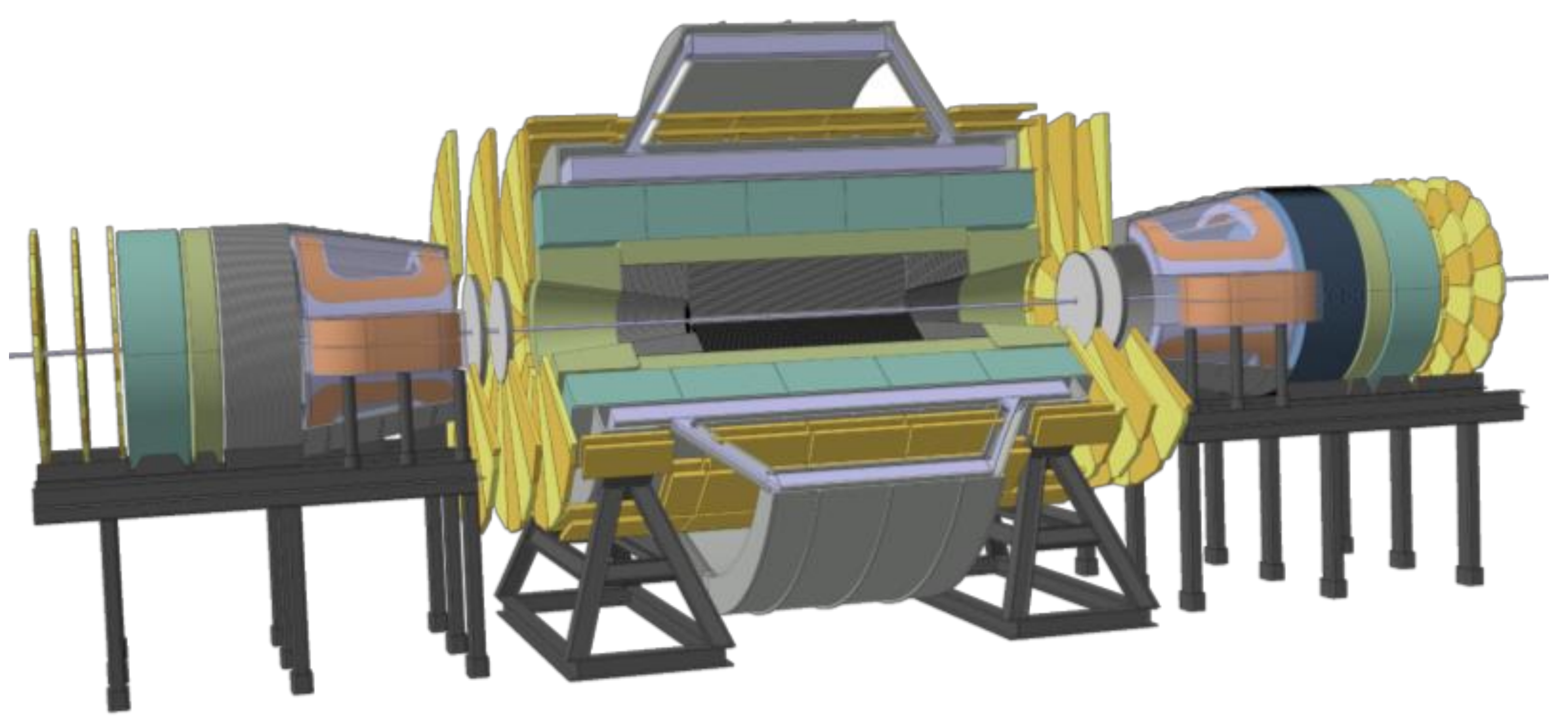
Review of SM Higgs studies at future hadron colliders (with a bias towards FCC-hh)

Heather M. Gray, CERN



Caveat Emptor

The future we imagined

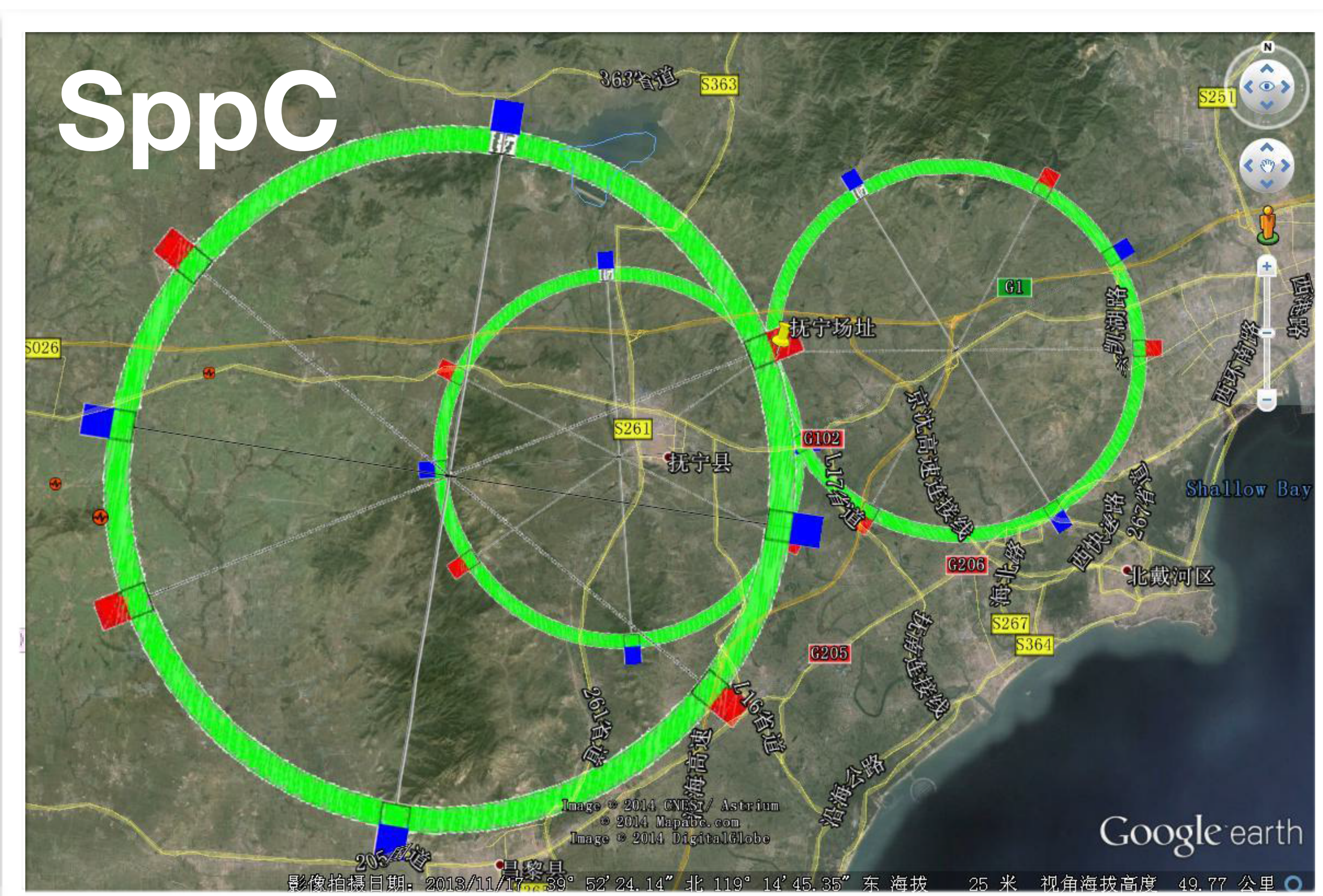
The actual future

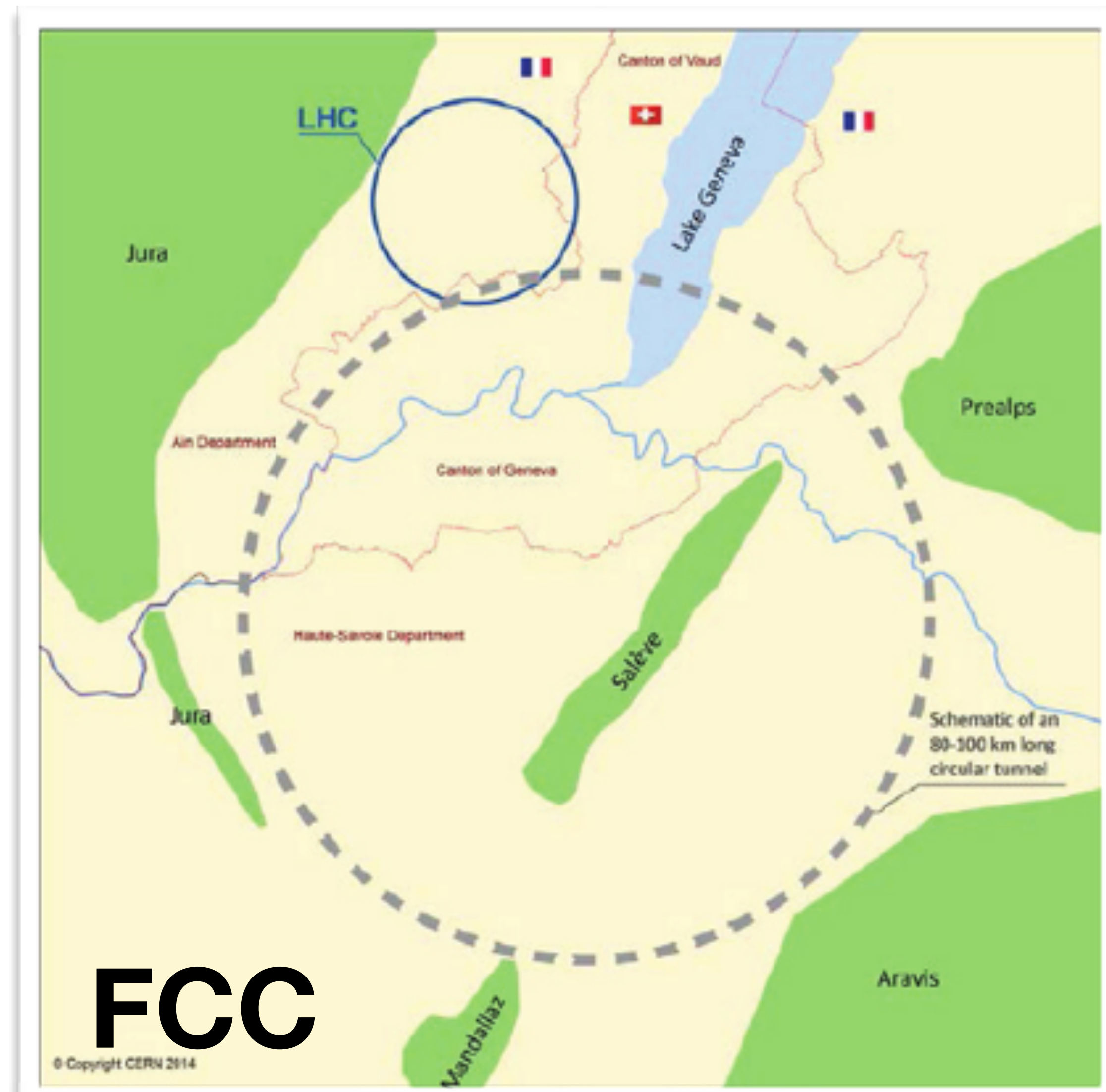
Spherical cow

Cow

Future hadron colliders

- Three proposed high-energy hadron colliders
  - HE-LHC (CERN): 26-33 TeV, ?
  - SppC (China): 70 TeV, 2042
  - FCC-hh (CERN): 100 TeV, 2035





FCC-hh

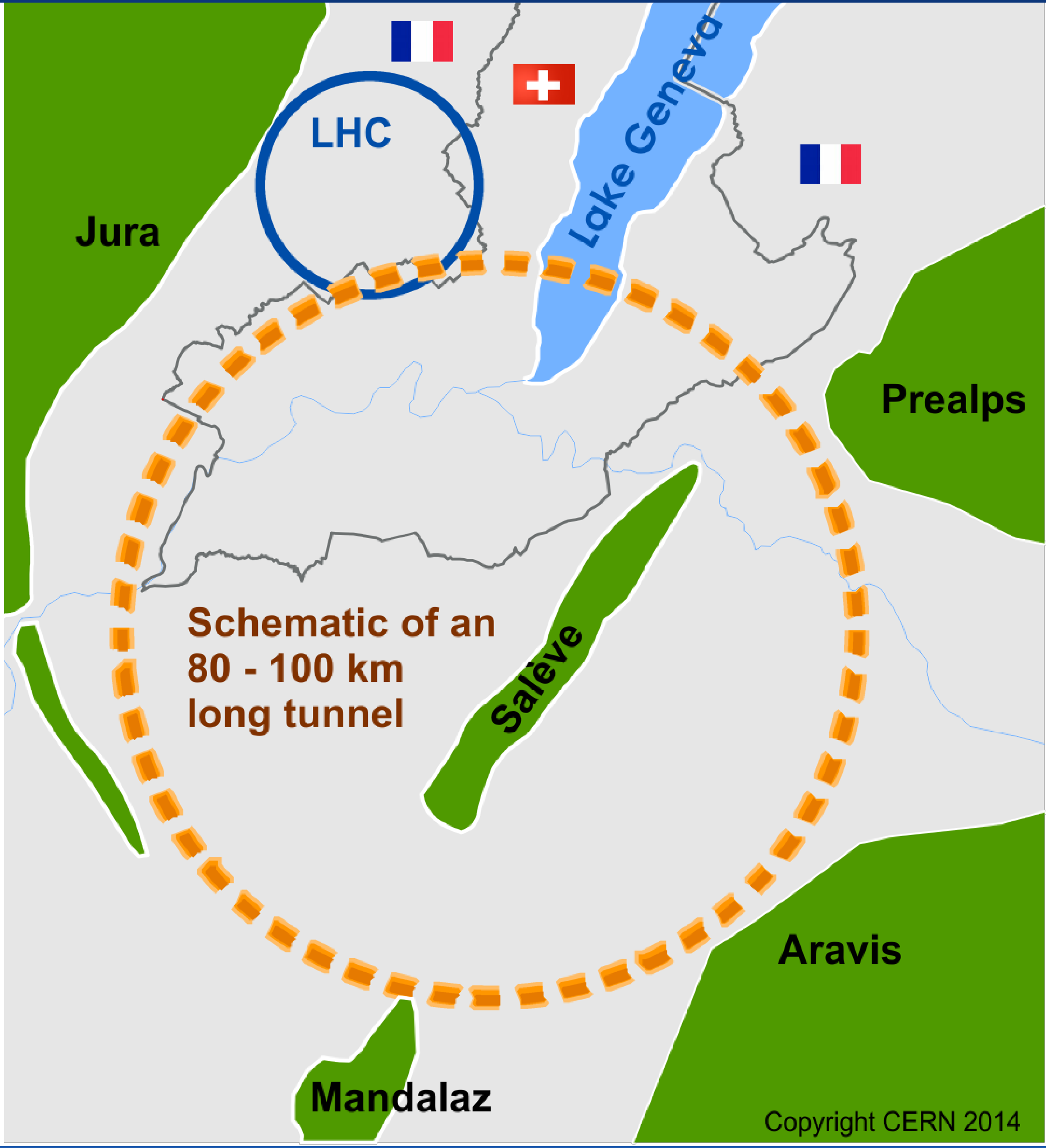
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

International FCC collaboration (CERN as host lab) to study:

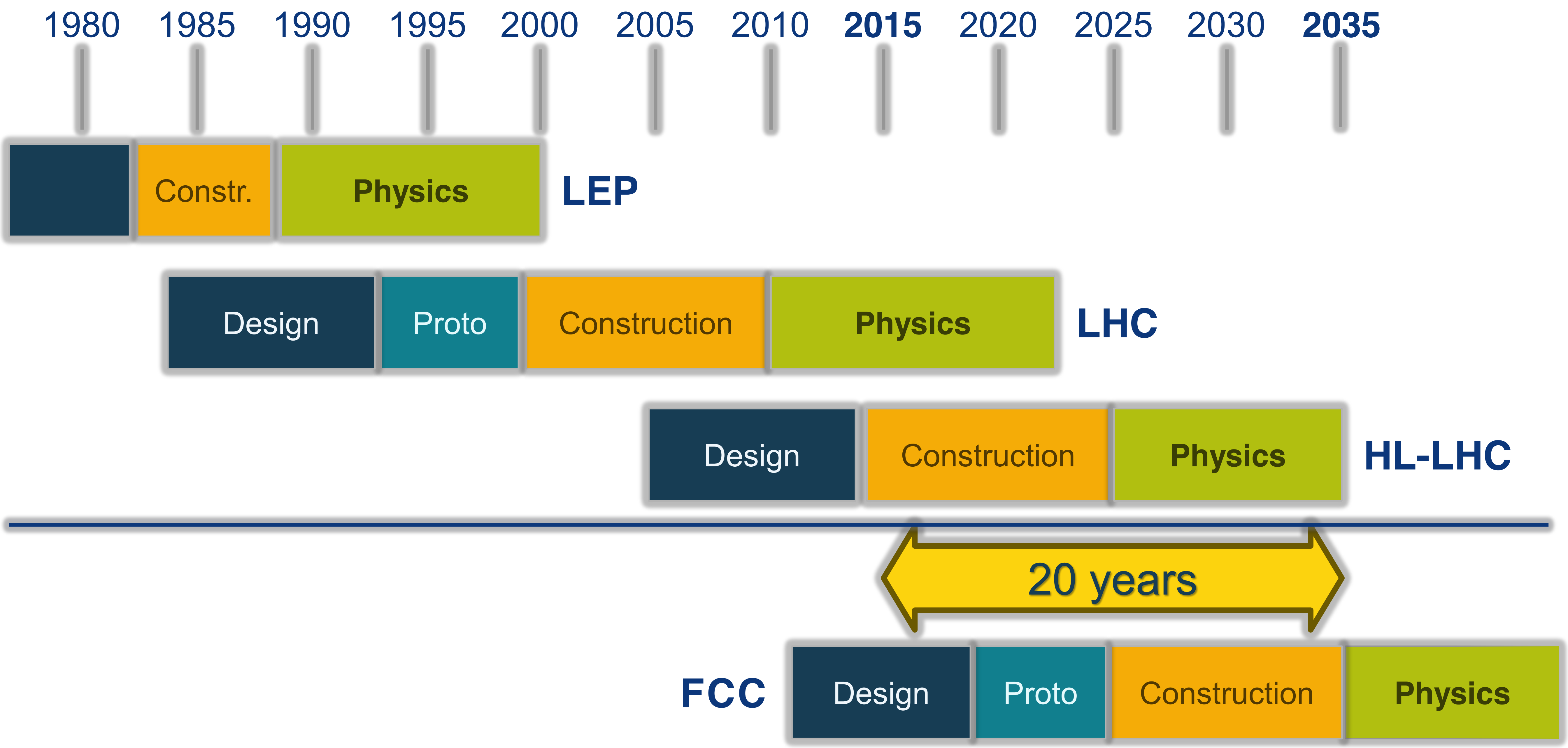
- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area
- ***e⁺e⁻* collider (*FCC-ee*)** as potential first step
- ***p-e* (*FCC-he*) option**
- **HE-LHC** with *FCC-hh* technology

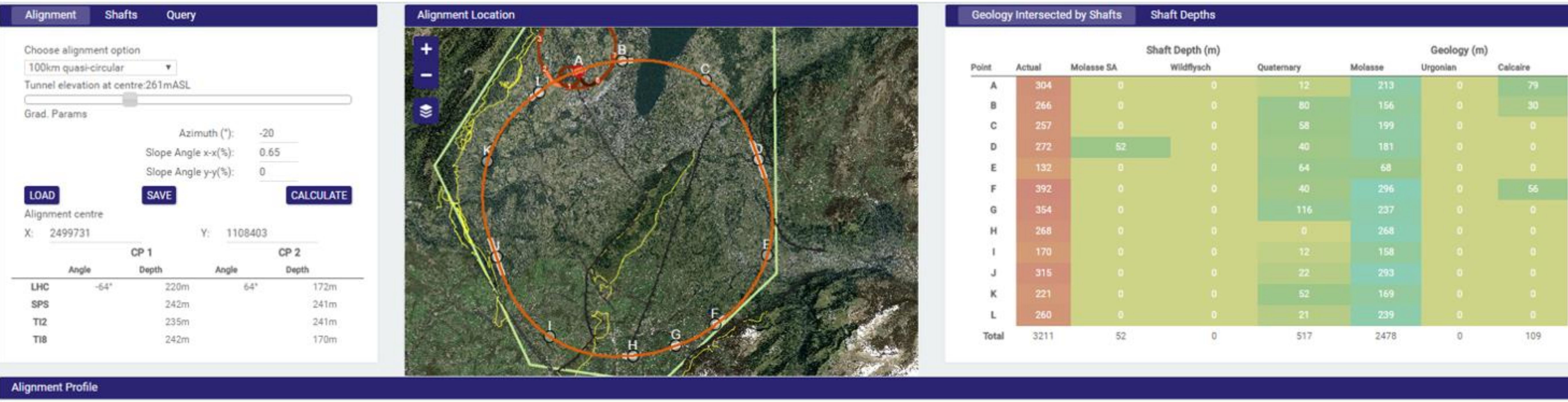


CERN Circular Colliders & FCC



Now is the time to plan for the period 2035 – 2040

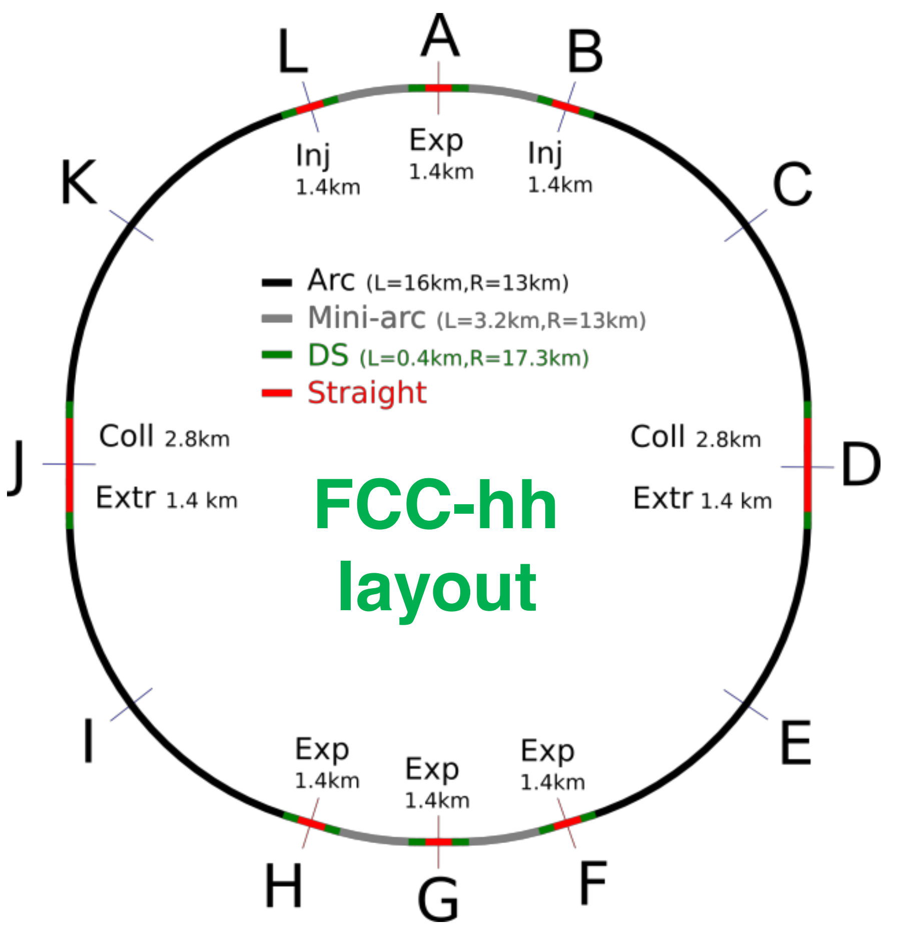
Progress on site investigations

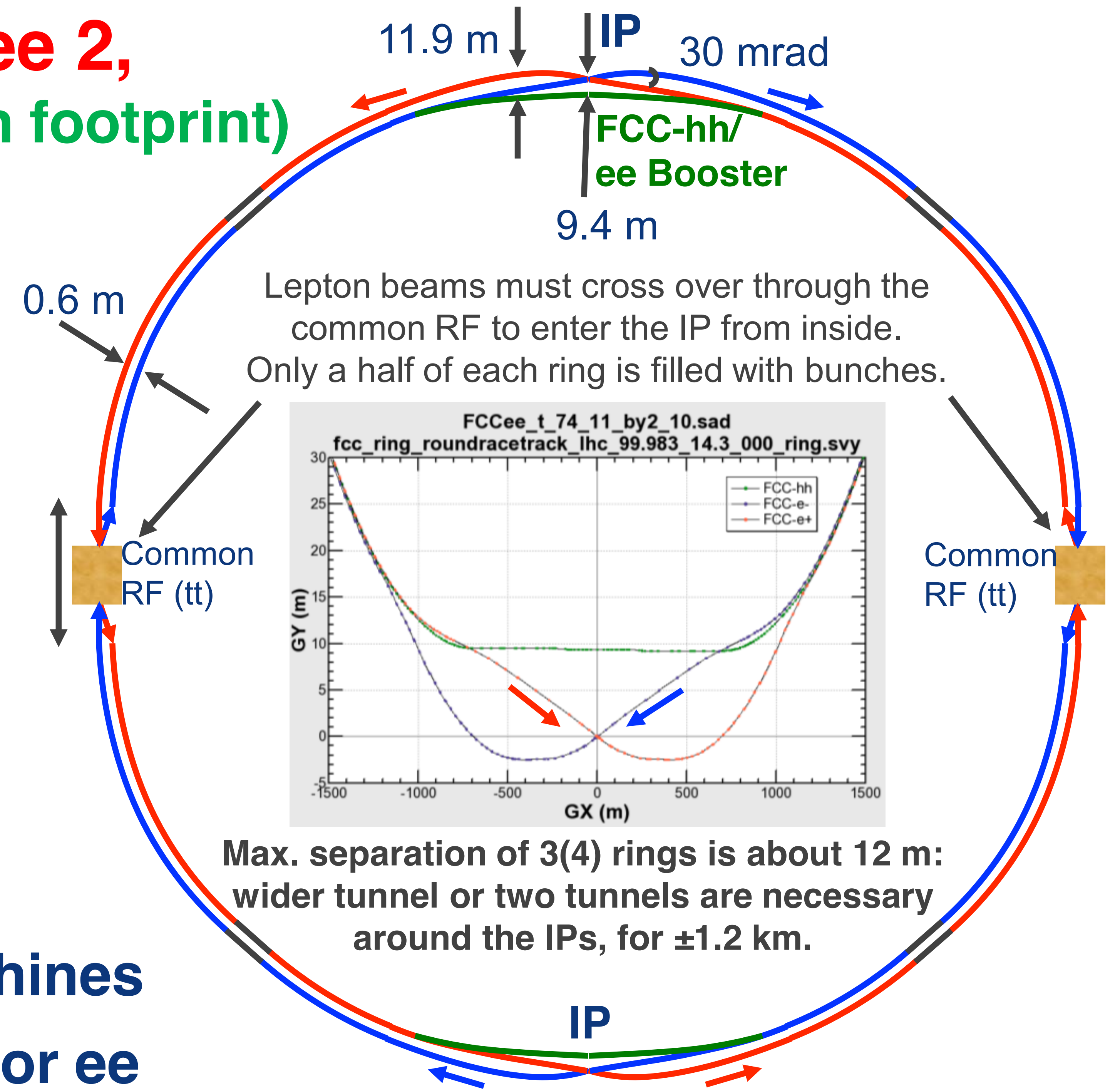


- 90 – 100 km fits geological situation well
- Review confirmed focus on 100 km, planar version
- LHC suitable as potential injector
- The 100 km version, intersecting LHC, is being studied now in more detail

Common layouts for hh & ee

FCC-ee 1, FCC-ee 2, FCC-ee booster (FCC-hh footprint)





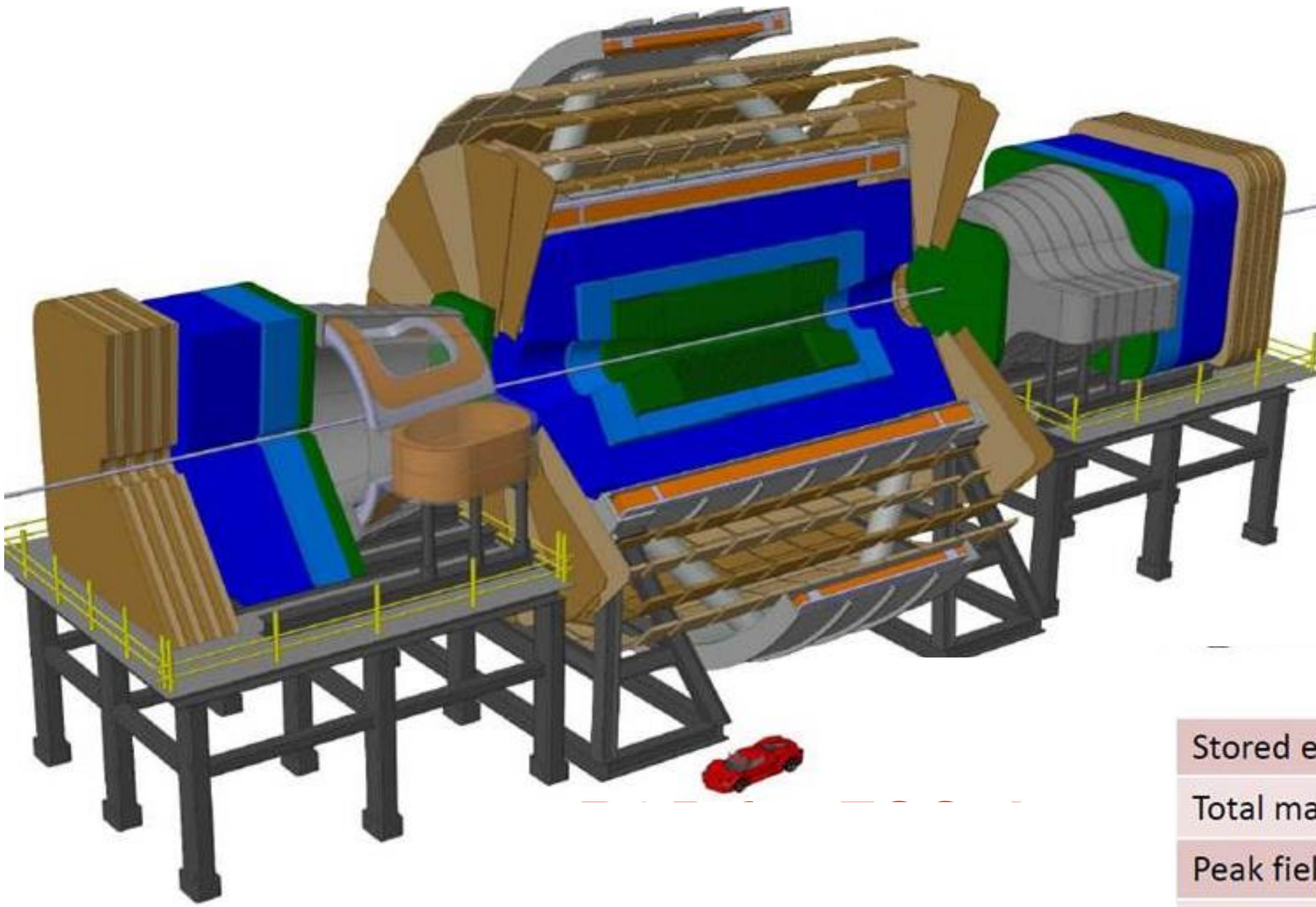
- 2 main IPs in A, G for both machines
- asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector

hadron collider parameters

parameter	FCC-hh		SPPC	HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		71.2	>25	14
dipole field [T]	16		20	16	8.3
circumference [km]	100		54	27	27
# IP	2 main & 2		2	2 & 2	2 & 2
beam current [A]	0.5		1.0	1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25	25
beta* [m]	1.1	0.3	0.75	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	12	>25	(5) 1
events/bunch crossing	170	<1020 (204)	400	850	(135) 27
stored energy/beam [GJ]	8.4		6.6	1.2	(0.7) 0.36
synchrotr. rad. [W/m/beam]	30		58	3.6	(0.35) 0.18

Detector Concepts for 100 TeV pp

A B=6 T, R=6 m solenoid with shielding coil and 2 dipoles has been engineered in detail.
Different alternative magnet systems are also being explored.



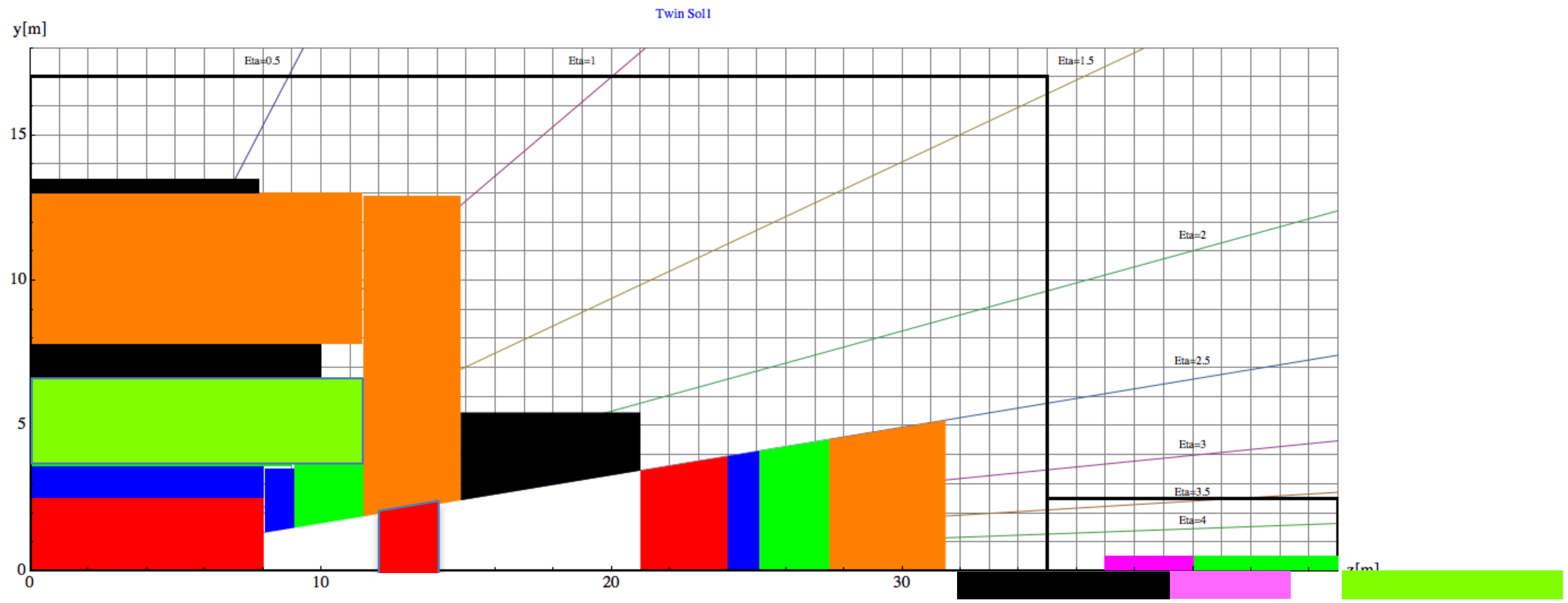
Some design challenges:

- large η acceptance
- radiation levels of >50 x LHC Phase II
- pileup of ~1000

	Twin Solenoid	Dipole
Stored energy	53 GJ	2 x 1.5 GJ
Total mass	6 kt	0.5 kt
Peak field	6.5 T	6.0 T
Current	80 kA	20 kA
Conductor	102 km	2 x 37 km
Bore x Length	12 m x 20 m	6 m x 6 m

Baseline Geometry

Baseline Geometry used up to now , Twin Solenoid, 6T, 12m bore, 10Tm dipole



Barrel:

Tracker available space:
R=2.1cm to R=2.5m, L=8m

EMCAL available space:
R=2.5m to R= 3.6m → dR= 1.1m

HCAL available space:
R= 3.6m to R=6.0m → dR=2.4m

Coil+Cryostat:
R= 6m to R= 7.825 → dR = 1.575m, L=10.1m

Muon available space:
R= 7.825m to R= 13m → dR = 5.175m
Revision of outer radius is ongoing.

Coil2:
R=13m to R=13.47m → dR=0.475m, L=7.6m

Endcap:

EMCAL available space:
z=8m to z= 9.1m → dz= 1.1m

HCAL available space:
z= 9.1m to z=11.5m → dz=2.4m

Muon available space:
z= 11.5m to z= 14.8m → dz = 3.3m

Forward:

Dipole:
z= 14.8m to z= 21m → dz=6.2m

FTracker available space:
z=21m to R=24m, L=3m

FEMCAL available space:
Z=24m to z= 25.1m → dz= 1.1m

FHCAL available space:
z= 25.1m to z=27.5m → dz=2.4m

FMuon available space:
z= 27.5m to z=31.5m → dz=4m

W. Riegler, FCC week

Baseline towards CDR

Development of 'Detector Baseline'

6T/12m bore:
Extreme magnet challenge, comfortable space for 2.4m tracker radius and 12 lambda of calorimeter.

4T/8m bore:
Extreme detector technology challenge, 1m tracker radius, short calorimeter, possibly Tungsten.

4T/10m bore:
Probably a good middle ground from which we can explore the performance towards smaller and larger values.

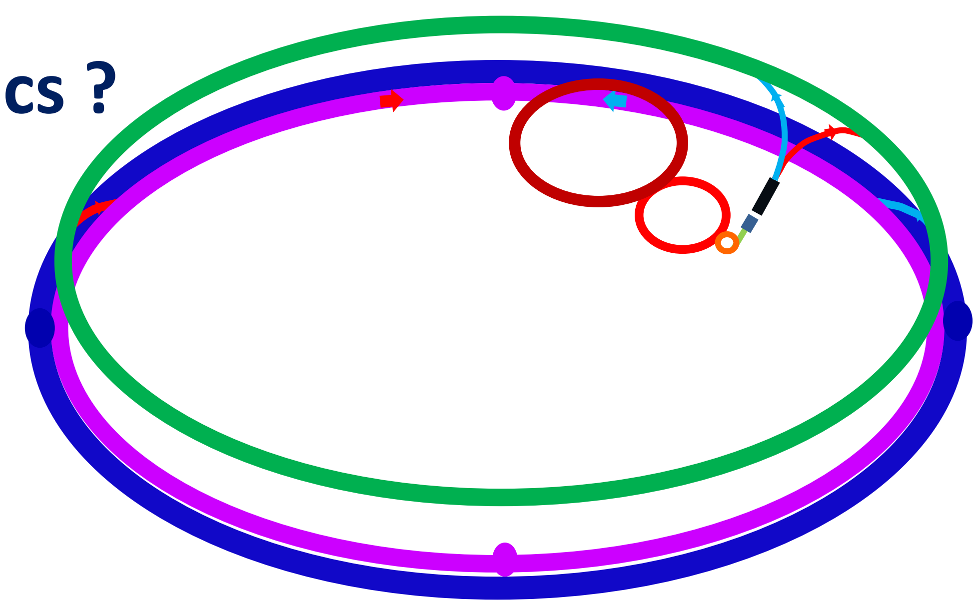
For the forward spectrometer:
Pushing the detector resolution and relaxing the field integram form 10 to 4-5Tm seems appropriate.

CEPC-SPPC

CEPC-SPPC

Y. Wang @ FCC week

- **Electron-positron collider(90, 250 GeV)**
  - **Higgs Factory: Precision study of Higgs**
    - **Higgs mass, width, couplings, J^{PC}, etc.**
    - **Looking for deviation from SM, new physics ?**
  - **Z & W factory: precision test of SM**
    - **Deviation from SM ?**
  - **Flavor factory: b, c, τ and QCD studies**

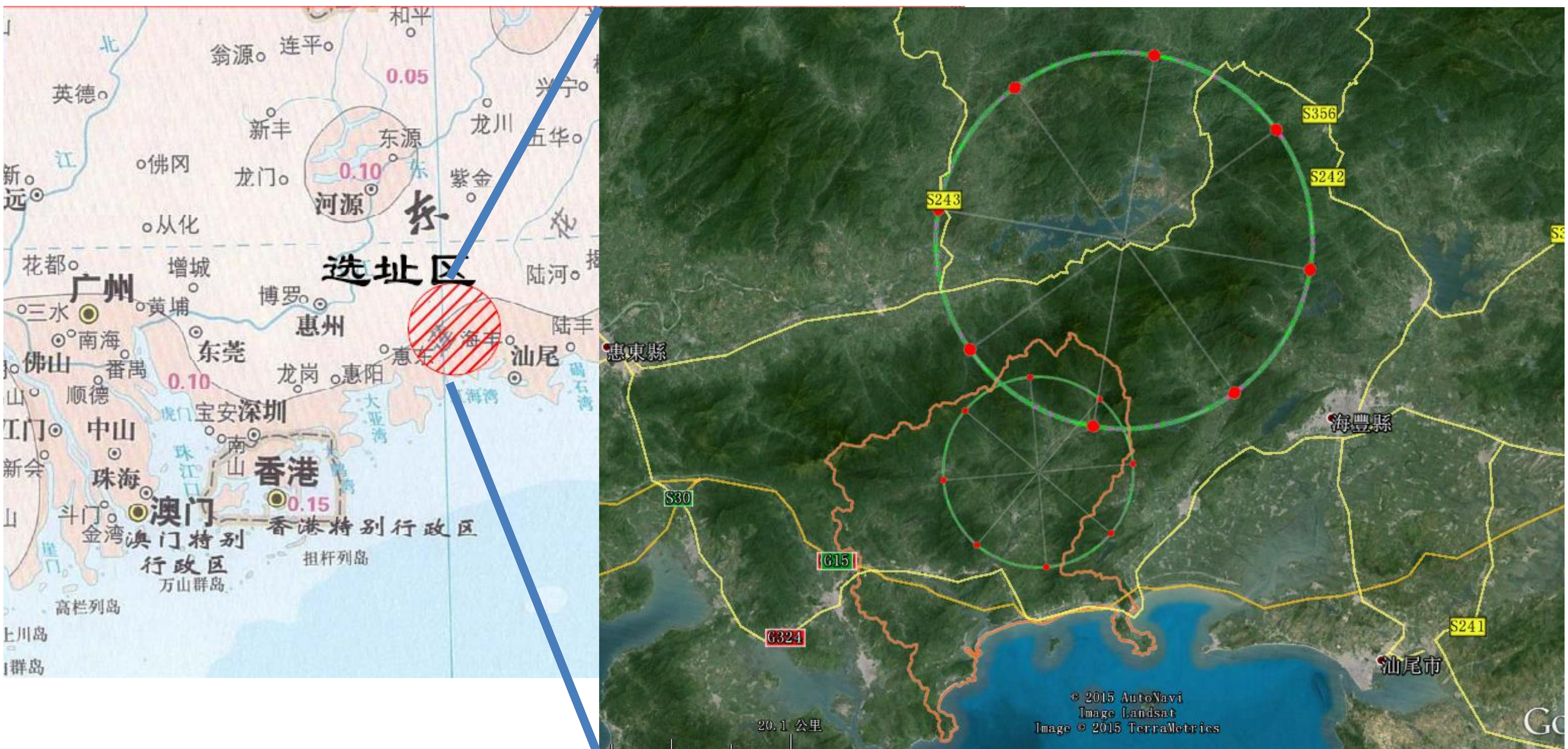


- **Proton-proton collider(~100 TeV)**
  - **Directly search for new physics beyond SM**
  - **Precision test of SM**
    - **e.g., h^3 & h^4 couplings**

Precision measurement + searches:
Complementary with each other !

Site Selection

- Continue to work on site selection
- A new possibility, invited by the local government



Southern China, near Daya Bay/Hong Kong

Timeline (dream)

- **CPEC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15
      - **Pre-CDR for R&D funding request**
    - R&D: 2016-2020
    - Engineering Design: 2015-2020
  - Construction: 2022-2028
  - Data taking: 2029-2035
- **SppC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-2020
    - R&D: 2020-2030
    - Engineering Design: 2030-2035
  - Construction: 2035-2042
  - Data taking: 2042 -

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China plans world's most powerful particle collider

By Cheng Yingqi (China Daily)

Updated: 2015-10-29 07:49

Comments Print Mail Large Medium Small

The first phase of the project's construction is scheduled to begin between 2020 and 2025

Media is media
Chinese media is also media
Don't get too excited, nor panic
CEPC will not be easy and quick
R&D will come gradually

Five-year plan boosts basic research funding

Blueprint gives few details, but scientists foresee more generous grants and new facilities

By **Hao Xin**, *in Beijing*

Science, vol. 351, no. 6280, pp. 1382, 2016

C a windfall for basic science. Cosmic evolution, the structure of matter, the origins of life, and understanding how the brain works all deserve strengthened support, according to China's latest 5-year development plan, which could triple funding for basic research by 2020.

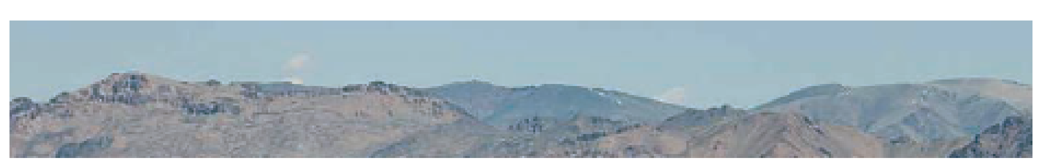
An outline of the plan, which covers 2016 through 2020, received pro forma approval by the National People's Congress (NPC) on 16 March at its closing session. The plan signals that top leaders are looking to researchers, even those doing fundamental work, for innovations that will drive the economy as it

of Science and Technology (MOST), which ...ed research, can ...s under the new 5-year plan. CAS is holding expert meetings to help it decide which programs to support, according to its website. MOST has already called for proposals in nine areas, including precision medicine, reproductive health, biomedical materials, global change, and cloud computing and big data mining.

New big science projects, too, are vying for a share of the increased funding. After the U.S.-based Advanced Laser Interferometer Gravitational-Wave Observatory an-

at the South Pole and made a premature detection claim 2 years ago. Some in the Chinese scientific community have suggested that the Ngari project should enlist international collaborators.

For one high-profile project the news is not as good. China plans to hold off on construction of the Circular Electron Positron Collider (CEPC), intended to generate large numbers of Higgs bosons to precisely measure the particle's mass. The project would cost somewhere between \$3.8 billion and \$5.4 billion, depending on its circumference. Wang Yifang, director of CAS's Institute of High Energy Physics in Beijing, the chief sponsor of the CEPC, says the project continues to get R&D funding.



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Higgs Physics at 100 TeV

Yellow Report on Higgs Studies

Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies

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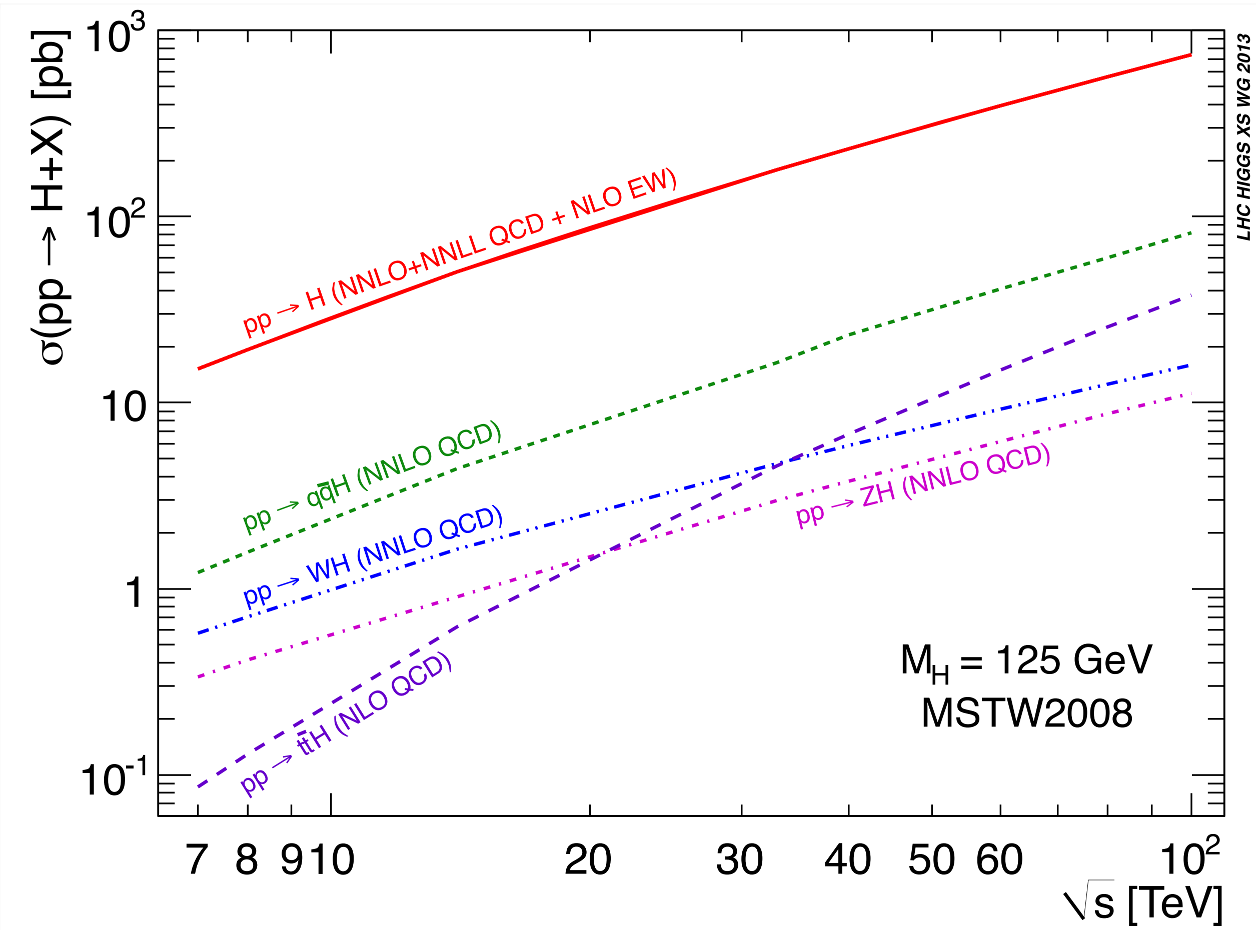
- Single Higgs Production, cross-sections
- Prospects for precision Higgs measurements
- MultiHiggs production and trilinear Higgs coupling
- (Extended Higgs sectors in BSM models)

Higgs Chapter

Single Higgs Production

Higgs production cross-sections



	$gg \to H$ (Sect 1.1)	VBF (Sect 1.5)	$HW^{\pm}$ (Sect 1.4)	HZ (Sect 1.4)	$t\bar{t}H$ (Sect 1.6)
σ(pb)	802	69	15.7	11.2	32.1
σ(100 TeV)/σ(14 TeV)	16.5	16.1	10.4	11.4	52.3

	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

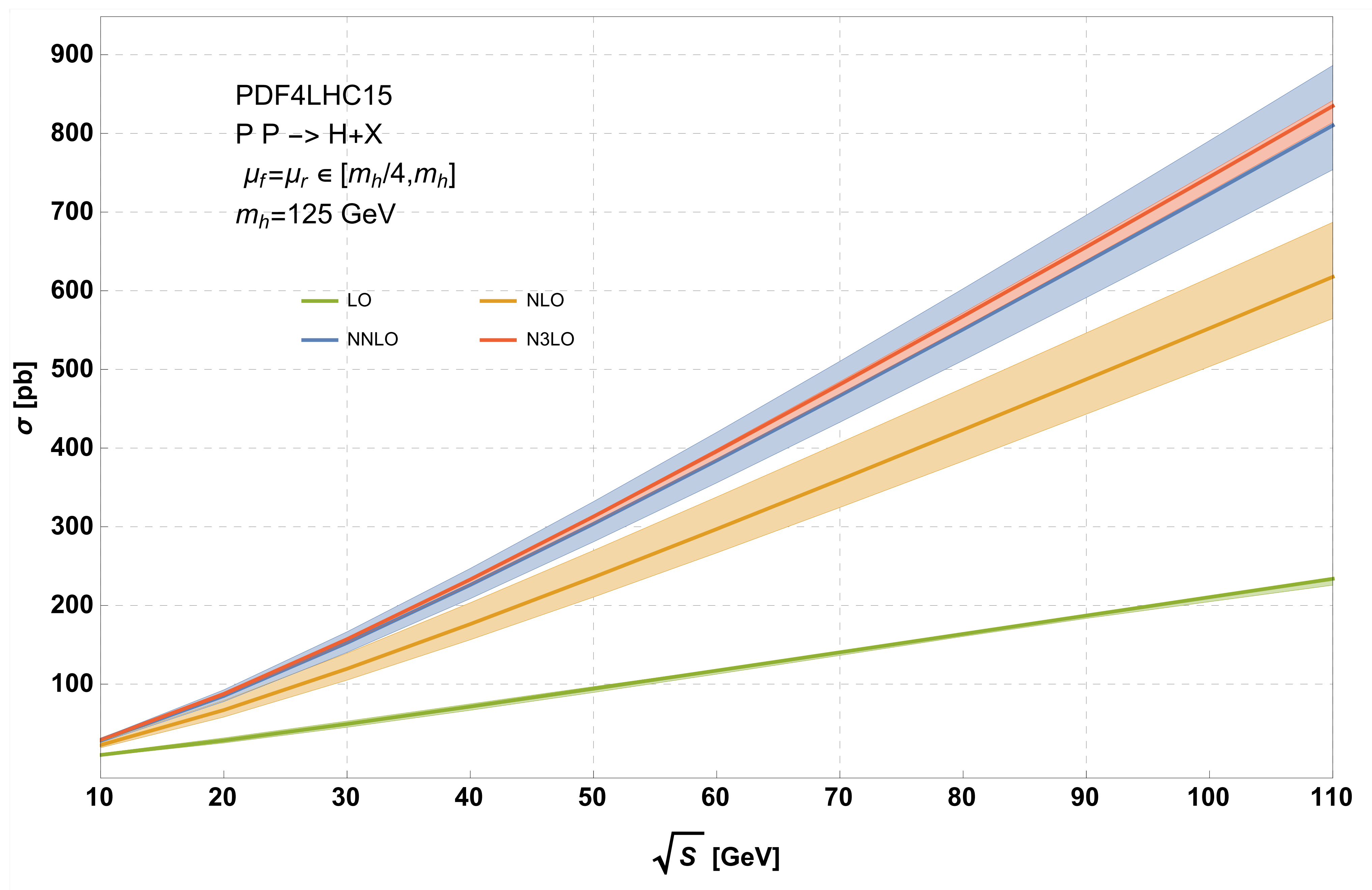
$N_{100} = \sigma_{100}$ x 20 ab^{-1}

$N_{14} = \sigma_{100}$ x 3 ab^{-1}

$N_8 = \sigma_8$ x 20 fb^{-1}

Precision @ 100 TeV

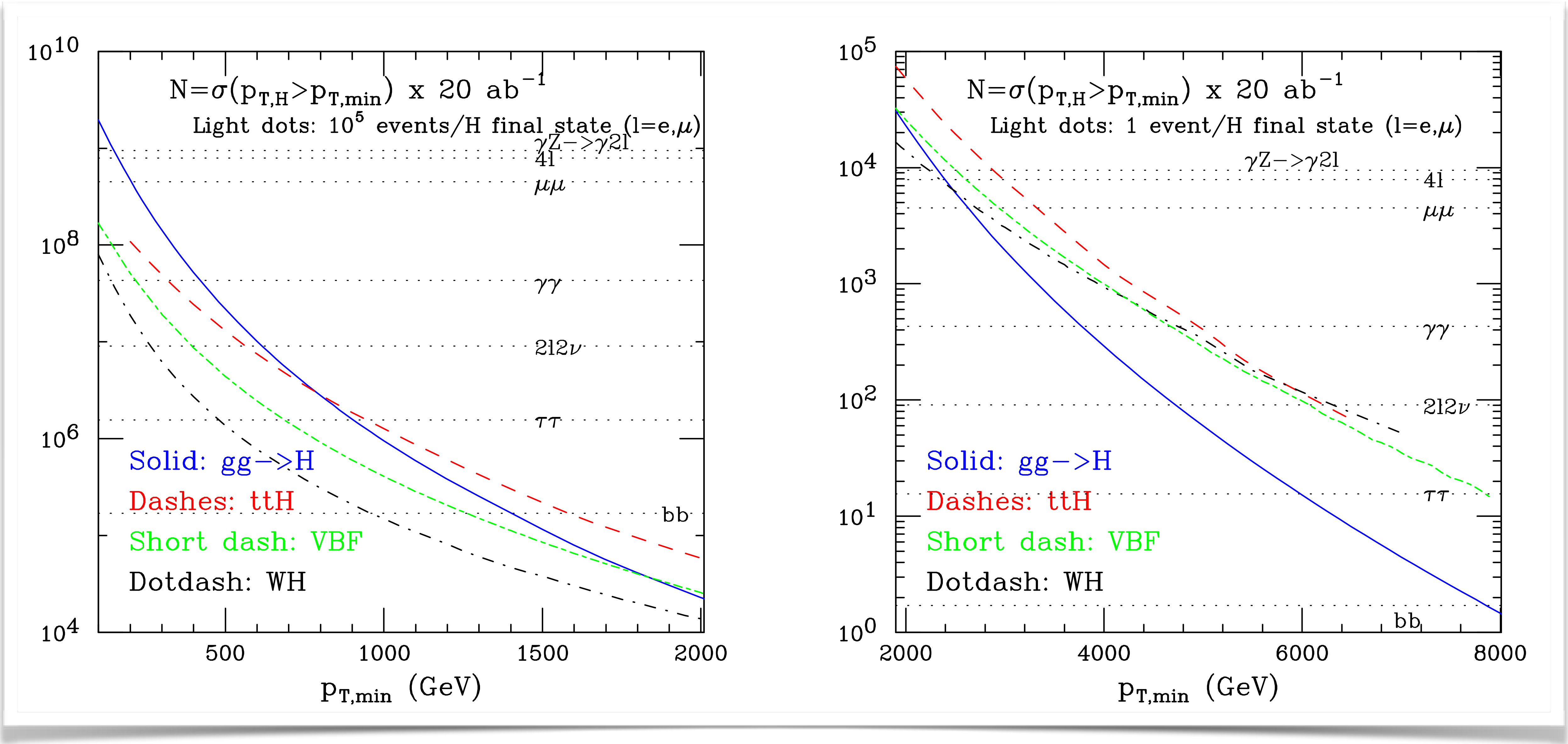
N3LO calculation of gg→H!



$$\sigma = 802\text{ pb}\,^{+6.1\%}_{-7.2\%}(\delta_{\text{theo}})^{+2.5\%}_{-2.5\%}(\delta_{\text{PDF}})^{+2.9\%}_{-2.9\%}(\delta_{\alpha_s}).$$

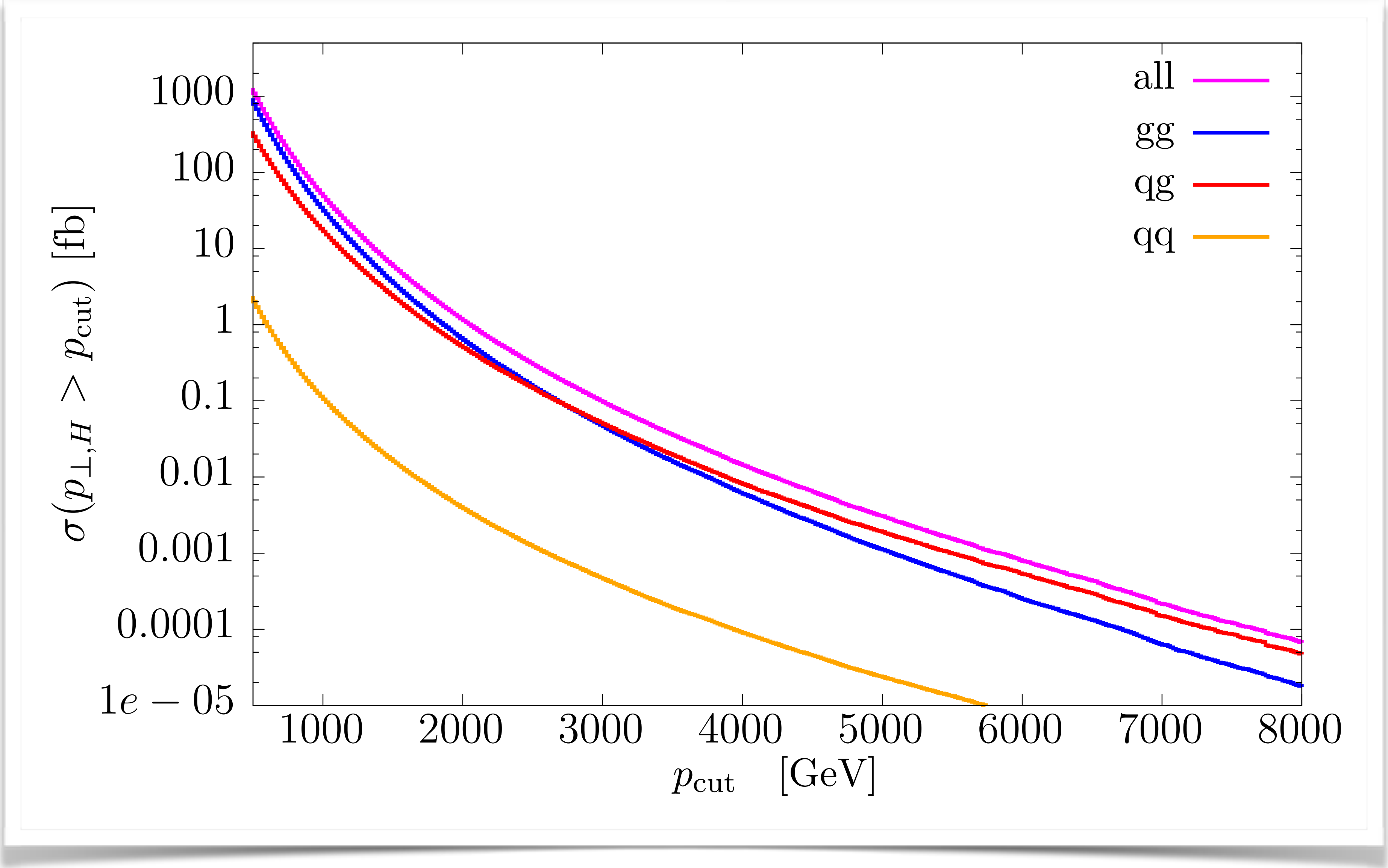
δ_{PDF}	δ_{α_S}	δ_{scale}	$\delta_{\text{PDF-theo}}$	δ_{EW}	δ_{tbc}	$\delta_{\frac{1}{m_t}}$
$\pm 2.5\%$	$\pm 2.9\%$	$^{+0.8\%}_{-1.9\%}$	$\pm 2.7\%$	$\pm 1\%$	$\pm 0.8\%$	$\pm 1\%$

Extreme kinematic regimes



- Hierarchy in production processes is strongly p_T dependent, ttH overtakes ggF around 700 GeV, then WH overtakes ttH around 6 TeV
- Reason: Form-factor-like suppression of the ggH vertex at large virtuality, due to finite-m_{top} effects

Extreme kinematics (II)

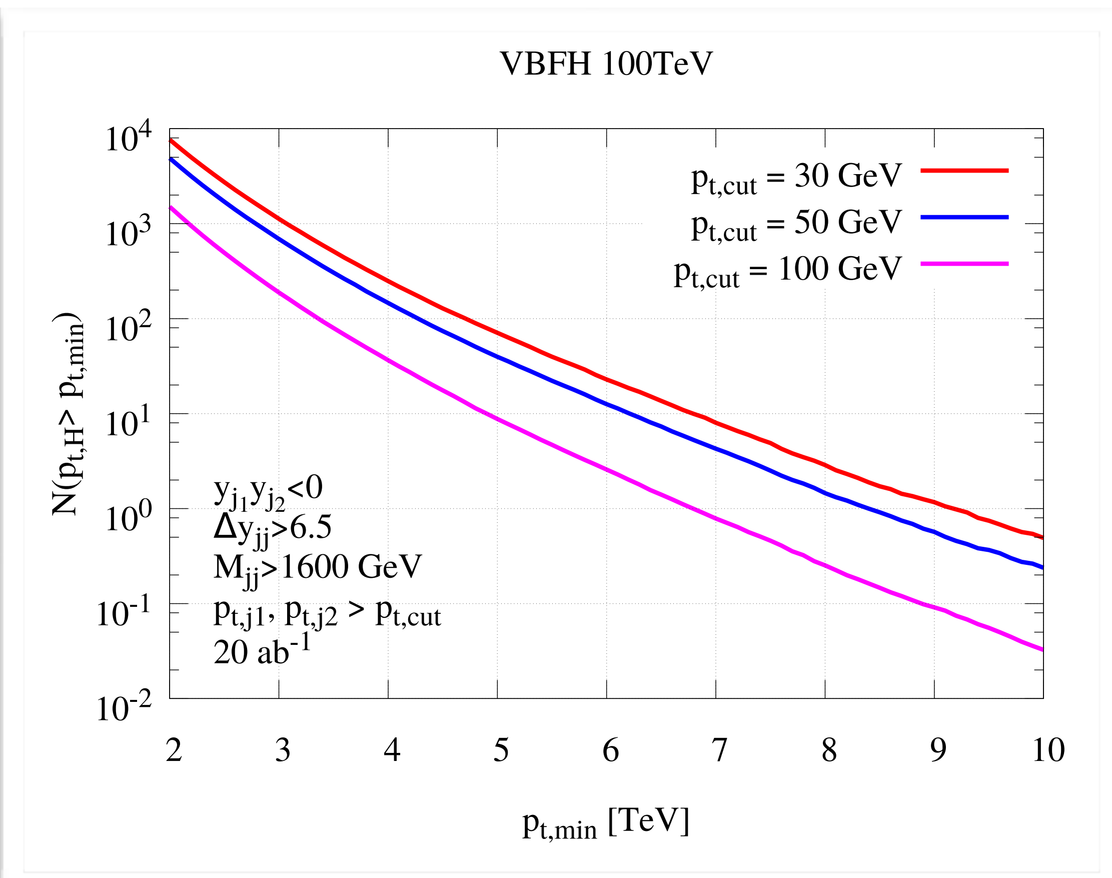


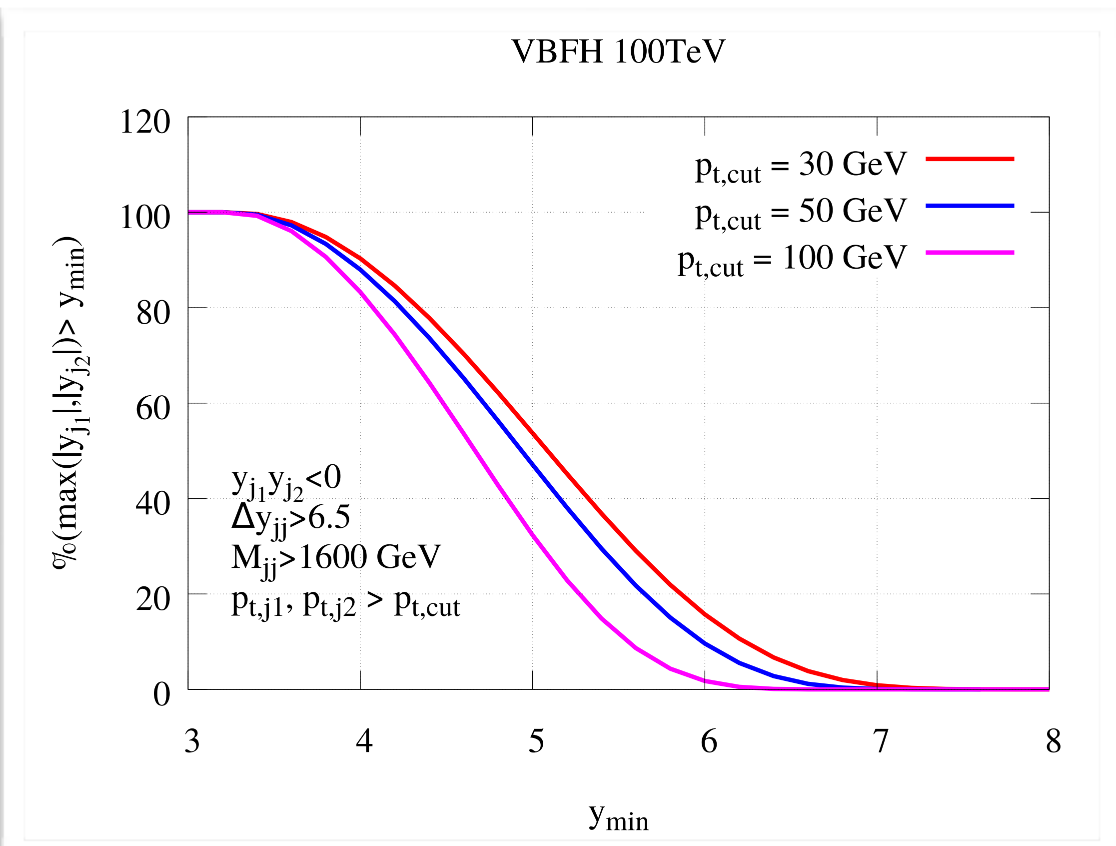
- Similarly, within ‘ggF’
- e.g. ‘gq’ has a larger cross-section than ‘gg’ for $p_T > 2.5$ TeV

VBF @ 100 TeV

- Study of VBF production with simple selection cuts
- Rapidity coverage is critical: 40% events retained for |η| < 4.5
- Would benefit from coverage up to |η| < 6 … challenging

	$\sigma(p_{t,j} > 30$ GeV) [pb]	$\sigma(p_{t,j} > 50$ GeV) [pb]	$\sigma(p_{t,j} > 100$ GeV) [pb]
VBFH	14.1	7.51	1.08
QCD Hjj	5.04	1.97	0.331
$S/\sqrt{B}$@(20 ab^{-1})	28100	24200	8500



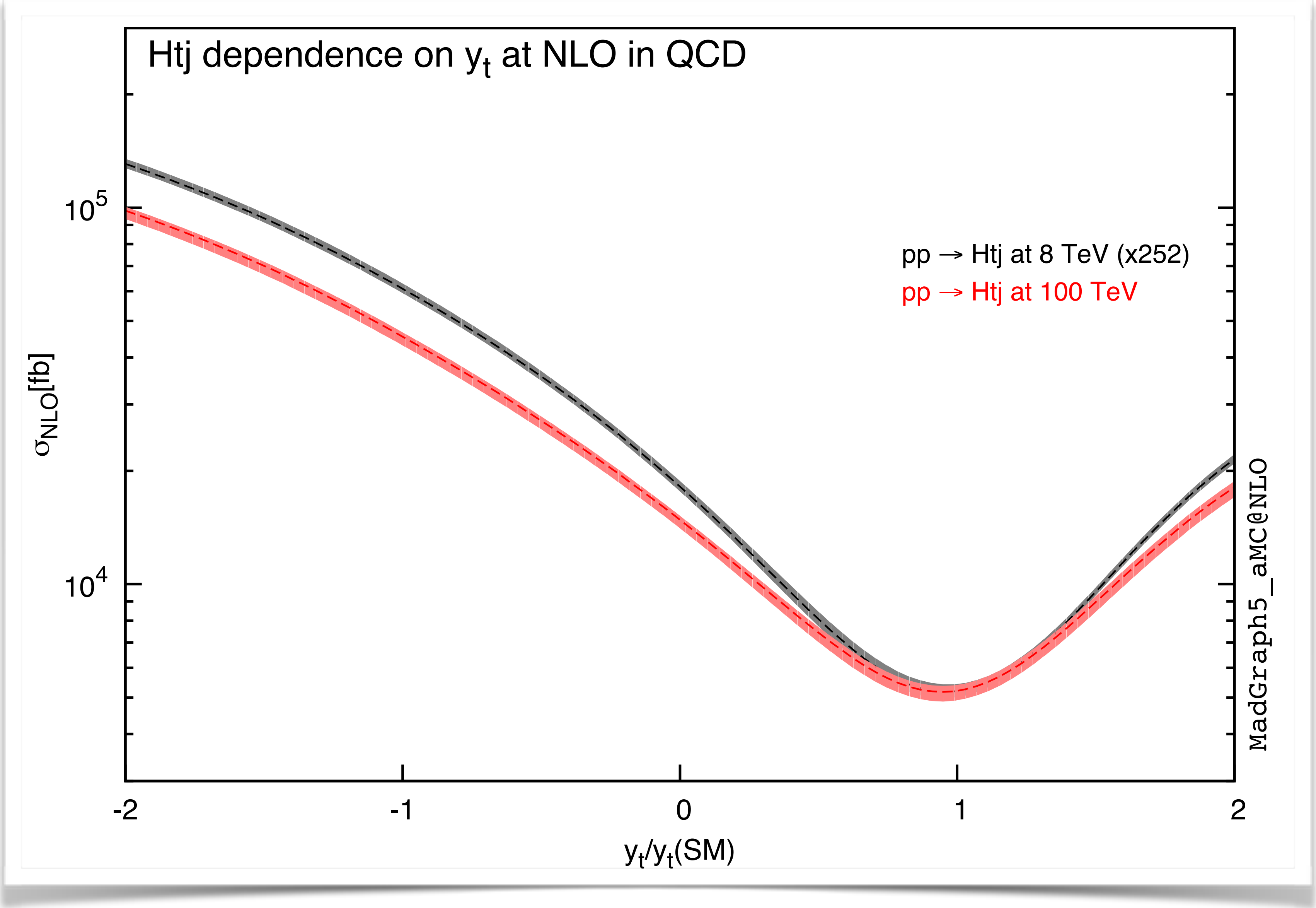


Rare modes

- At 100 TeV, production cross-sections for very rare modes become non-negligible
- Huge increase for pp→Htj: 250x 8 TeV (no cuts)
- Could use HVV to constrain possible anomalous Higgs couplings to vector-boson (and fermion) pairs?,
  - perturbative unitarity at high energy
  - anomalous triple-vector-boson vertices

Process	σ_{NLO}(8 TeV) [fb]	σ_{NLO}(100 TeV) [fb]	ρ
$pp \to Htj$	$2.07 \cdot 10^{1}\,{}^{+2\%}_{-1\%}\,{}^{+2\%}_{-2\%}$	$5.21 \cdot 10^{3}\,{}^{+3\%}_{-5\%}\,{}^{+1\%}_{-1\%}$	252
$pp \to HW^+W^-$ (4FS)	$4.62 \cdot 10^{0}\,{}^{+3\%}_{-2\%}\,{}^{+2\%}_{-2\%}$	$1.68 \cdot 10^{2}\,{}^{+5\%}_{-6\%}\,{}^{+2\%}_{-1\%}$	36
$pp \to HZW^\pm$	$2.17 \cdot 10^{0}\,{}^{+4\%}_{-4\%}\,{}^{+2\%}_{-2\%}$	$9.94 \cdot 10^{1}\,{}^{+6\%}_{-7\%}\,{}^{+2\%}_{-1\%}$	46
$pp \to HW^\pm\gamma$	$2.36 \cdot 10^{0}\,{}^{+3\%}_{-3\%}\,{}^{+2\%}_{-2\%}$	$7.75 \cdot 10^{1}\,{}^{+7\%}_{-8\%}\,{}^{+2\%}_{-1\%}$	33
$pp \to HZ\gamma$	$1.54 \cdot 10^{0}\,{}^{+3\%}_{-2\%}\,{}^{+2\%}_{-2\%}$	$4.29 \cdot 10^{1}\,{}^{+5\%}_{-7\%}\,{}^{+2\%}_{-2\%}$	28
$pp \to HZZ$	$1.10 \cdot 10^{0}\,{}^{+2\%}_{-2\%}\,{}^{+2\%}_{-2\%}$	$4.20 \cdot 10^{1}\,{}^{+4\%}_{-6\%}\,{}^{+2\%}_{-1\%}$	38

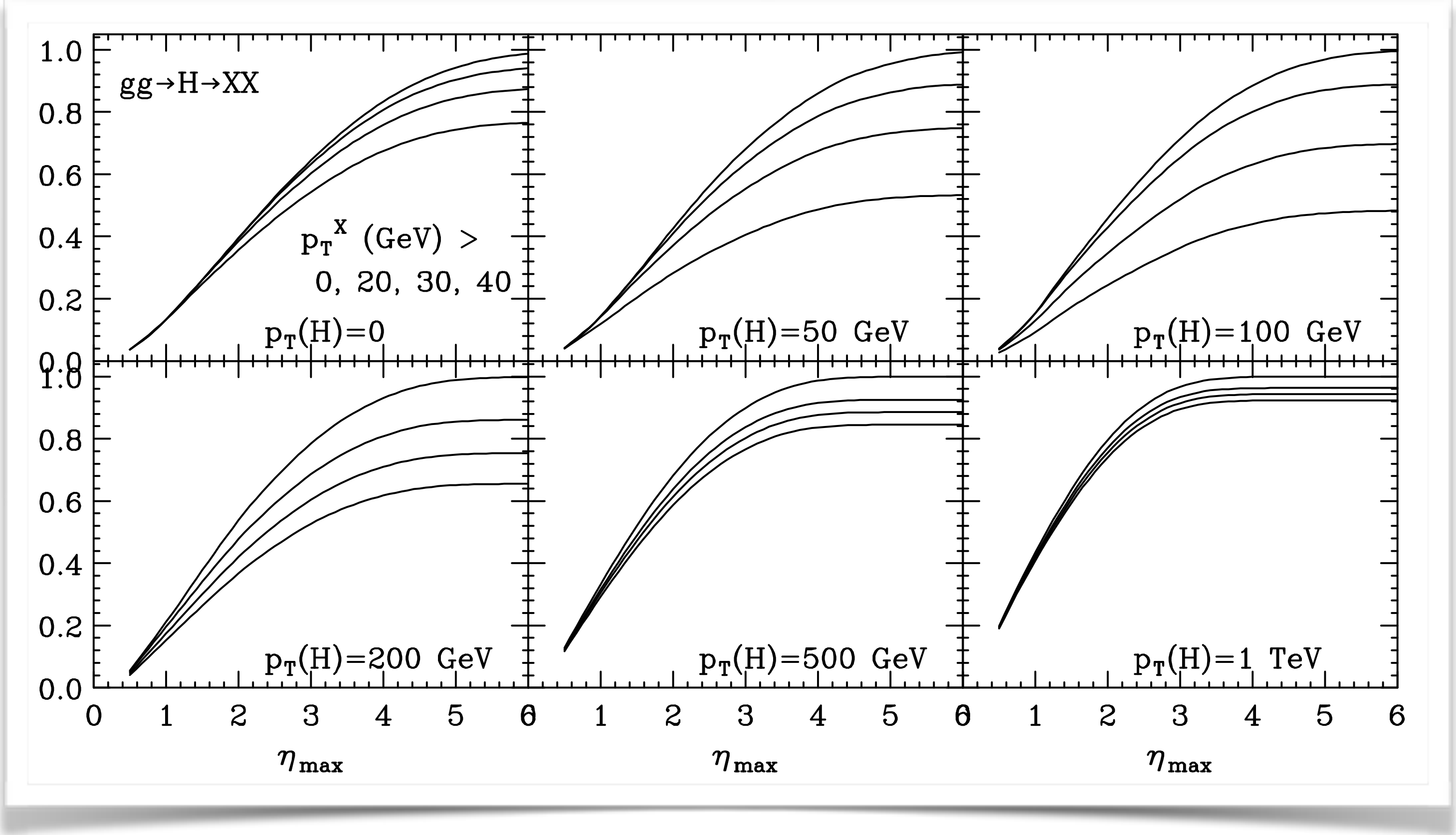
Htj



Can this channel be used for a measurement of y_t?

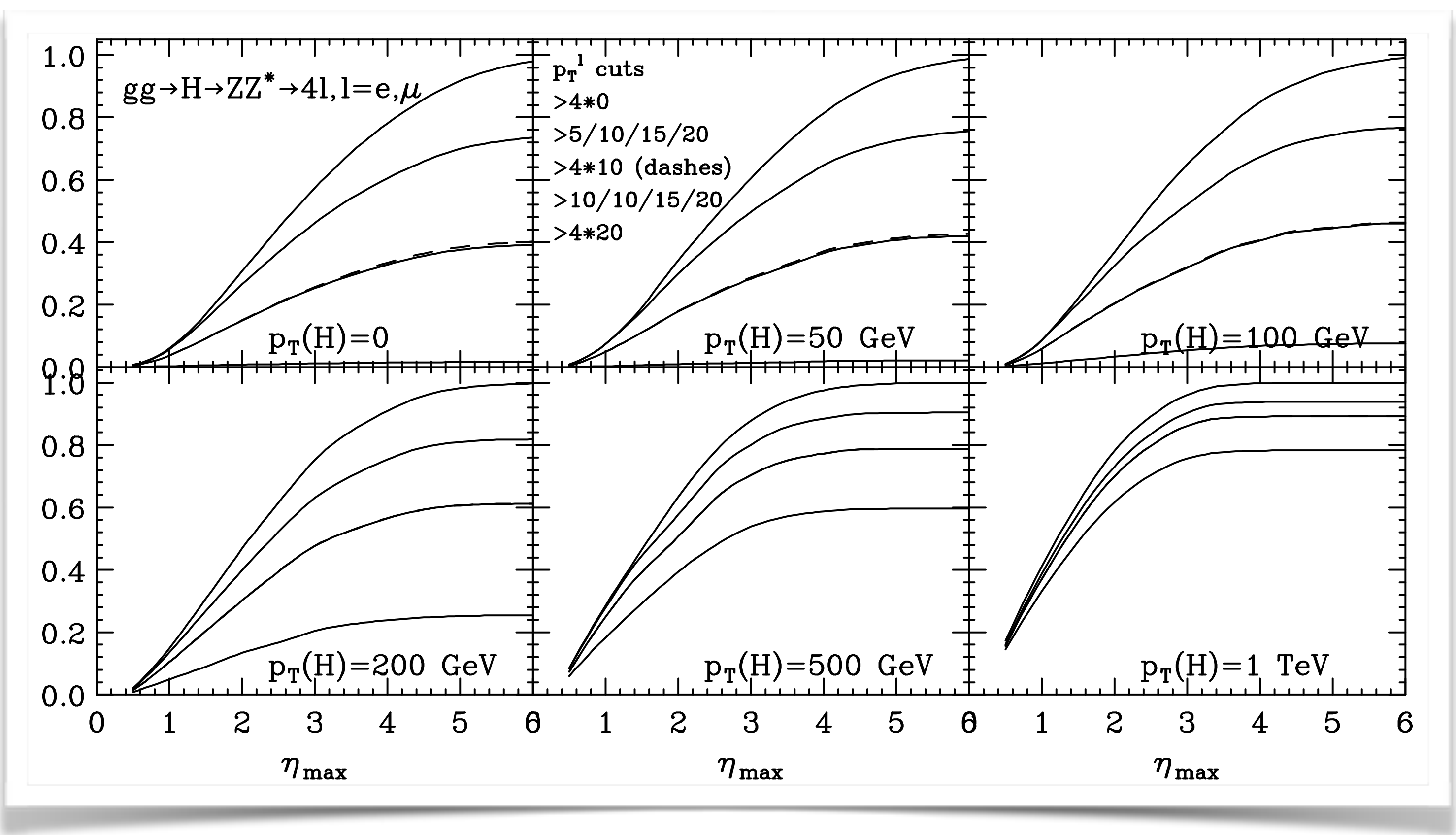
Detector Acceptance

2 body decay



Caveats: only signal, no detector resolution effects, etc.

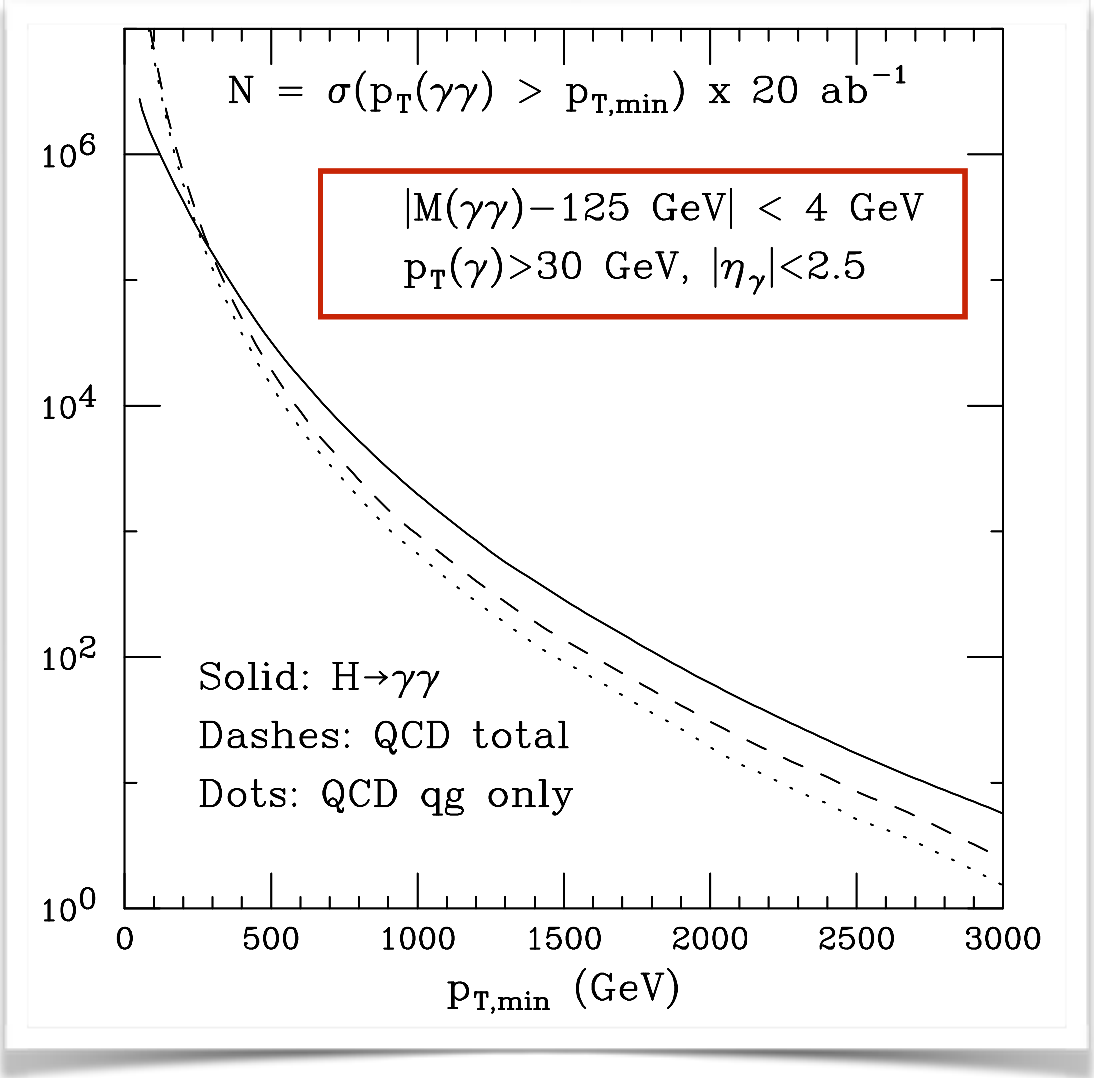
4 body decay, e.g. ZZ→4l

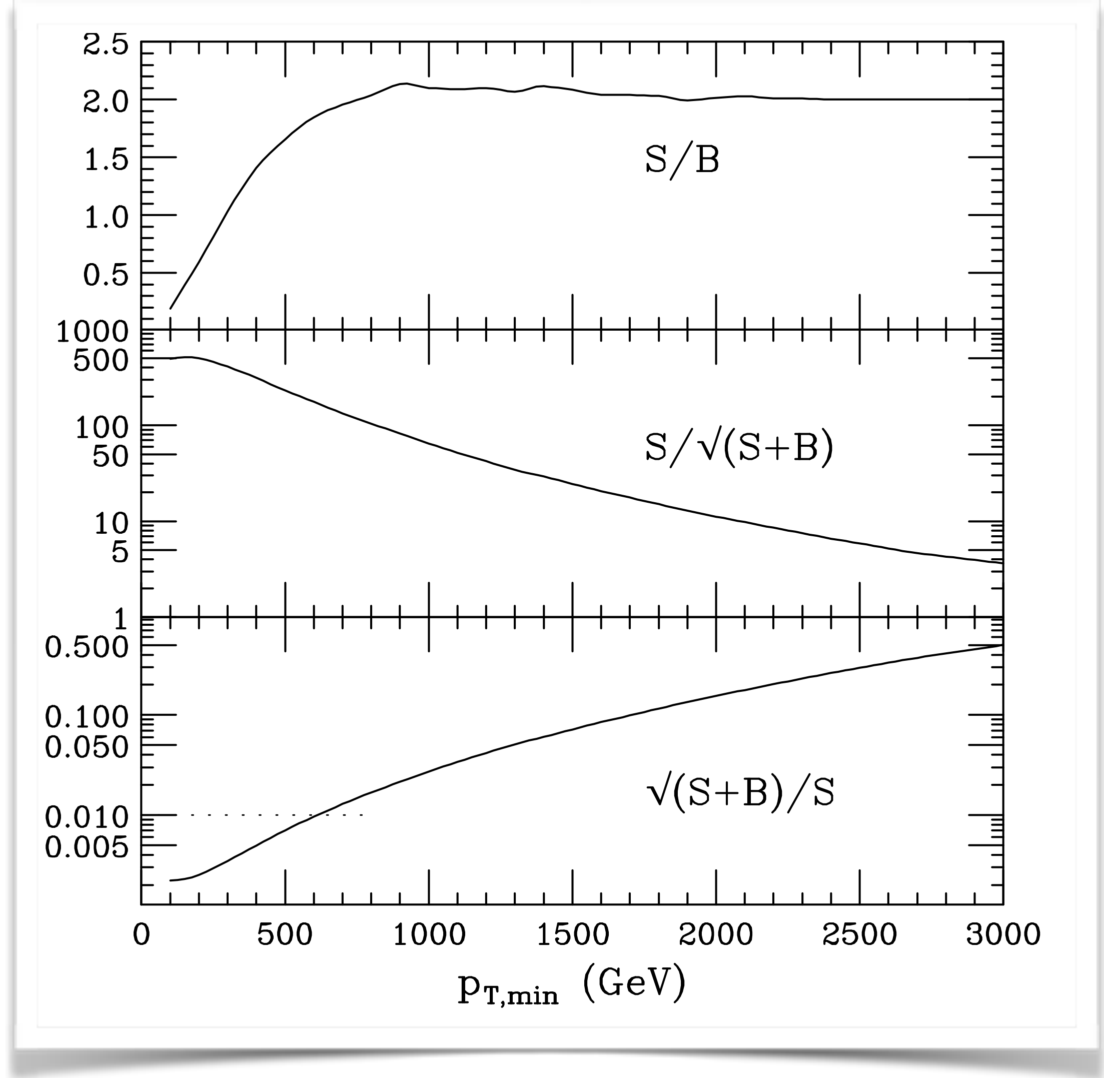


p_T threshold is very important

Very challenging with current design and expected pile up!

Example: H→ɣɣ

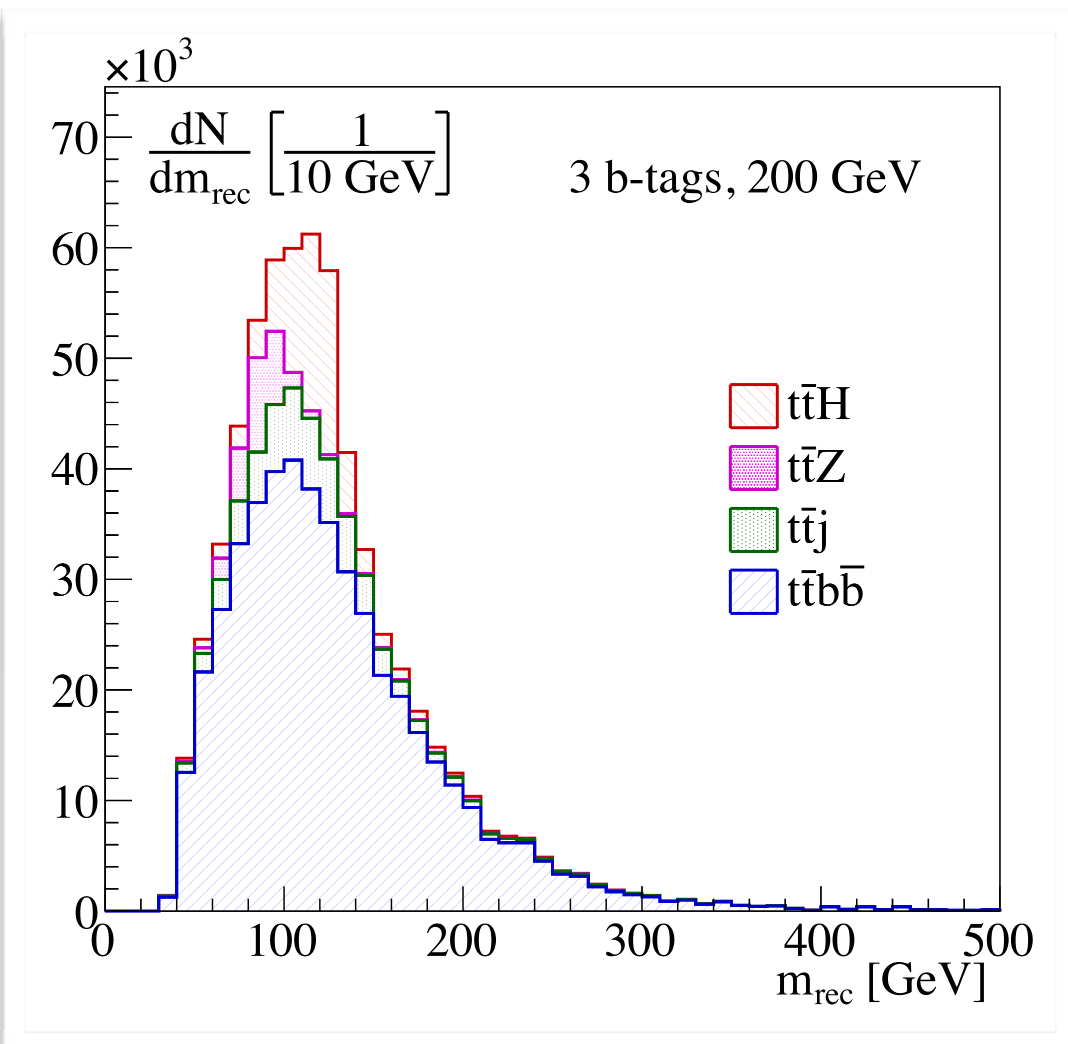


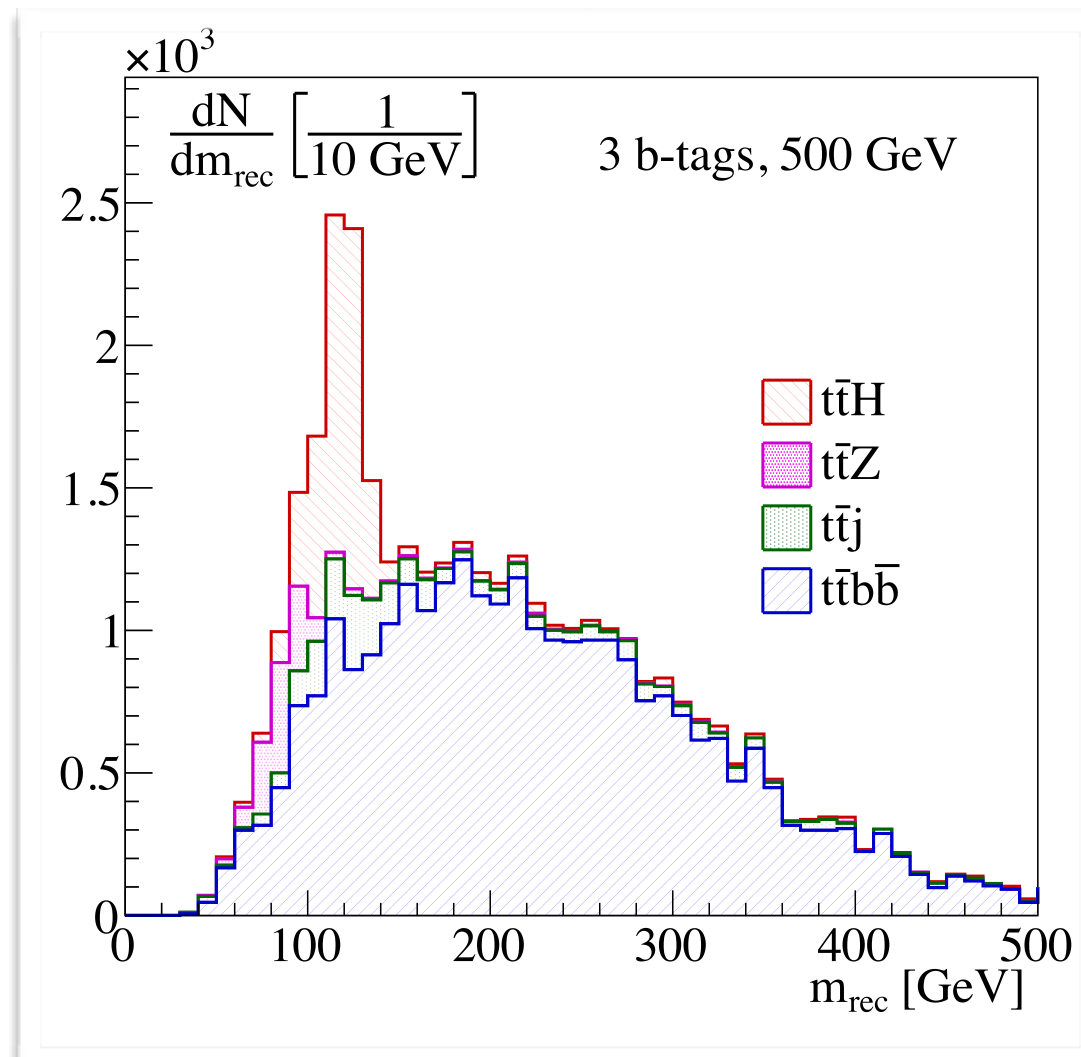


- Simplified study of H→ɣɣ
- Consider only background from pp→ɣɣ, no detector effects
- 4 GeV window in invariant mass to suppress background
- Statistical precision of 1%

t-H coupling

1. an isolated lepton with $|y_\ell| < 2.5$ and $p_{T,\ell} > 15$ GeV.
2. a tagged top ($R = 1.8$, $p_{T,j} > 200$ GeV, $|y_j^{(t)}| < 4$) without any b-tag requirement
3. a tagged Higgs jet with two b-tags inside ($R = 1.2$, $p_{T,j} > 200$ GeV, $|y_j^{(H)}| < 2.5$)
4. a b-tagged jet ($R = 0.6$, $p_{T,j} > 30$ GeV, $|y_b| < 2.5$) outside the top and Higgs fat jets, corresponding to the top decaying semileptonically.





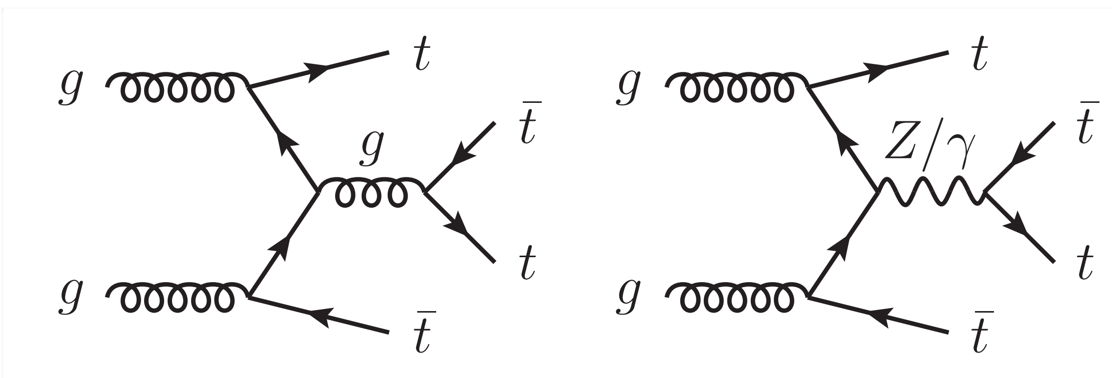
Assuming perfect background knowledge from side bands, obtain a 1-2% uncertainty on κ_t

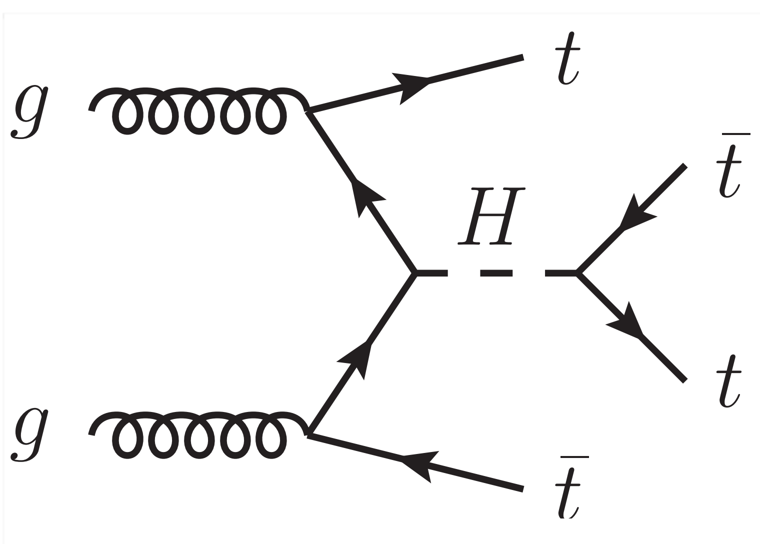
Top Yukawa Coupling & Higgs Width

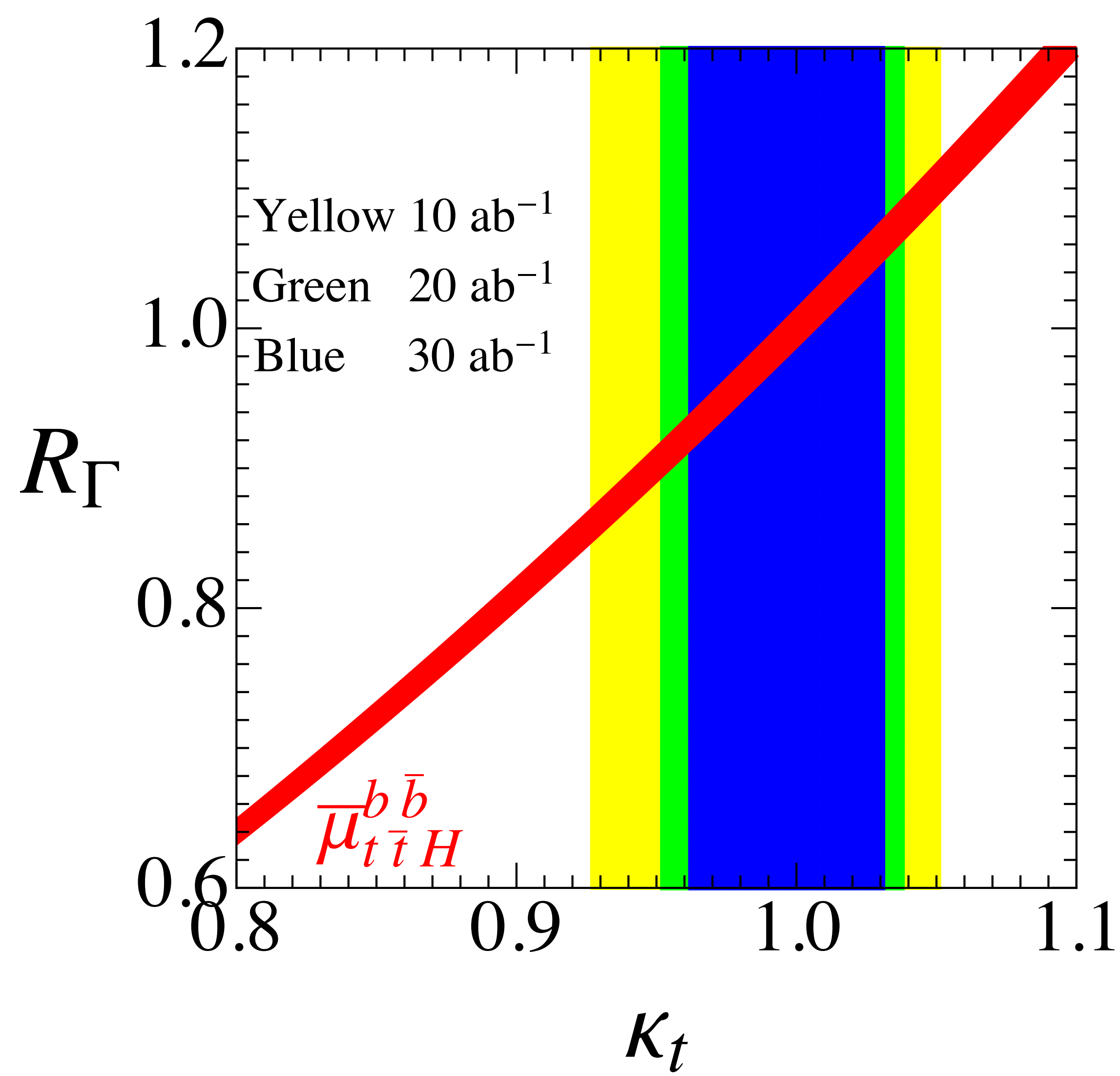
$$\sigma(pp \to t\bar{t}H \to t\bar{t}b\bar{b}) = \sigma^{\rm SM}(pp \to t\bar{t}H \to t\bar{t}b\bar{b}) \times \kappa_t^2\kappa_b^2\frac{\Gamma_H^{\rm SM}}{\Gamma_H}$$

$$\mu_{t\bar{t}H}^{bb} = \frac{\kappa_t^2\kappa_b^2}{R_\Gamma}$$

tttt production for width independent measurement of κ_t







Summary of ‘Precision’ Coupling Measurements

- Currently only have a very rough estimate of the detector design, let alone the detector performance
  - Very challenging (impossible?) to make accurate estimates
- Study $S/\sqrt{S+B}$ in various channels estimated in the semi-boosted region (p_T (H) ~ a few × 100 GeV) where backgrounds are smaller. Indicative of possible achievable sensitivities on Higgs couplings
  - Percent sensitivity reachable with 20 ab^{-1} in most channels in the semi-boosted region with S/B of O(1)
- More precise assessment of the precision reachable at FCC-hh requires detailed analyses of the threshold region (with larger signal rate and larger backgrounds)
- Ability of the FCC to maintain sensitivity on relatively softer final states is likely to be key for precision Higgs physics

Double Higgs Production

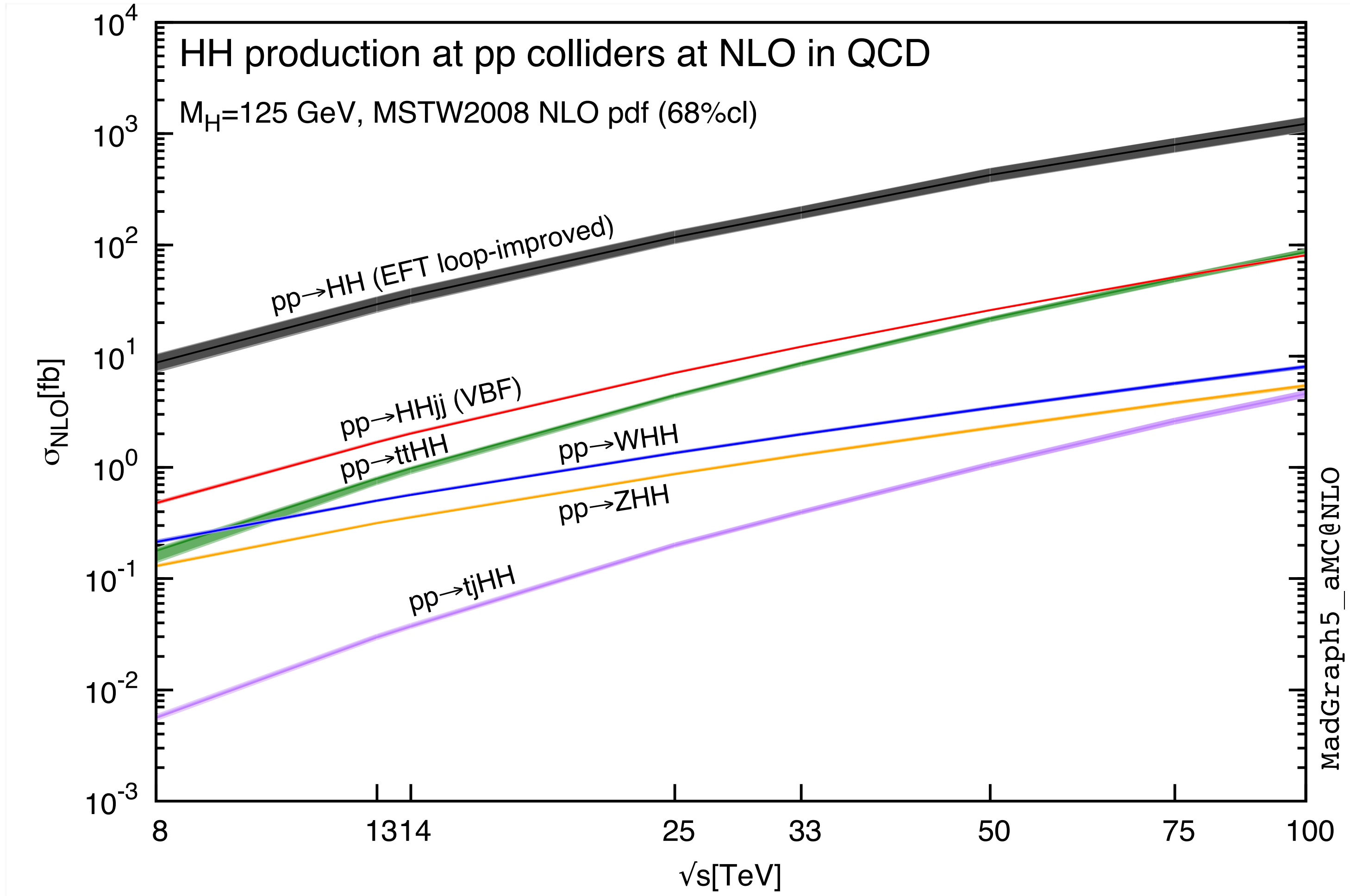
Introduction

- Main goal: use multi-Higgs production to probe the Higgs potential
- In the SM, the shape is completely fixed by Higgs mass and vev
  - Independent measurement of trilinear and quadrilinear self-interactions tests validity of SM
- Szeable corrections to Higgs self-coupling from BSM
- Help to understand features of EW phase transition (e.g. via baryogenesis)?
- Test unitarity of amplitudes at high energy: e.g. HH with VBF

$$\mathcal{L} = -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

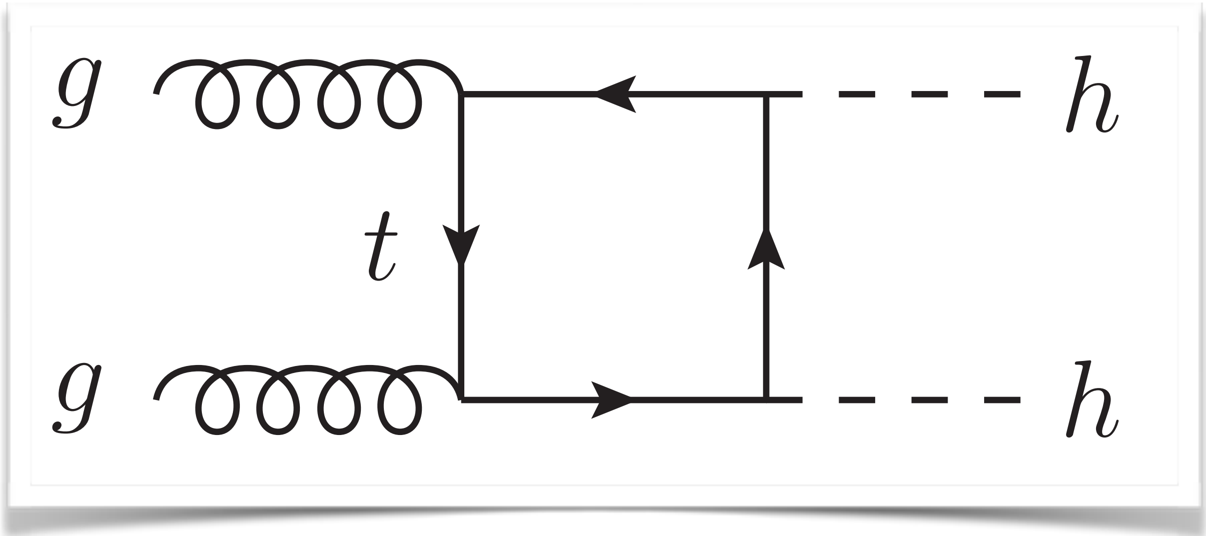
Effective field theory Lagrangian

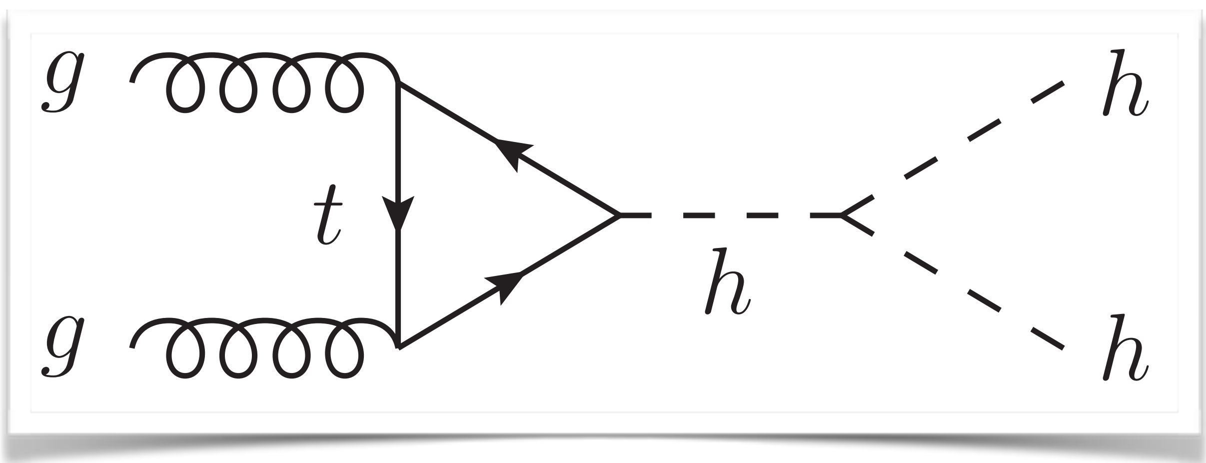
HH Production



process	$\sigma(14\text{ TeV})$ (fb)	$\sigma(100\text{ TeV})$ (fb)	accuracy
HH (ggf)	$45.05^{+4.4\%}_{-6.0\%} \pm 3.0\% \pm 10\%$	$1749^{+5.1\%}_{-6.6\%} \pm 2.7\% \pm 10\%$	NNLL matched to NNLO
$HHjj$ (VBF)	$1.94^{+2.3\%}_{-2.6\%} \pm 2.3\%$	$80.3^{+0.5\%}_{-0.4\%} \pm 1.7\%$	NLO
HHZ	$0.415^{+3.5\%}_{-2.7\%} \pm 1.8\%$	$8.23^{+5.9\%}_{-4.6\%} \pm 1.7\%$	NNLO
HHW^+	$0.269^{+0.33\%}_{-0.39\%} \pm 2.1\%$	$4.70^{+0.90\%}_{-0.96\%} \pm 1.8\%$	NNLO
HHW^-	$0.198^{+1.2\%}_{-1.3\%} \pm 2.7\%$	$3.30^{+3.5\%}_{-4.3\%} \pm 1.9\%$	NNLO
$HHt\bar{t}$	$0.949^{+1.7\%}_{-4.5\%} \pm 3.1\%$	$82.1^{+7.9\%}_{-7.4\%} \pm 1.6\%$	NLO
$HHtj$	$0.0364^{+4.2\%}_{-1.8\%} \pm 4.7\%$	$4.44^{+2.2\%}_{-2.6\%} \pm 2.4\%$	NLO
HHH	$0.0892^{+14.8\%}_{-13.6\%} \pm 3.2\%$	$4.82^{+12.3\%}_{-11.9\%} \pm 1.8\%$	NLO

DiHiggs → Self-coupling





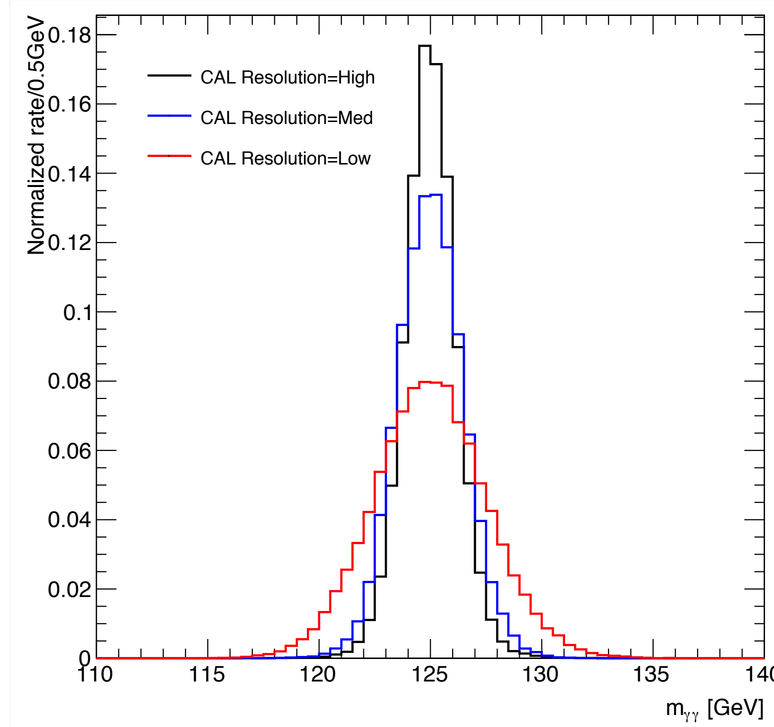
Not just enough to measure HH; need to extract self-coupling

Channels

process
$HH \to b\bar{b}\gamma\gamma$
$HH \to b\bar{b}b\bar{b}$
$HH \to b\bar{b}4\ell$
$HH \to b\bar{b}\ell^+\ell^-$
$HH \to b\bar{b}\ell^+\ell^-\gamma$
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$

bbγγ Channel

Acceptance cuts	Final selection
γ isolation $R = 0.4$ $(p_T(had)/p_T(\gamma) < 0.15)$	γ isolation $R = 0.4$ $(p_T(had)/p_T(\gamma) < 0.15)$
jets: anti-k_T, parameter $R = 0.4$	jets: anti-k_T, parameter $R = 0.4$
$\lvert\eta_{b,\gamma,j}\rvert < 6$	$\lvert\eta_{b,\gamma}\rvert < 4.5$
$p_T(b), p_T(\gamma), p_T(j) > 35$ GeV	$p_T(b_1), p_T(\gamma_1) > 60$ GeV
	$p_T(b_2), p_T(\gamma_2) > 35$ GeV
$m_{bb} \in [60, 200]$ GeV	$m_{bb} \in [100, 150]$ GeV
$m_{\gamma\gamma} \in [100, 150]$ GeV	$\lvert m_{\gamma\gamma} - m_h\rvert < 2.0, 3.0, 4.5$ GeV
	$p_T(bb), p_T(\gamma\gamma) > 100$ GeV
	$\Delta R(bb), \Delta R(\gamma\gamma) < 3.5$
	no isolated leptons with $p_T > 25$ GeV



	ECAL $\lvert\eta\rvert \le 4$ a	ECAL $\lvert\eta\rvert \le 4$ b	ECAL $4 < \lvert\eta\rvert \le 6$ a	ECAL $4 < \lvert\eta\rvert \le 6$ b	HCAL $\lvert\eta\rvert \le 4$ a	HCAL $\lvert\eta\rvert \le 4$ b	HCAL $4 < \lvert\eta\rvert \le 6$ a	HCAL $4 < \lvert\eta\rvert \le 6$ b
low	0.02	0.2	0.01	0.1	0.05	1.0	0.05	1.0
medium	0.01	0.1	0.01	0.1	0.03	0.5	0.05	1.0
high	0.007	0.06	0.01	0.1	0.01	0.3	0.03	0.5

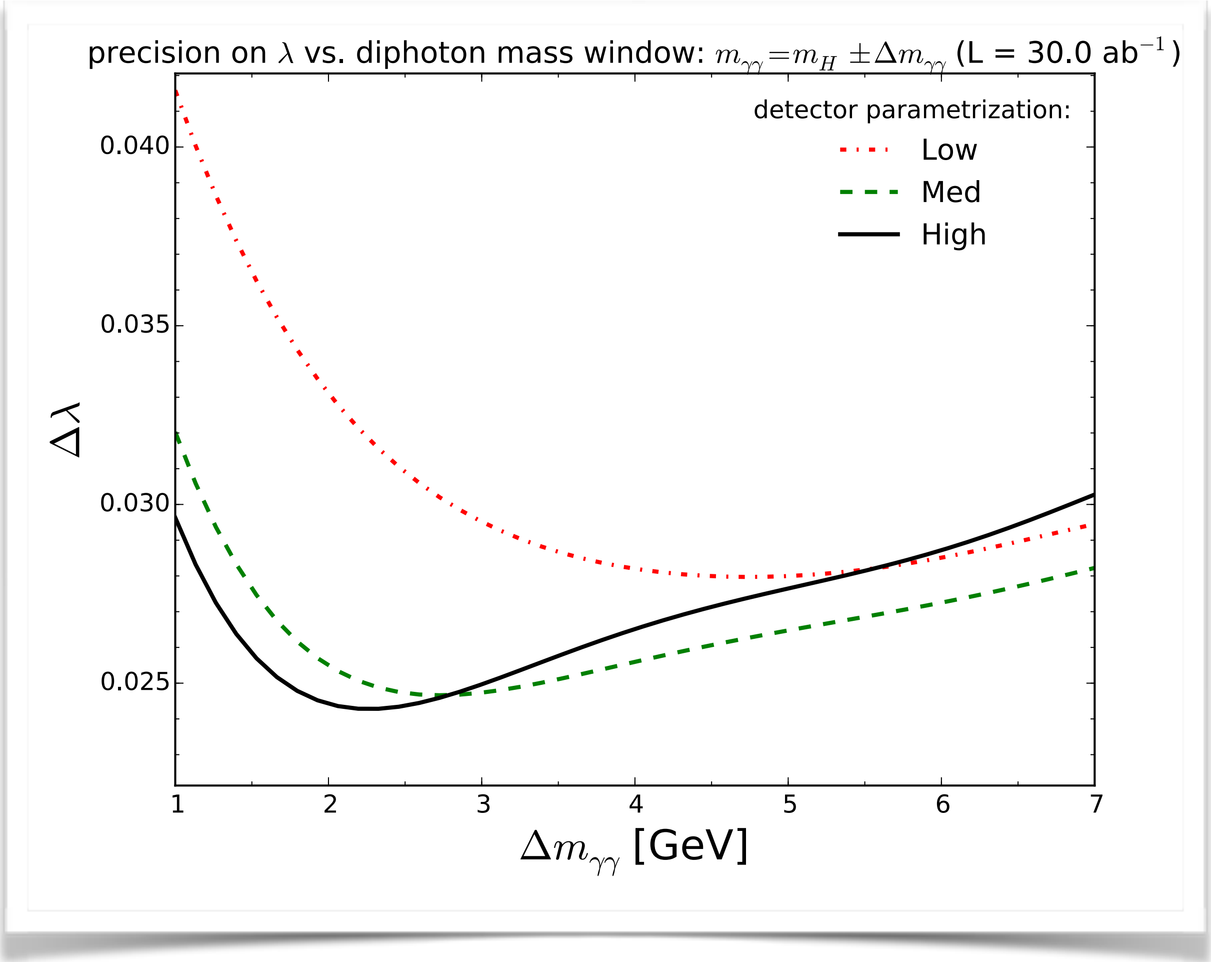
bbγγ Study

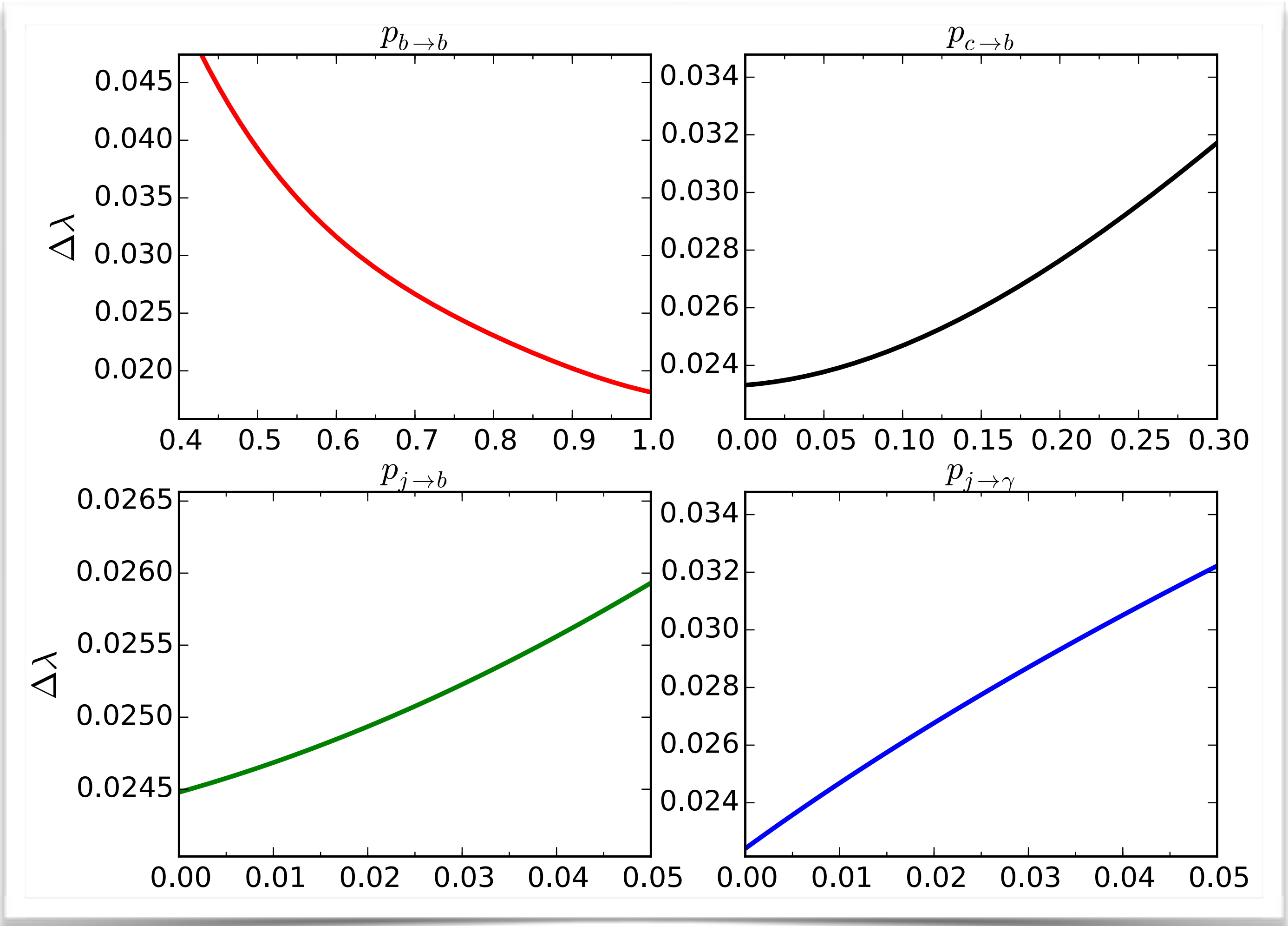
Process	Acceptance cuts [fb]	Final selection [fb]	Events ($L = 30$ ab^{-1})
$h(b\bar{b})h(\gamma\gamma)$ (SM)	0.76	0.44	13200
$bbj\gamma$	147	0.203	6110
$t\bar{t}h(\gamma\gamma)$	1.9	0.164	4930
$jj\gamma\gamma$	83	0.082	2460
$b\bar{b}\gamma\gamma$	14.7	0.074	2220
$b\bar{b}h(\gamma\gamma)$	0.10	8.1×10^{-3}	240
Total background	247	0.53	15960

In optimizing the selection cuts two different strategies can in principle be used: one can either maximize the precision on the SM signal or that on the Higgs trilinear coupling. The two procedures lead to significantly different set of cuts. The effect of a change in the Higgs self-couplings mostly affects the threshold behavior, thus "looser" cuts aimed at preserving a large fraction of the threshold events improve the precision on λ_3. On the other hand, the threshold region is also the one that has a larger background, hence harder cuts might be convenient to improve the precision on the SM signal rate.

	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$	$\Delta_S = 0.025$
$r_B = 0.5$	2.1%	2.8%	3.5%	4.3%	5.1%
$r_B = 1.0$	2.5%	3.1%	3.7%	4.5%	5.3%
$r_B = 1.5$	2.8%	3.4%	4.0%	4.7%	5.4%
$r_B = 2.0$	3.1%	3.6%	4.2%	4.8%	5.6%

Dependence on detector conditions

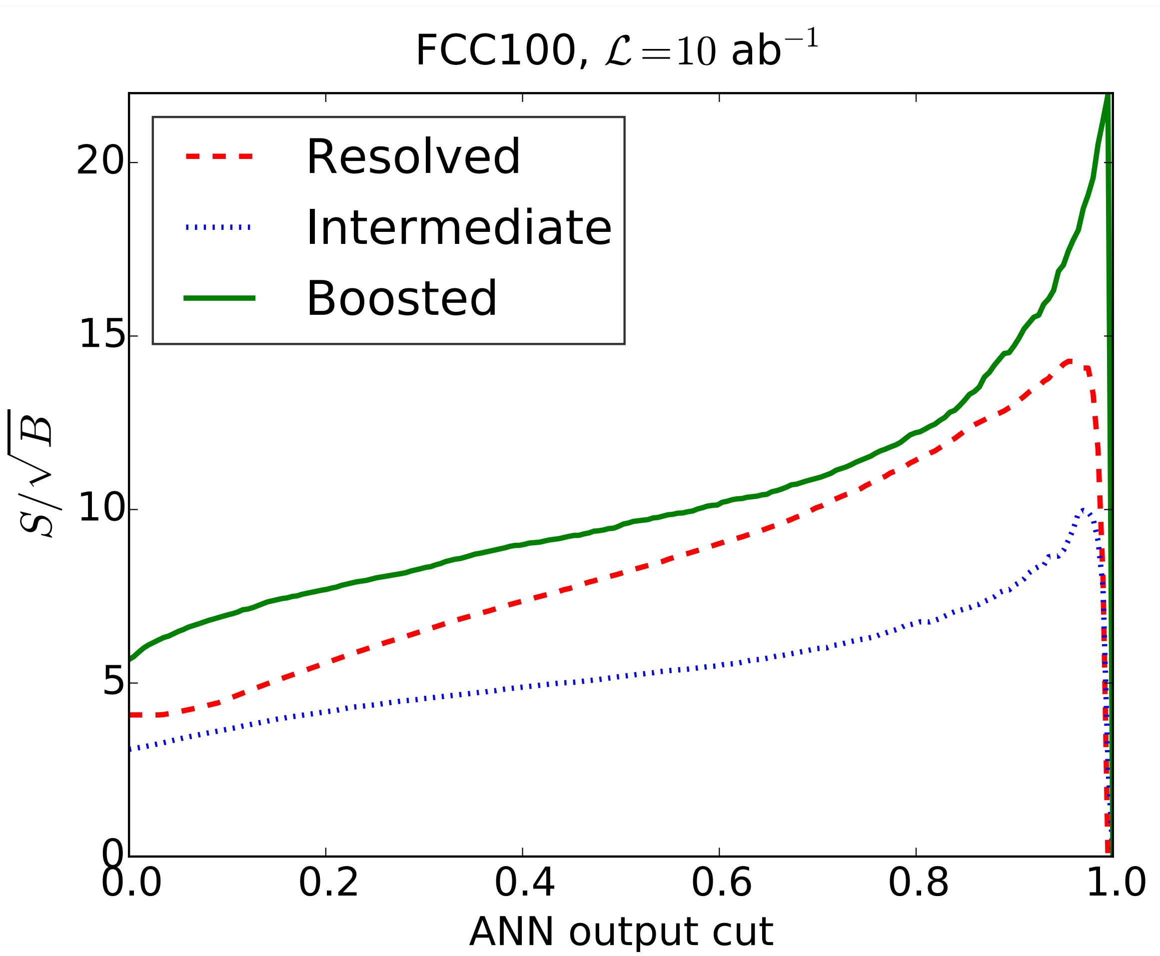




strong dependence on b, some on c, little dependence on mistag

4b

- 3 categories: resolved, intermediate, boosted
- All selected jets are b-tagged
- 40 GeV window around the Higgs mass
- Background: only irreducible QCD 4b background



Category		N_{ev} signal	N_{ev} back	$S/\sqrt{B}$	S/B
Boosted	$y_{cut}=0$	$5\cdot10^4$	$8\cdot10^7$	6	$6\cdot10^{-4}$
	$y_{cut}=0.99$	$2\cdot10^4$	$1\cdot10^6$	22	$2\cdot10^{-2}$
Intermediate	$y_{cut}=0$	$3\cdot10^4$	$1\cdot10^8$	3	$3\cdot10^{-4}$
	$y_{cut}=0.98$	$2\cdot10^4$	$2\cdot10^6$	10	$7\cdot10^{-3}$
Resolved	$y_{cut}=0$	$1\cdot10^5$	$8\cdot10^8$	4	$1\cdot10^{-4}$
	$y_{cut}=0.95$	$6\cdot10^4$	$2\cdot10^7$	15	$4\cdot10^{-3}$

	$\delta_{sys}\sigma=25\%$	$\delta_{sys}\sigma=100\%$
Boosted	$\lambda_3\in[-0.1,2.2]$	$\lambda_3\in[-1.5,>9]$
Intermediate	$\lambda_3\in[0.7,1.6]$	$\lambda_3\in[-0.4,>9]$
Resolved	$\lambda_3\in[0.9,1.5]$	$\lambda_3\in[-0.1,7]$

syst. on measured x-sect

Summary of Multi-Higgs Production

process	precision on σ_{SM}	precision on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	2%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$\sim 25\%$	$\lambda_3 \in [\sim 0.6, \sim 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$\sim 15\%$	$\lambda_3 \in [\sim 0.8, \sim 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–

WW, ττ, μμ w/wo MET

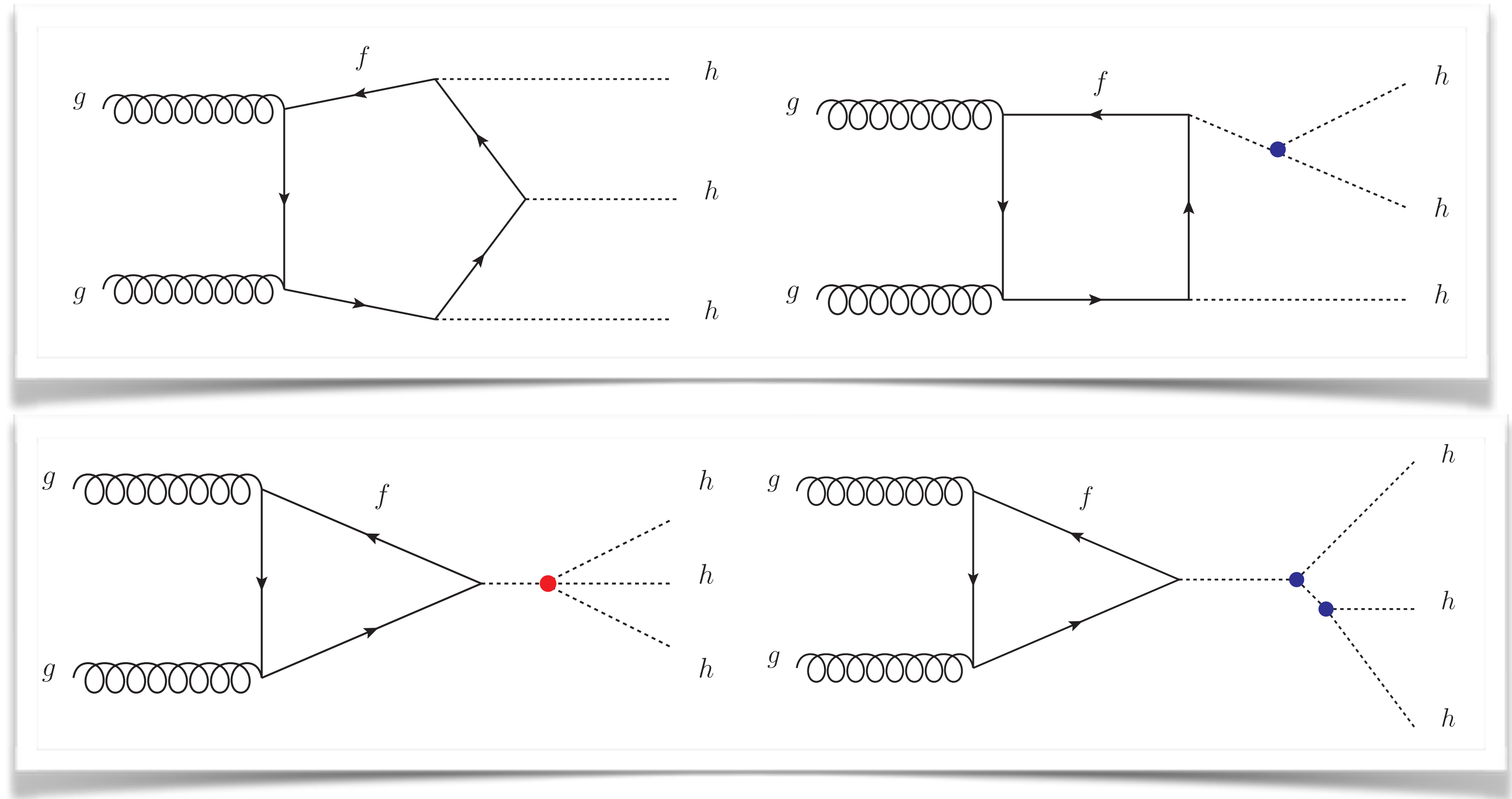
S/B: 2-3%

- bbɣɣ is the most sensitive channel
- Contributions from other channels have been examined
- Analyses will depend quite critically on detector performance assumptions
  - Expect numbers to change !

Triple Higgs Production

Decay Modes

- Potential decay modes
  - 4b2W (22%)
    - tt+bb background ?
    - boosted techniques
  - 6b (19.5%)
    - boosted techniques?
  - 4b2ɣ (0.23%):
    - Clean, but tiny BR
    - Studied, see the next slide
  - 4b2τ (6.46%)
    - Significant BR
    - New study, but less sensitivity



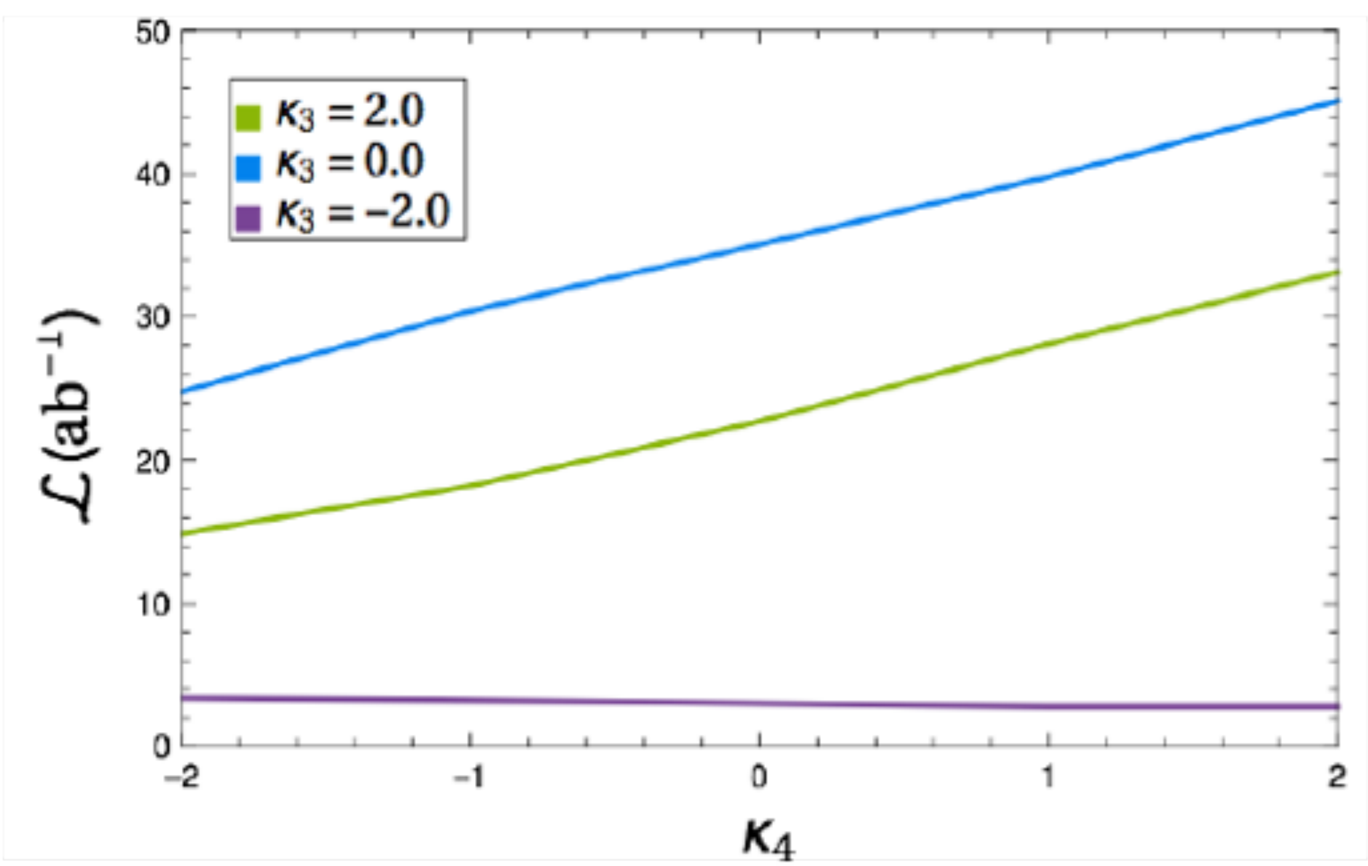
$$V_h = \boxed{\frac{m_h^2}{2}h^2} + \boxed{(1+\kappa_3)\lambda_{hhh}^{\mathrm{SM}} v h^3} + \boxed{\frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{\mathrm{SM}} h^4}$$

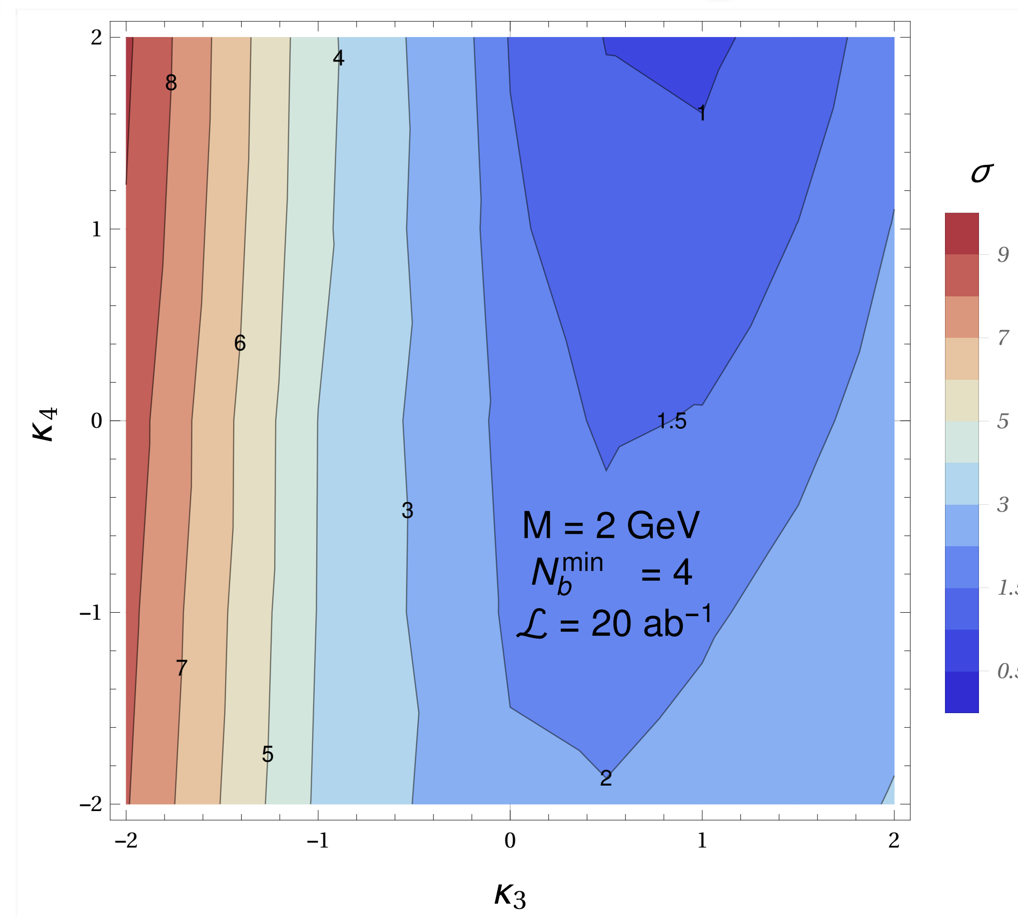
σ_{SM}=3-4 fb

4b2ɣ

- Benchmark using 4b2ɣ
- Parton level-study and 4 momentum smearing
- Loose (70%) and tight (60%) b-tagging, 4-bjets
- Dijet & diphoton systems compatible with higgs mass

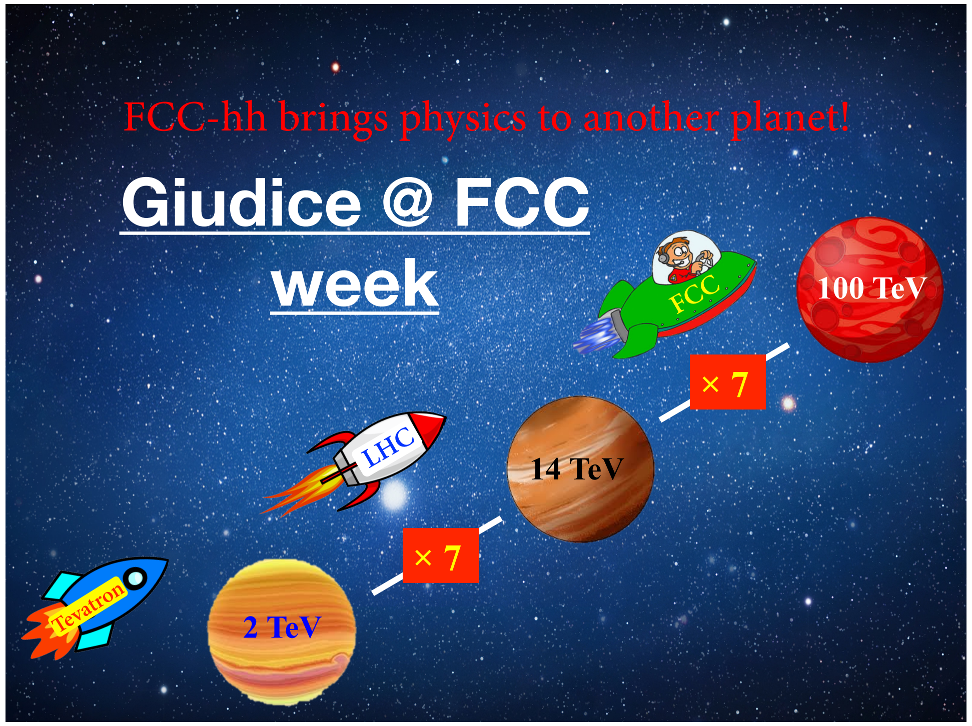
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$\sim 100\%$	$\lambda_4 \in [\sim -4, \sim +16]$





Conclusion

- Exciting projects are currently being explored as potential future hadron collider machines: CppC and FCC-hh
- Accelerator and detector studies are progressing rapidly
- Aset of studies of the physics potential of a 100 TeV collider have (just!) been documented in a yellow report
- High energy and luminosity make a wealth of Higgs studies accessible
- Key benchmarks in the Higgs sector include
  - HH and the Higgs potential
  - Top Yukawa coupling
  - Rare Higgs production and decay modes
  - Your favourite Higgs measurement !



Back up