Future Circular Colliders

UK Annual Theory Meeting
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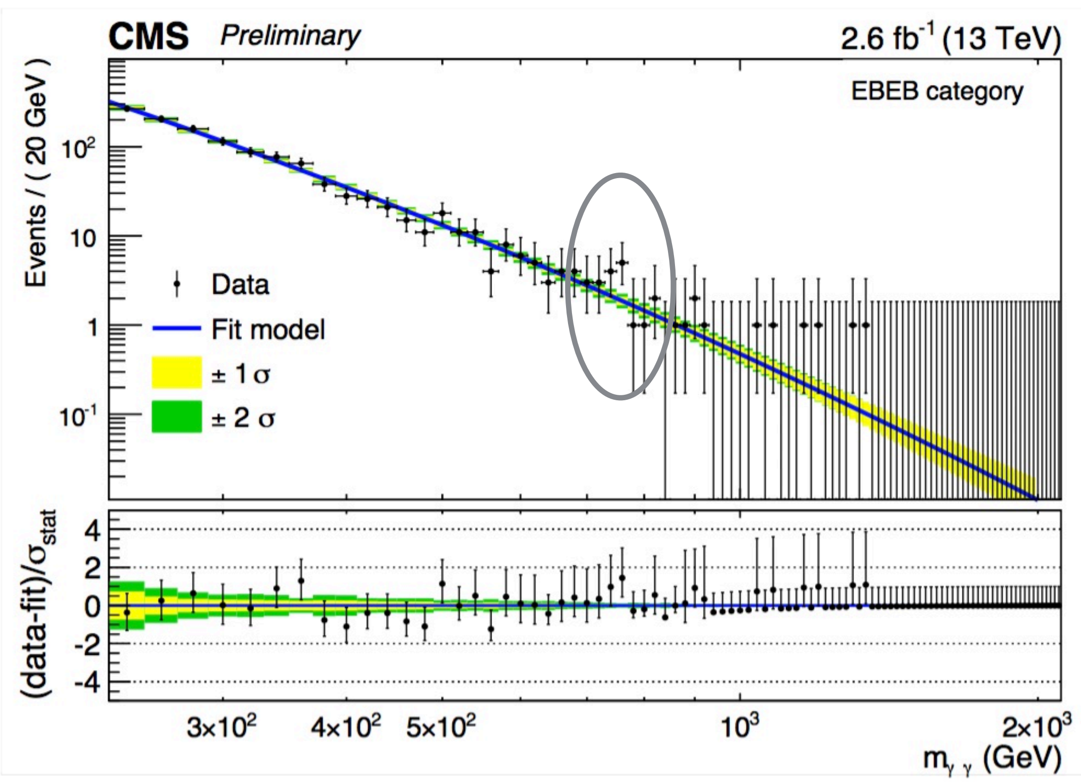
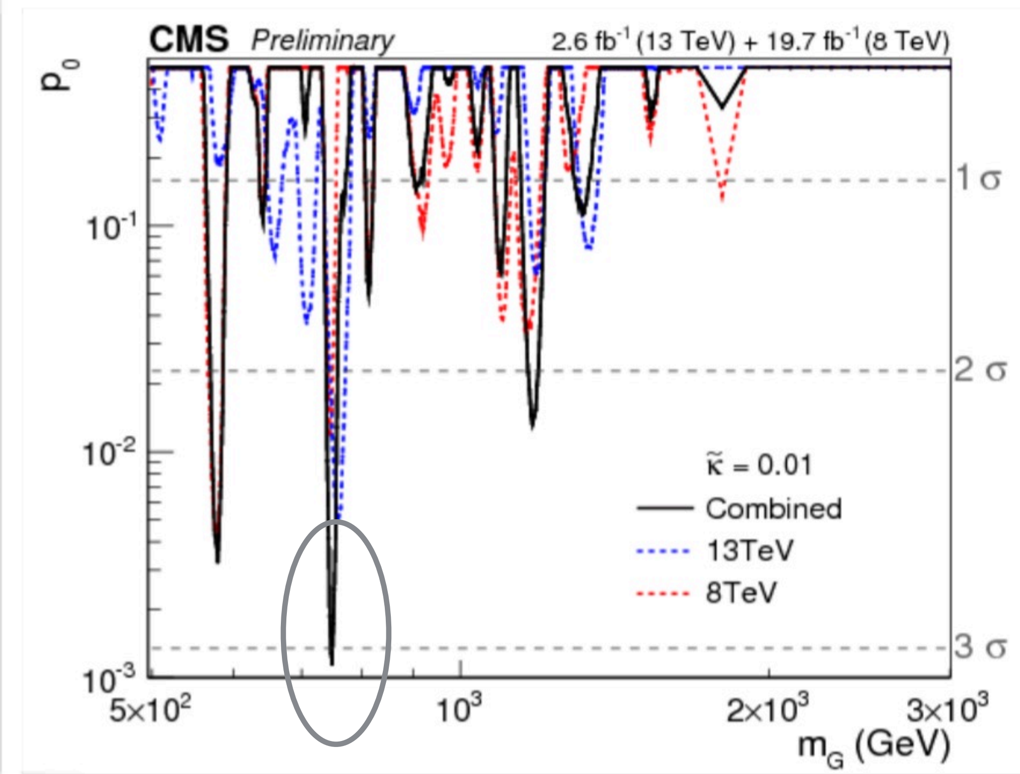
CMS PAS EXO-15-004





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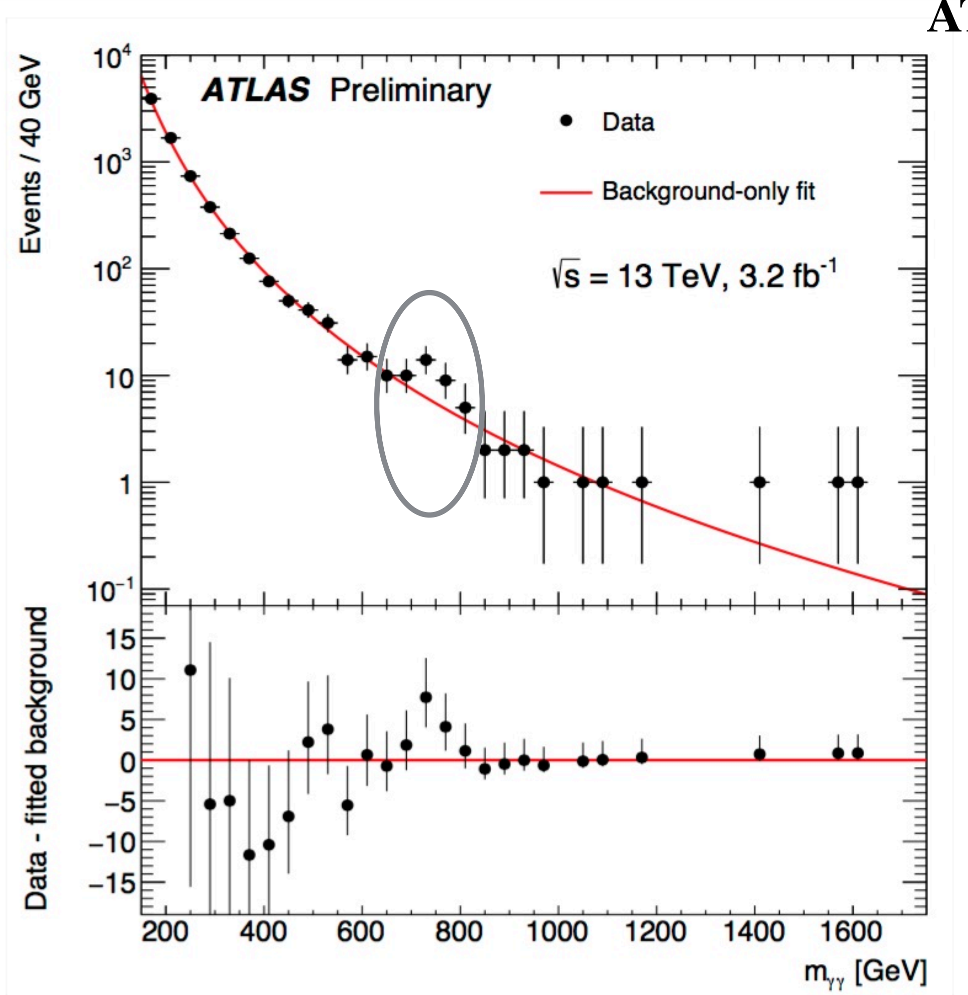

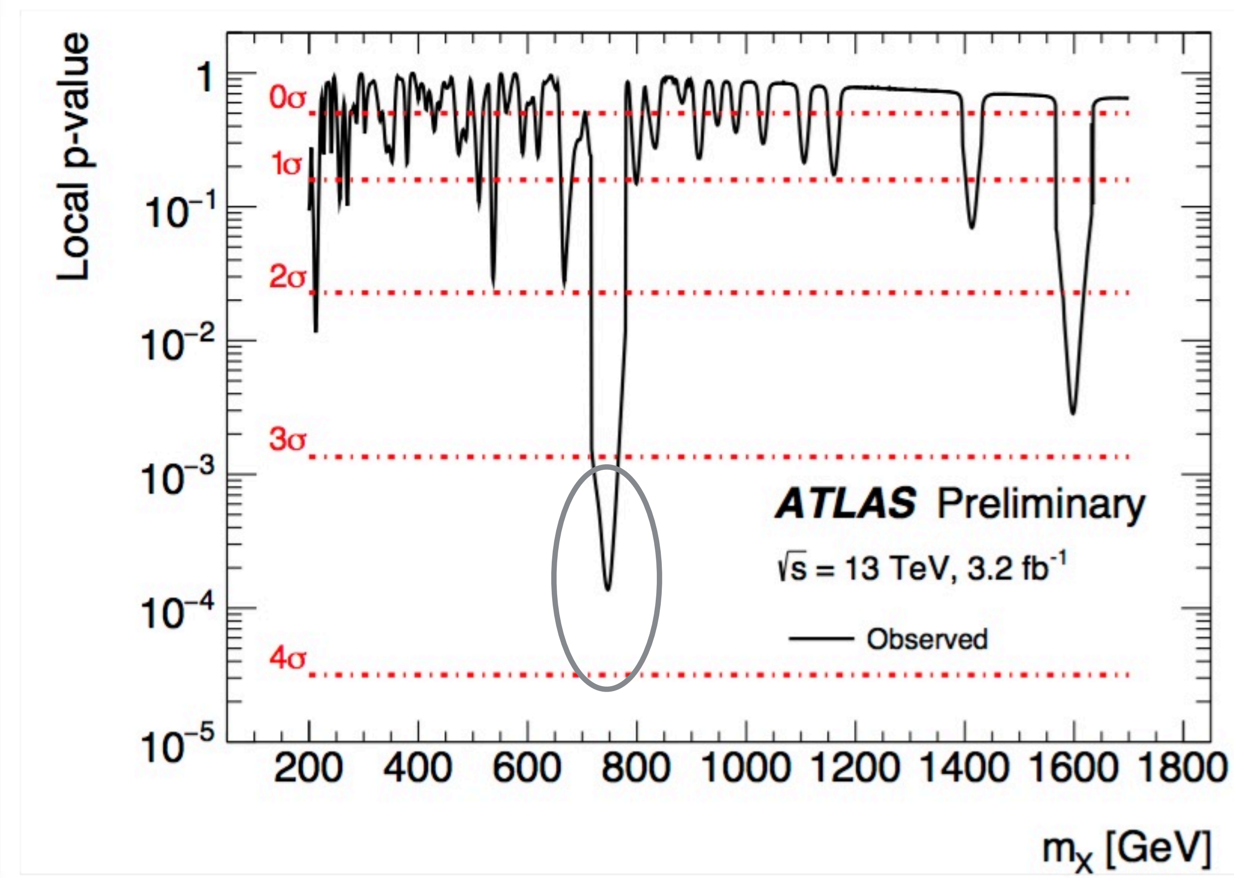

Theory papers appeared in the subsequent 3 days

A 750 GeV Dark Pion: Cousin of a Dark G-parity-odd WIMP
Yang Bai, Joshua Berger, Ran Lu. Dec 17, 2015. 9 pp.

2 **Phenomenology of a 750 GeV Singlet**
Adam Falkowski, Oren Slone, Tomer Volansky. Dec 17, 2015. 18 pp.

3 **The Minimal Model of a Diphoton Resonance: Production without Gluon Couplings**
Csaba Csaki, Jay Hubisz, John Terning. Dec 17, 2015. 8 pp.

4 **A hidden confining world on the 750 GeV diphoton excess**
Ligong Bian, Ning Chen, Da Liu, Jing Shu. Dec 17, 2015. 19 pp.

5 **Quirky Explanations for the Diphoton Excess**
David Curtin, Christopher B. Verhaaren. Dec 17, 2015. 6 pp.

6 **Scattering Light by Light at 750 GeV at the LHC**
Sylvain Fichet, Gero von Gersdorff, Christophe Royon. Dec 17, 2015. 6 pp.

7 **The Minimal Scalar-Stealth Top Interpretation of the Diphoton Excess**
Wei Chao, Ran Huo, Jiang-Hao Yu. Dec 17, 2015. 14 pp.

8 **On sgoldstino interpretation of the diphoton excess**
S.V. Demidov, D.S. Gorbunov. Dec 17, 2015. 9 pp.

9 **See-Saw Composite Higgses at the LHC: Linking Naturalness to the**
750

10 **Can the new resonance at LHC be a CP-Odd Higgs boson?**
Damir Becirevic, Enrico Bertuzzo, Olcyr Sumensari, Renata Zukanovich Funchal. Dec 17, 2015. 15 pp.

11 **Experimental Considerations Motivated by the Diphoton Excess at the LHC**
Prateek Agrawal, JiJi Fan, Ben Heidenreich, Matthew Reece, Matthew Strassler. Dec 17, 2015.

12 **Higgs-radion interpretation of 750 GeV di-photon excess at the LHC**
Aqeel Ahmed, Barry M. Dillon, Bohdan Grzadkowski, John F. Gunion, Yun Jiang. Dec 17, 2015. 13 pp.

13 **Diphoton Excess at 750 GeV from a Radion in the Bulk-Higgs Scenario**
Peter Cox, Anibal D. Medina, Tirtha Sankar Ray, Andrew Spray. Dec 17, 2015. 8 pp.

14 **LHC diphoton excess explained as a heavy scalar in top-seesaw model**
Archil Kobakhidze, Fei Wang, Lei Wu, Jin Min Yang, Mengchao Zhang. Dec 17, 2015. 10 pp.

15 **Interpretation of the diphoton excess at CMS and ATLAS**
Bhaskar Dutta, Yu Gao, Tathagata Ghosh, Ilia Gogoladze, Tianjun Li. Dec 16, 2015. 8 pp.

16 **The 750 GeV diphoton excess from the goldstino superpartner**
Christoffer Petersson, Riccardo Torre. Dec 16, 2015. 3 pp.

17 **A pseudoscalar decaying to photon pairs in the early LHC run 2 data**
Matthew Low, Andrea Tesi, Lian-Tao Wang. Dec 16, 2015. 23 pp.

18 **Singlet Scalar Resonances and the Diphoton Excess**
Samuel D. McDermott, Patrick Meade, Harikrishnan Ramani. Dec 16, 2015.

19 **Strong dynamics or axion origin of the diphoton excess**
Emiliano Molinaro, Francesco Sannino, Natascia Vignaroli. Dec 16, 2015. 5 pp.

20 **Interpreting a 750 GeV Diphoton Resonance**
Rick S. Gupta, Sebastian Jäger, Yevgeny Kats, Gilad Perez, Emmanuel Stamou. Dec 16, 2015. 26 pp.

21 **On the Interpretation of a Possible**
~750

22 **Rays of light from the LHC**
Simon Knapen, Tom Melia, Michele Papucci, Kathryn Zurek. Dec 15, 2015. 20 pp.

23 **What is the gamma gamma resonance at 750 GeV?**
Roberto Franceschini, Gian F. Giudice, Jernej F. Kamenik, Matthew McCullough, Alex Pomarol, Riccardo Rattazzi, Michele Redi, Francesco Riva, Alessandro Strumia, Riccardo

24 **Footprints of New Strong Dynamics via Anomaly**
Yuichiro Nakai, Ryosuke Sato, Kohsaku Tobioka. Dec 15, 2015. 6 pp.

The lesson, so far

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- So little we know about what happens at the TeV scale !!
- So many alternative TeV-scale physics scenarios can be thought of, which would not have been detected experimentally, or considered theoretically, until now …

This underscores the importance of a thorough exploration of the TeV scale

Important questions about the weak scale need an answer:

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- **EW Symmetry Breaking**
  - what’s the underlying dynamics? weakly interacting? strongly interacting?
  - Is there a “natural” solution to the hierarchy problem?
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- **ν masses**
  - what's the role of the Higgs and EWSB, if any ?

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

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

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and promising

(1) **guaranteed deliverables:**

- knowledge that will be acquired independently of possible discoveries (*the value of "measurements"*)

(2) **exploration potential:**

- target broad and well justified BSM scenarios .... *but guarantee sensitivity to more exotic options*

(3) potential to provide conclusive **yes/no answers** to relevant, broad questions.

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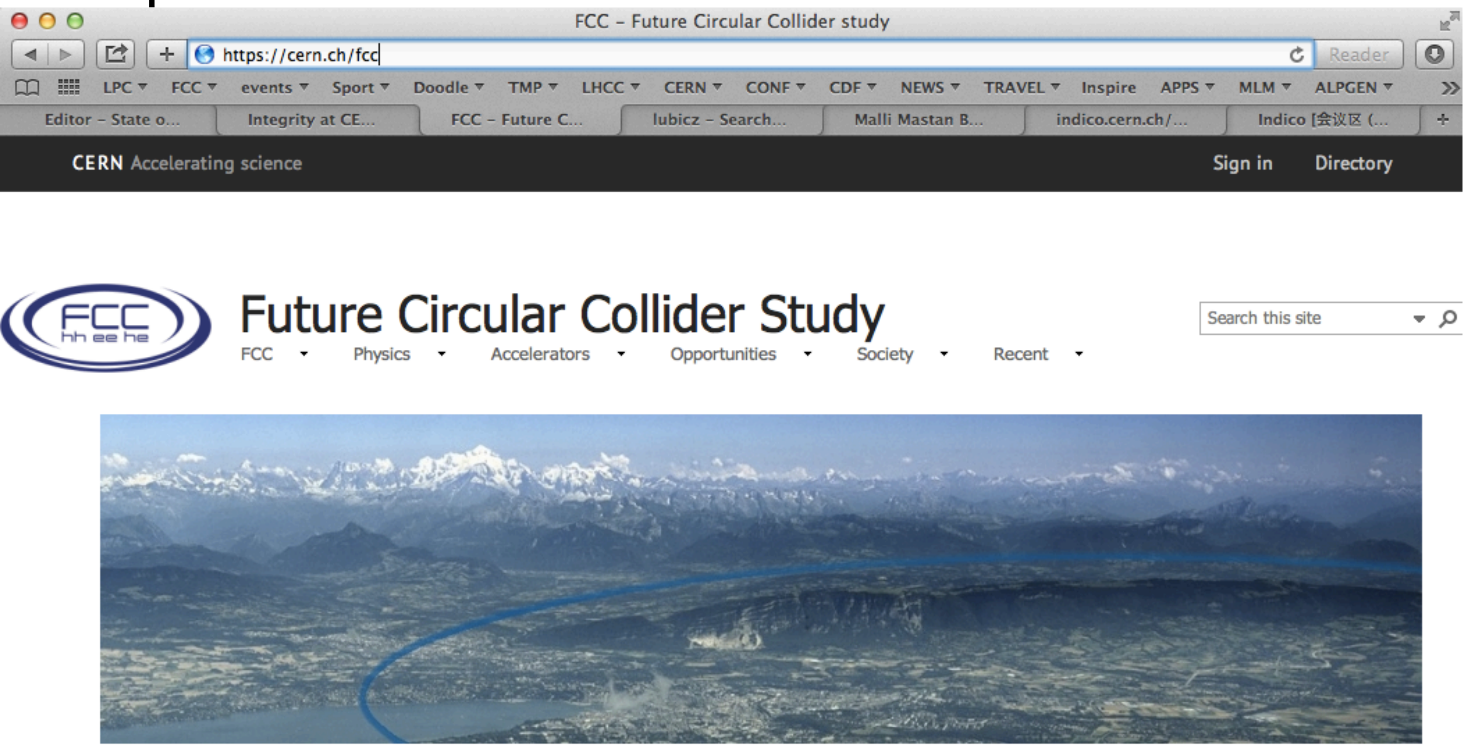
- Possible Yes/No answers (*under active study*):
  - fully address questions tied to the TeV scale (e.g. WIMPs, EW Baryogenesis, TeV-scale naturalness)

http://cern.ch/fcc



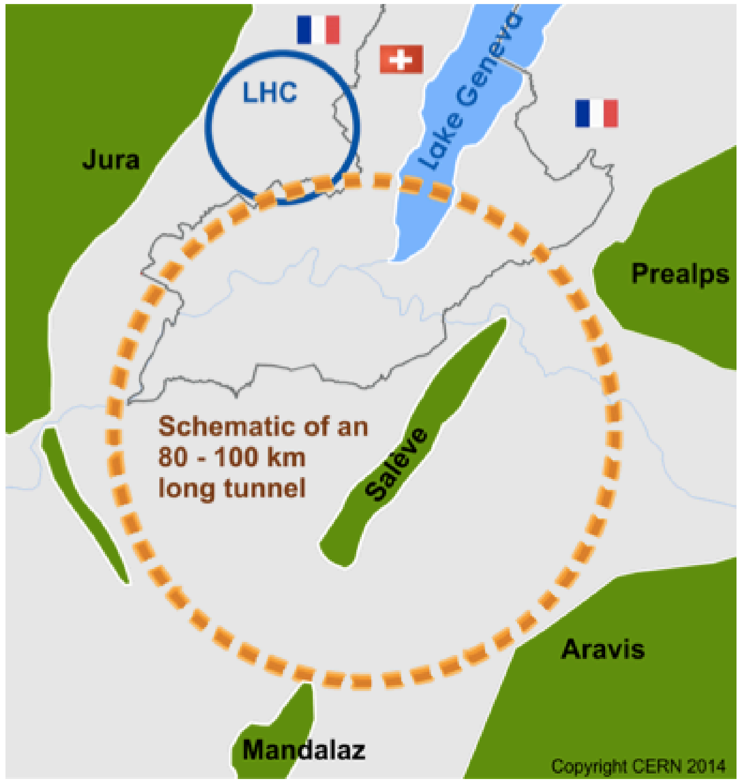
http://cepc.ihep.ac.cn

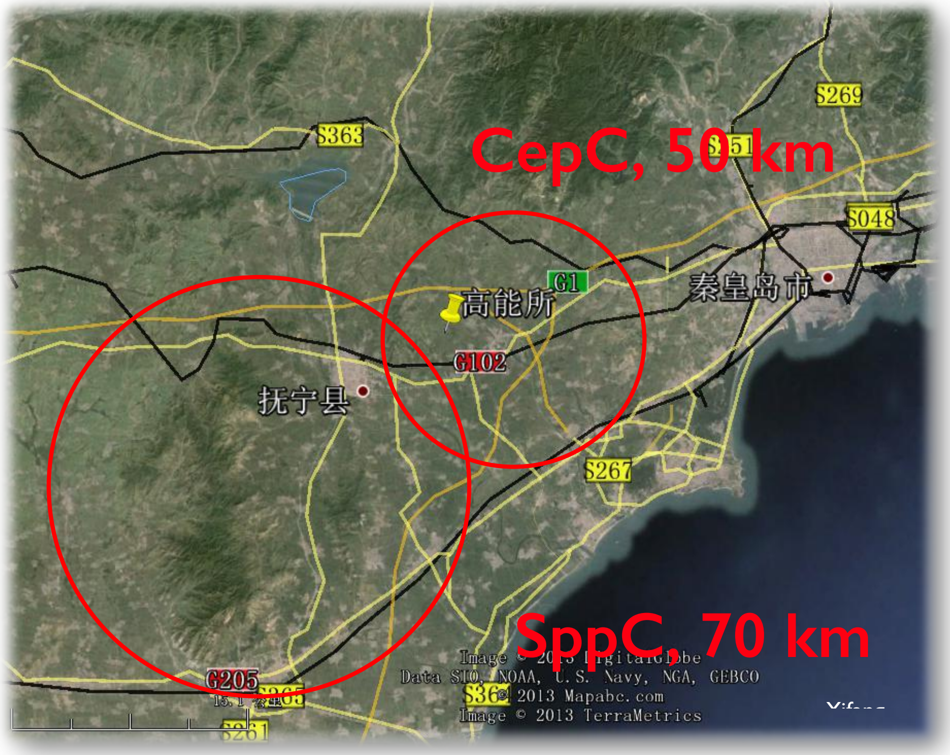
Forming an international collaboration to study:

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

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area





http://fccw2016.web.cern.ch/fccw2016/

FCC-hh parameters and lum goals

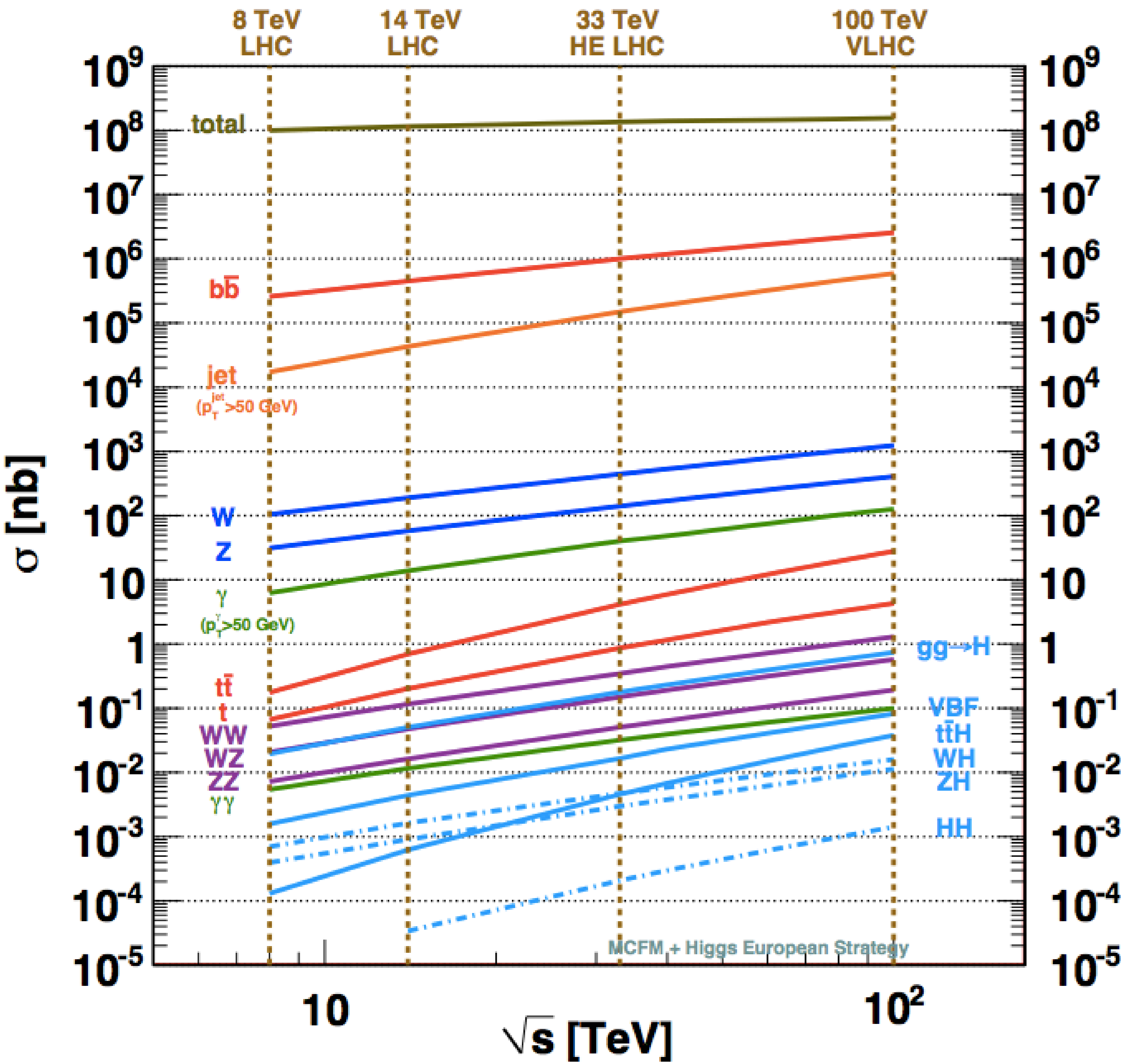
Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

- **Phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
  250 fb^{-1}/year (averaged)
  2500 fb^{-1} within 10 years (~HL LHC total luminosity)

- **Phase 2 (ultimate): ~2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
  1000 fb^{-1}/year (averaged)
  ➔ 15,000 fb^{-1} within 15 years

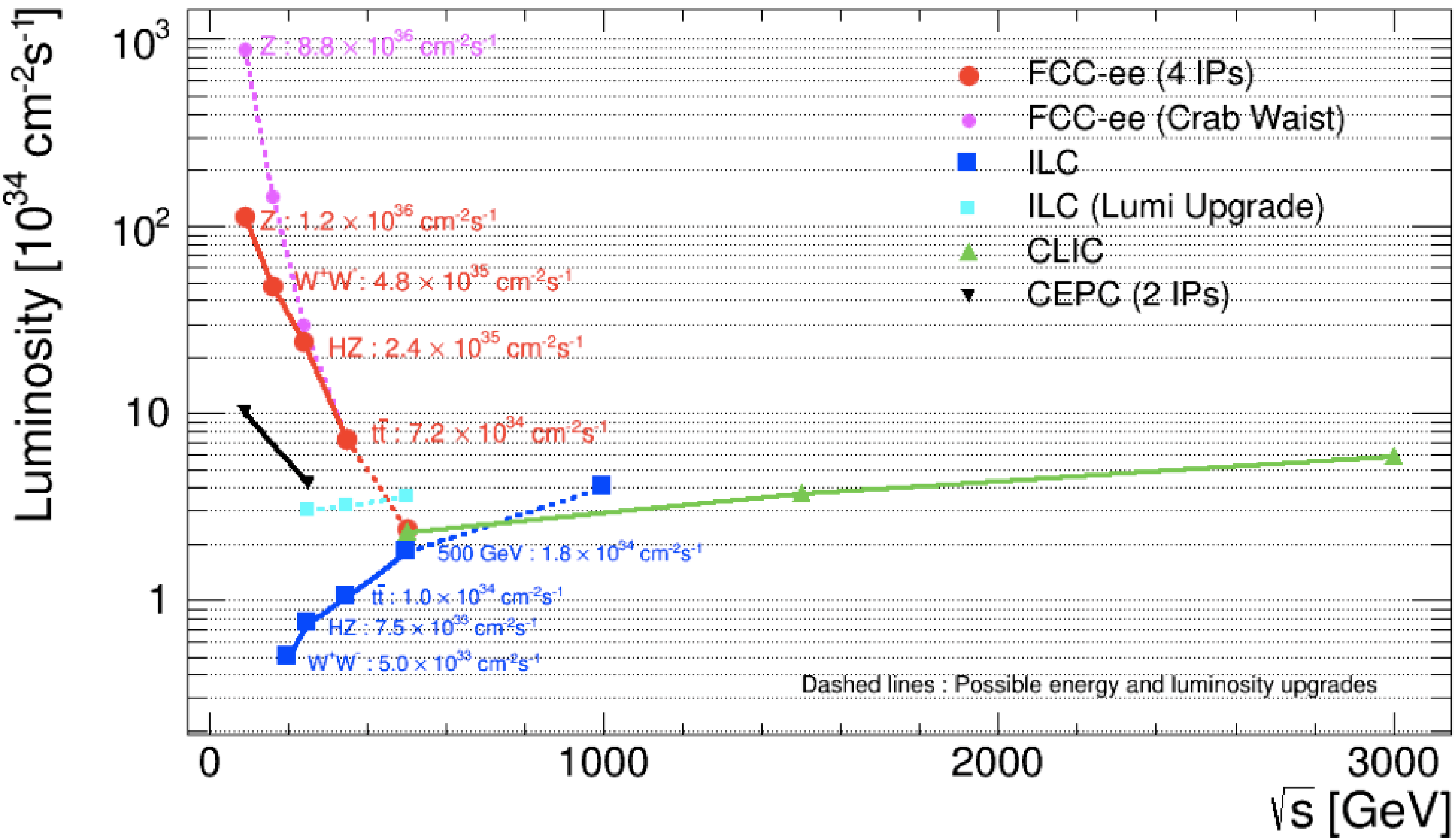
- **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**

Rates at 8 - 100 TeV



final state	$N_{ev}/10ab^{-1}$
W	10^{13}
t tbar	3×10^{11}
H	10^{10}
HH	10^{6}
jets (p_T>5 TeV)	10^{6}
jets (p_T>10 TeV)	10^{4}

FCC-ee energy and lum goals



A possible TLEP running programme

1. ZH threshold scan and 240 GeV running (200 GeV to 250 GeV)
   5+ years @2 10^35 /cm2/s => 210^6 ZH events
   ++ returns at Z peak with TLEP-H configuration
   for detector and beam energy calibration

   Higgs boson HZ studies
   + WW, ZZ etc..

2. Top threshold scan and (350) GeV running
   5+ years @5 10^34 /cm2/s ➔ 10^6 ttbar pairs ++Zpeak

   Top quark mass
   Hvv Higgs boson studies

3. Z peak scan and peak running , TLEP-Z configuration ➔ 10^12 Z decays
   → transverse polarization of 'single' bunches for precise E_beam calibration
   2 years

   M_Z, Γ_Z R_b etc…
   Precision tests and
   rare decays

4. WW threshold scan for W mass measurement and W pair studies
   1-2 years ➔ 10^8 W pairs ++Zpeak

   M_W, and W properties
   etc…

5. Polarized beams (spin rotators) at Z peak 1 year at BBTS=0.01/IP => 10^{11} Z decays.

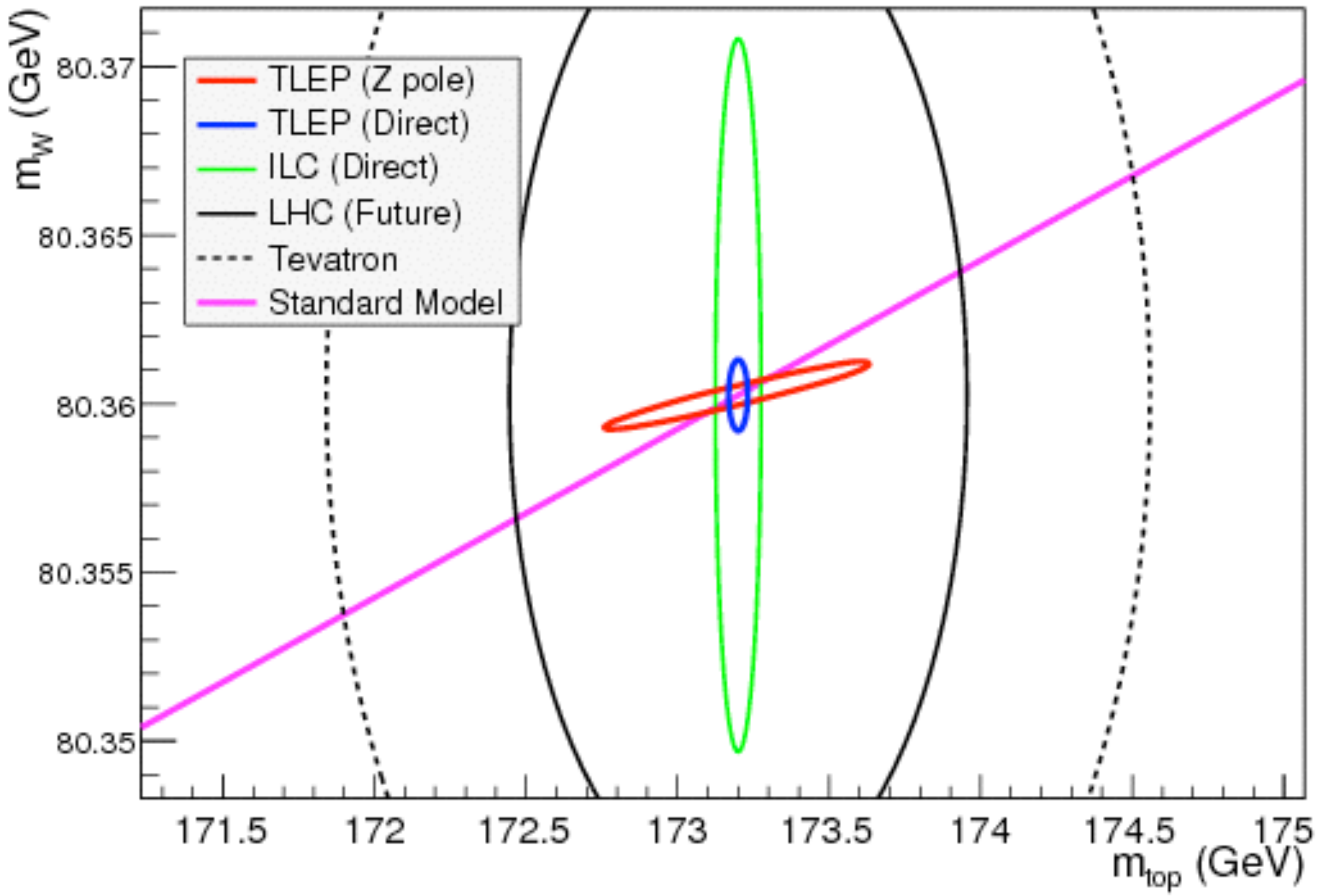
   A_{LR}, A_{FB}^{pol} etc

6. more and upgrades….

NB: TLEP = FCC-ee

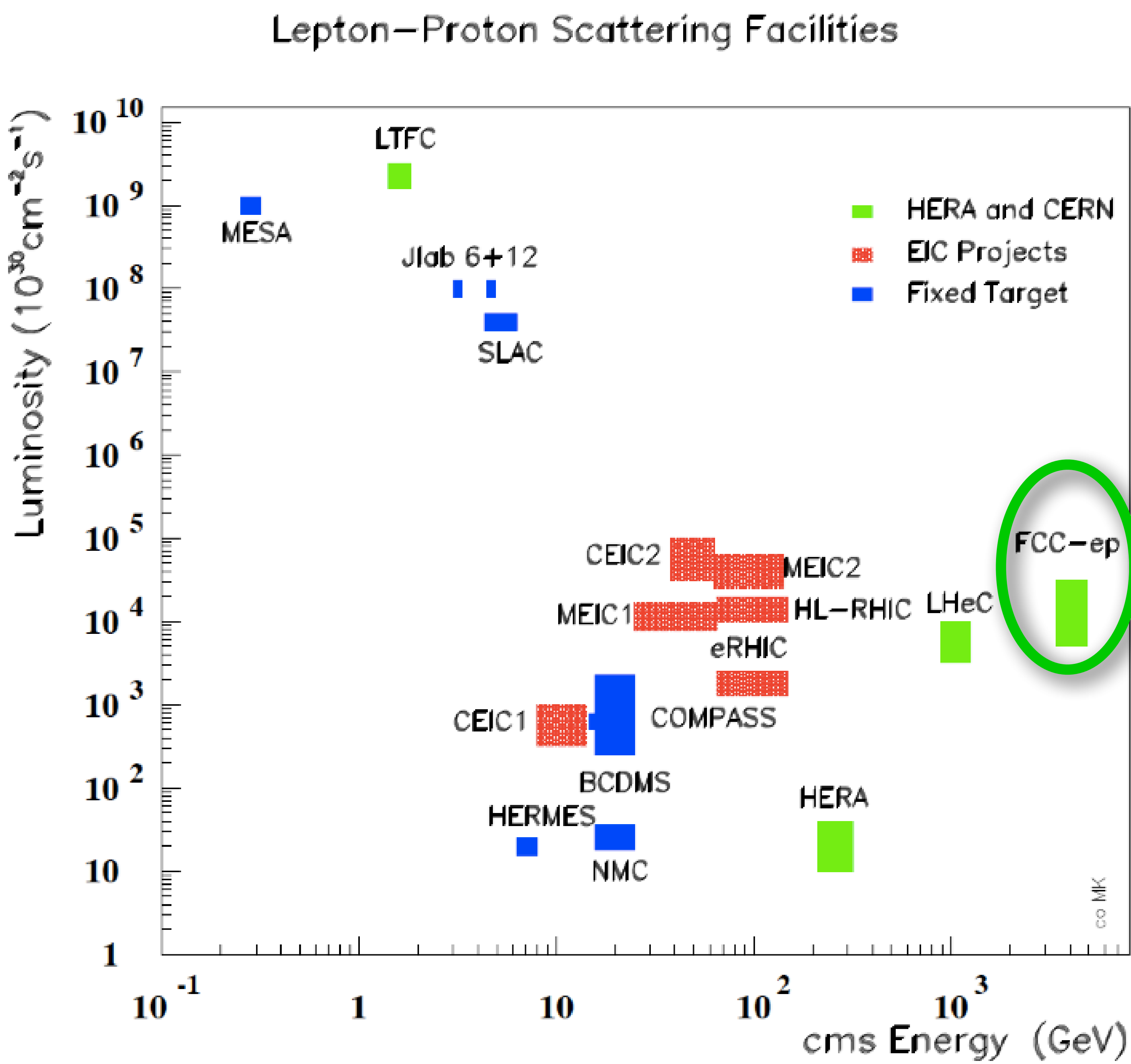
From the global programme, 1–2 orders of magnitude more precise measurements of EW parameters

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	Input	91187.5 ±2.1	Z Line shape scan	0.005 MeV <±0.1 MeV	E_cal	QED corrections
Γ_Z MeV/c2	$\Delta\rho$ (T) (no $\Delta\alpha$!)	2495.2 ±2.3	Z Line shape scan	0.008 MeV <±0.1 MeV	E_cal	QED corrections
R_l	α_s, δ_b	20.767 ± 0.025	Z Peak	0.0001 ± 0.002 - 0.0002	Statistics	QED corrections
N_ν	Unitarity of PMNS, sterile ν's	2.984 ±0.008	Z Peak Z+γ(105/161)	0.00008 ±0.004 0.0004-0.001	->lumi meast Statistics	QED corrections to Bhabha scat.
R_b	δ_b	0.21629 ±0.00066	Z Peak	0.000003 ±0.000020 - 60	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)	0.1514 ±0.0022	Z peak, polarized	±0.000015	4 bunch scheme	Design experiment
M_W MeV/c2	$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$ (T, S, U)	80385 ± 15	Threshold (161 GeV)	0.3 MeV <1 MeV	E_cal & Statistics	QED corections
m_{top} MeV/c2	Input	173200 ± 900	Threshold scan	10 MeV	E_cal & Statistics	Theory limit at 100 MeV?


TLEP (Z pole)
TLEP (Direct)
ILC (Direct)
LHC (Future)
Tevatron
Standard Model
m_W (GeV)
80.37
80.365
80.36
80.355
80.35
171.5
172
172.5
173
173.5
174
174.5
175
m_{top} (GeV)

TLEP report

FCC-eh parameters and lum goals

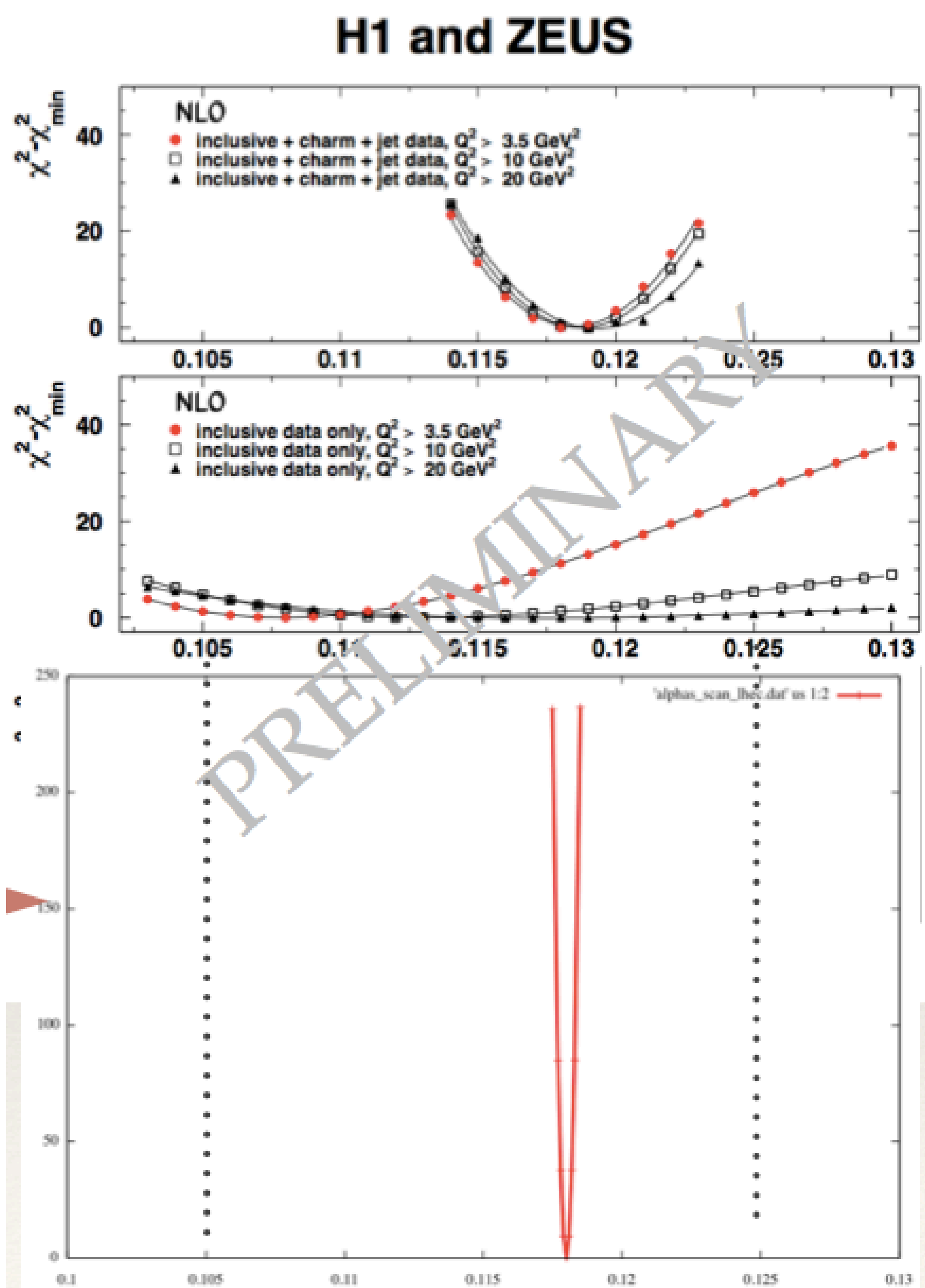


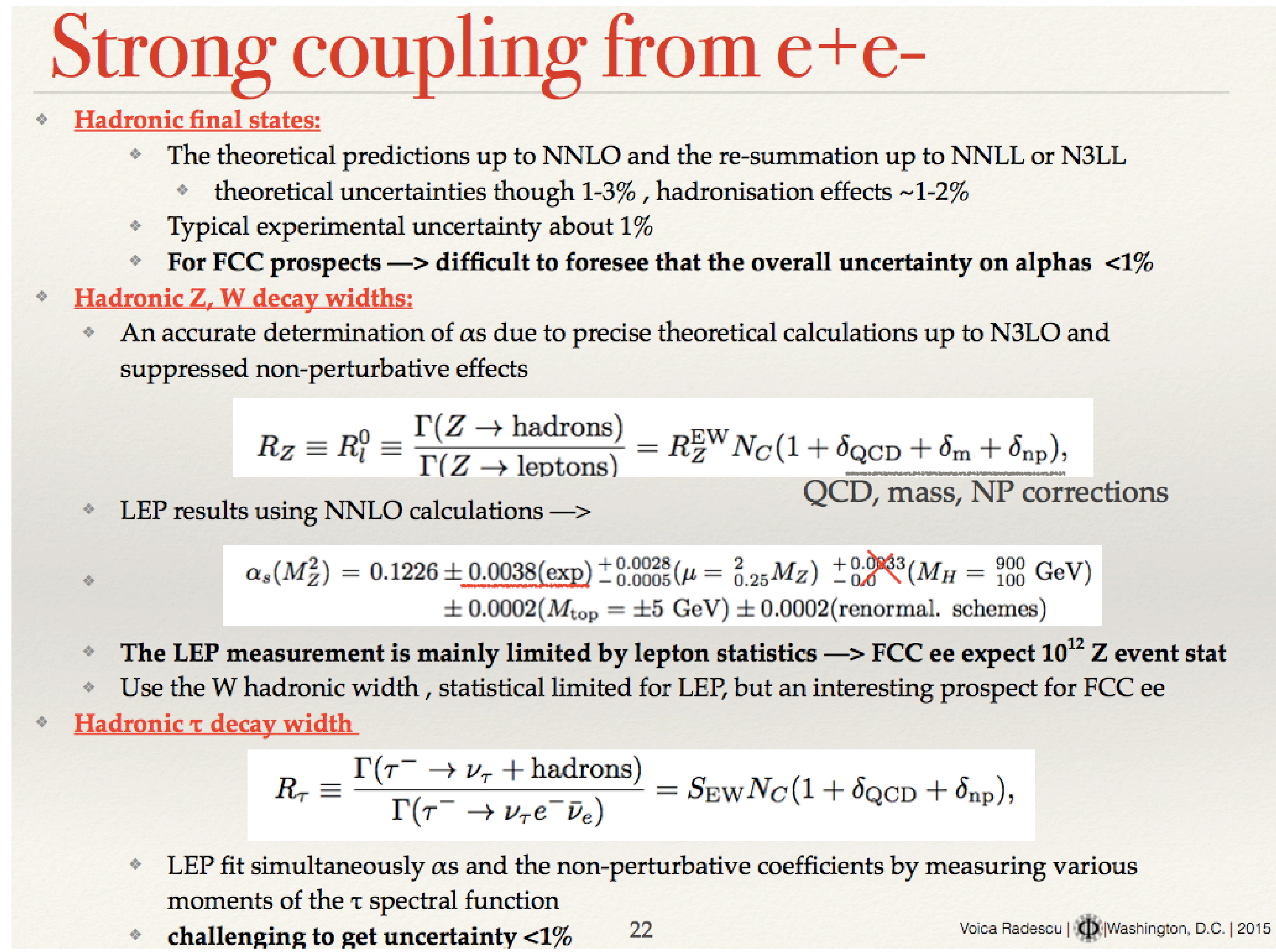
175 GeV e- beam from FCC-ee and 50 TeV p beam from FCC-hh

Highest centre-of-mass energy ep collider, ~6 TeV

Luminosity ~10^{34}cm^{-2}s^{-1}

QCD precision physics





Strong coupling from e+e-

- Hadronic final states:
  - The theoretical predictions up to NNLO and the re-summation up to NNLL or N3LL
    - theoretical uncertainties though 1-3% , hadronisation effects ~1-2%
  - Typical experimental uncertainty about 1%
  - **For FCC prospects —> difficult to foresee that the overall uncertainty on alphas <1%**
- Hadronic Z, W decay widths:
  - An accurate determination of αs due to precise theoretical calculations up to N3LO and suppressed non-perturbative effects

$$R_Z \equiv R_l^0 \equiv \frac{\Gamma(Z\to \text{hadrons})}{\Gamma(Z\to \text{leptons})} = R_Z^{\rm EW} N_C(1+\delta_{\rm QCD}+\delta_{\rm m}+\delta_{\rm np}),$$

QCD, mass, NP corrections

  - LEP results using NNLO calculations —>
  - $$\alpha_s(M_Z^2) = 0.1226 \pm 0.0038(\text{exp}) {}^{+0.0028}_{-0.0005}(\mu = {}^{2}_{0.25} M_Z)\ {}^{+0.0033}_{-0.0}(M_H = {}^{900}_{100}\ \text{GeV}) \pm 0.0002(M_{\rm top} = \pm 5\ \text{GeV}) \pm 0.0002(\text{renormal. schemes})$$
  - **The LEP measurement is mainly limited by lepton statistics —> FCC ee expect 10^{12} Z event stat**
  - Use the W hadronic width , statistical limited for LEP, but an interesting prospect for FCC ee
- Hadronic τ decay width

$$R_\tau \equiv \frac{\Gamma(\tau^-\to \nu_\tau + \text{hadrons})}{\Gamma(\tau^-\to \nu_\tau e^- \bar\nu_e)} = S_{\rm EW} N_C(1+\delta_{\rm QCD}+\delta_{\rm np}),$$

  - LEP fit simultaneously αs and the non-perturbative coefficients by measuring various moments of the τ spectral function
  - **challenging to get uncertainty <1%**

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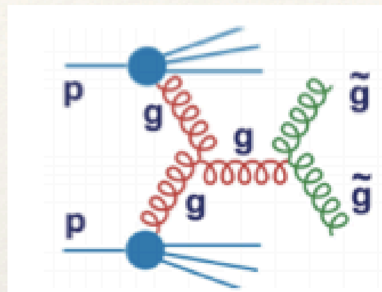
αs extraction from DIS at FCC-eh, vs HERA

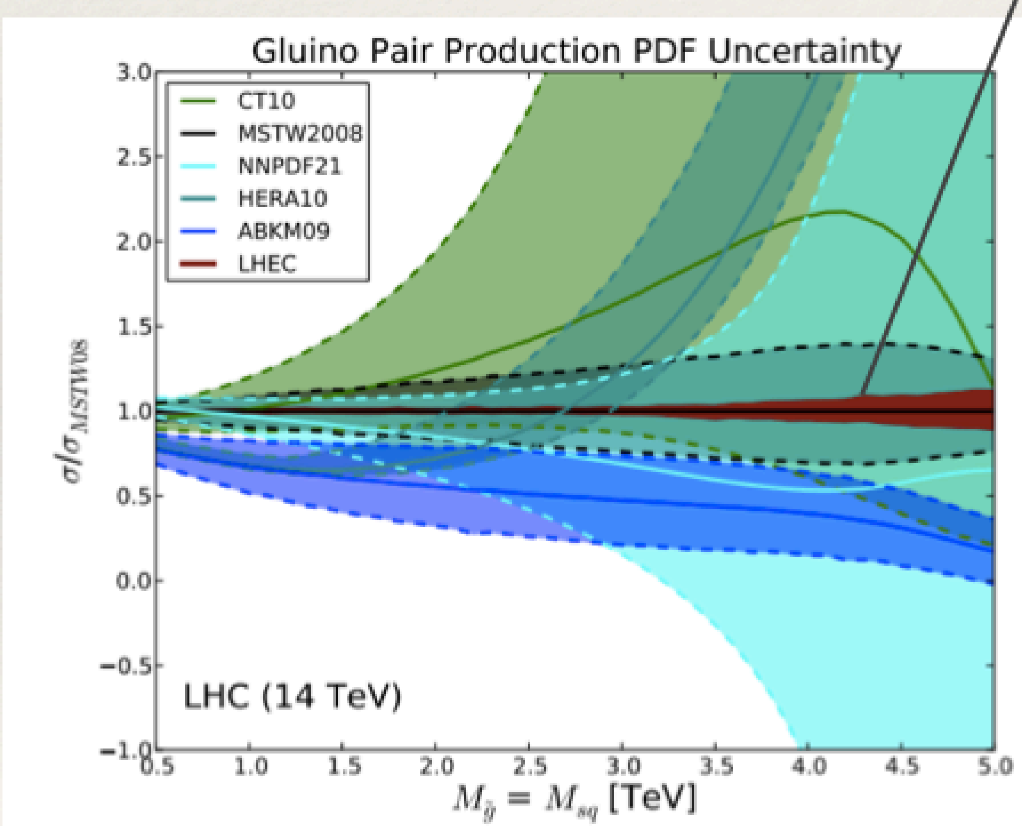
At LEP limited by TH uncertainties or statistics. New opportunities at FCC-ee, such as use of Γ_W

QCD precision physics

High Precision DIS data at high scale

- One of the dominant SUSY production channels is the gluino-gluino pair production:

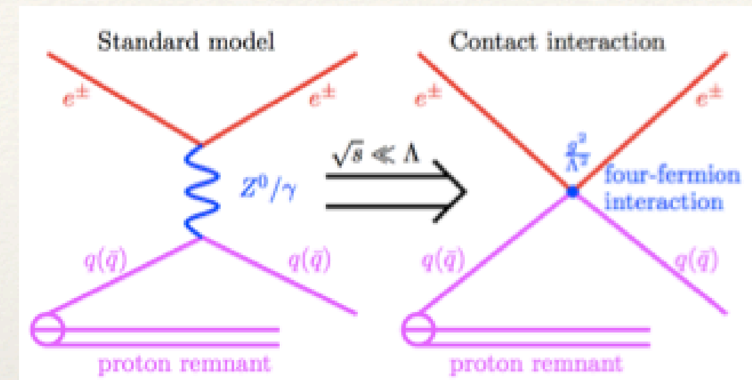


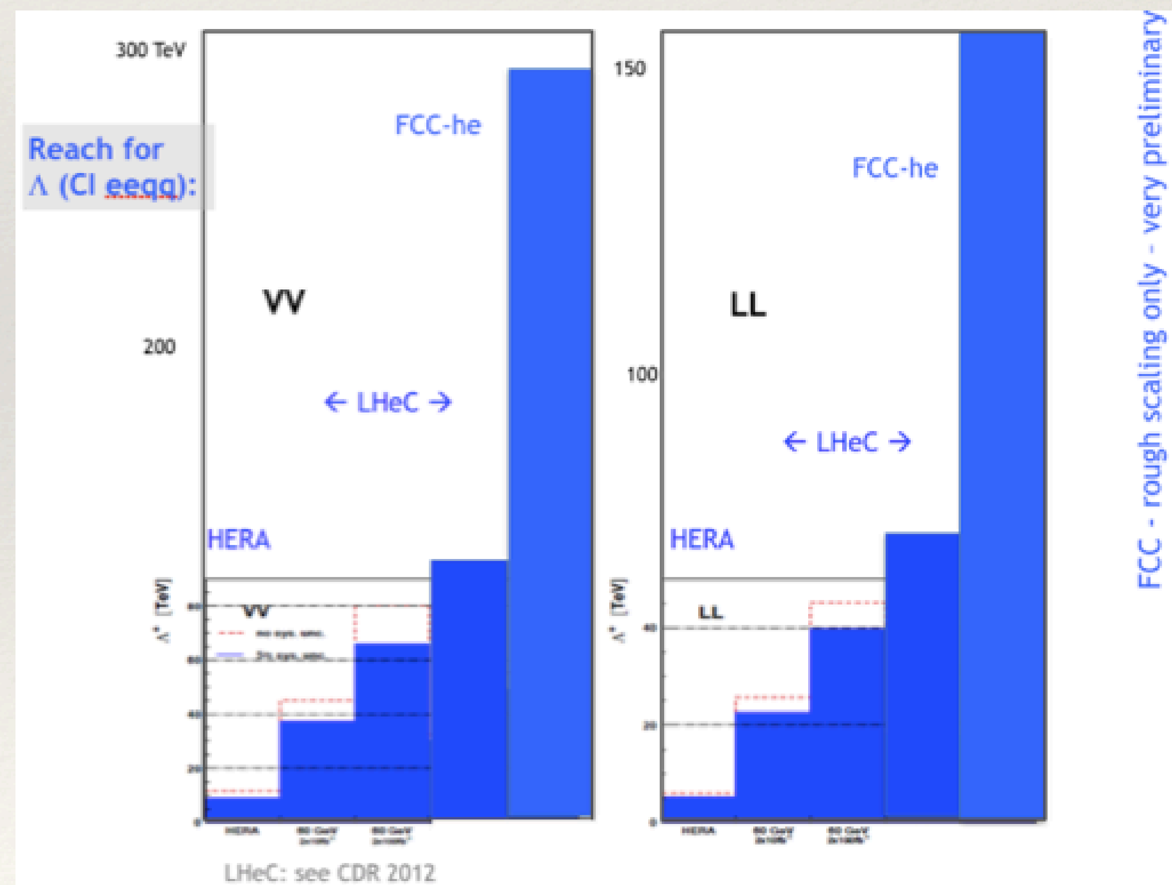


LHeC PDF set

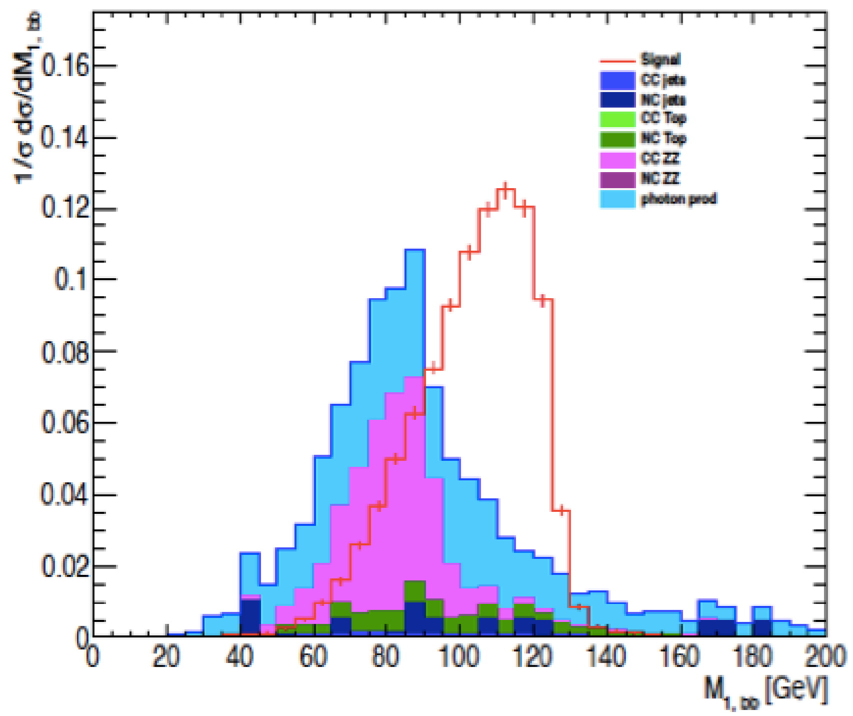
predictability power of the production cross section suffers from high x PDF uncertainties

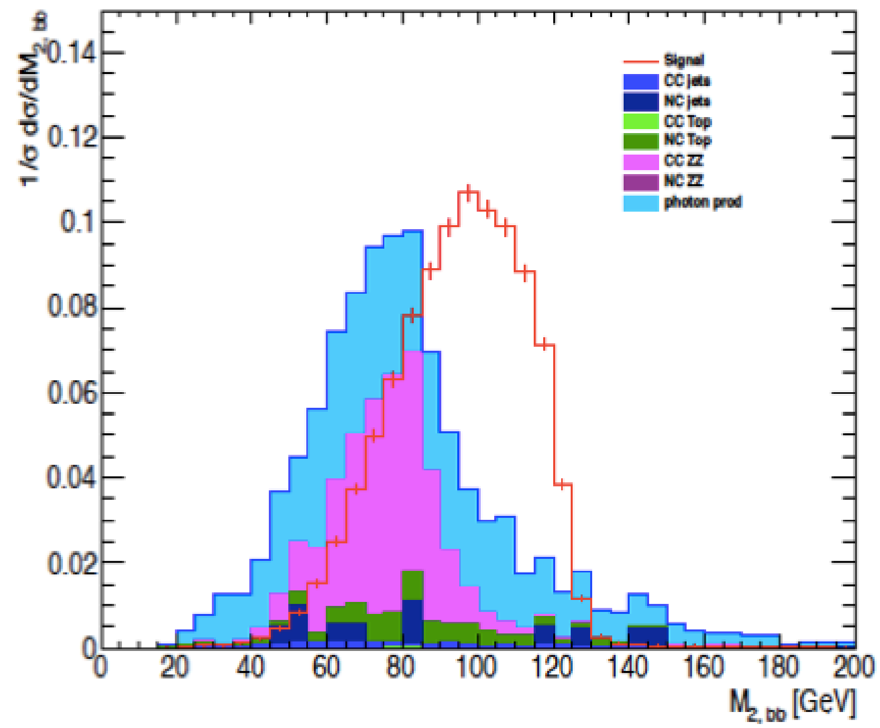
- The very high Q2 data would allow to search for CI (eeqq)

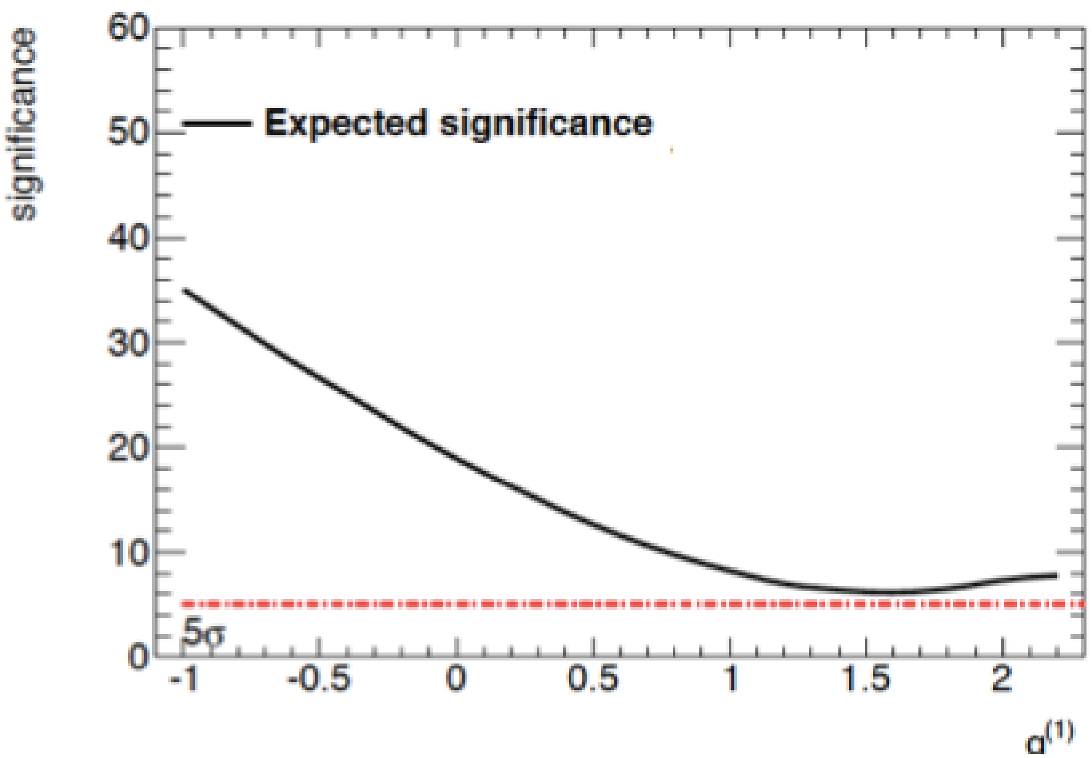


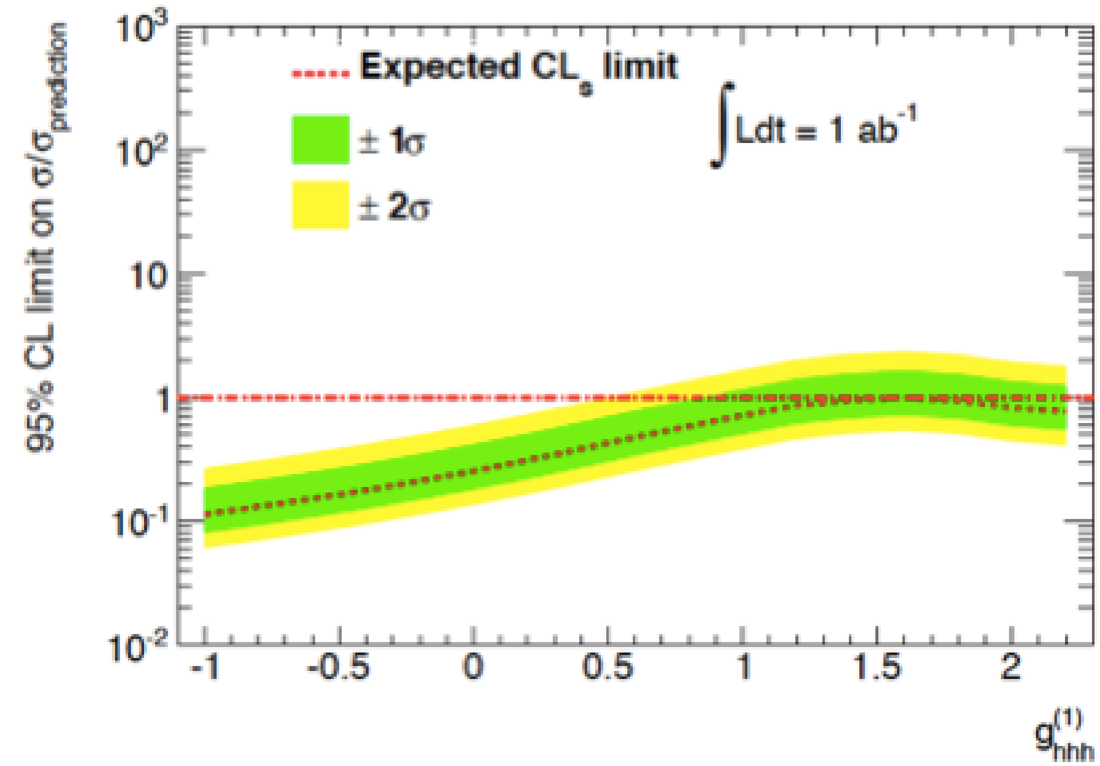


HH→4b reconstruction in FCC-eh









Higgs couplings programme

- Precise measurement of main Higgs couplings:
  - W,Z bosons, 3rd generation fermions (⇒probe existence of BSM effective couplings, e.g. due to non-elementary nature of H, determine CP properties, etc.)
- Couplings to 2nd and 1st generation (⇒universality of Higgs mass-generation mechanism)
- Higgs selfcouplings (⇒probe Higgs potential, to test possible underlying structure of Higgs, deviations from "mexican hat", etc)
- Couplings to non-SM objects (e.g. invisible decays)
- non-SM couplings (e.g. forbidden decays)

Projections

g_{HXY}	FCC-ee
ZZ	0.15%
WW	0.19%
$\gamma\gamma$	1.5%
$Z\gamma$	
tt	
bb	0.42%
$\tau\tau$	0.54%
cc	0.71%
ss	
$\mu\mu$	6.4%
uu,dd	
ee	
HH	
BR_{exo}	0.45%
Γ_{tot}	1%

model indep. fit of 240 GeV data

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Γ_{tot} 1%

model indep. fit of 240 GeV data

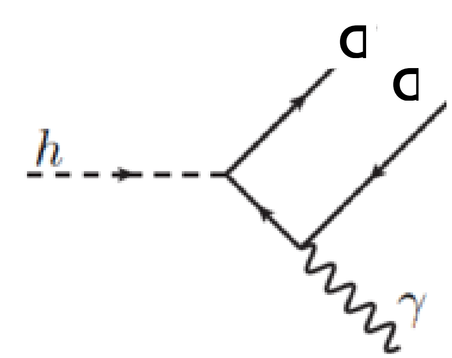
$H \to J/\Psi\,\gamma$ → y_c

$H \to \phi\,\gamma$ → y_s

50 evts

$H \to \rho\,\gamma$

$H \to \omega\,\gamma$ → y_u, y_d



$e^+e^- \to H$

L = 10 ab^{-1}

$\kappa_e < 2.2$ at 3σ

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μμ	6.4%
uu,dd	H→Vγ, in progr.
ee	e^+e^-→H, in progr.
HH	
BR_{exo}	0.45%

Γ_{tot} 1%

	σ	N / $10ab^{-1}$
gg→H	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

Projections

g_{HXY}	FCC-ee	FCC-hh
ZZ	0.15%	
WW	0.19%	
γ γ	1.5%	
Zγ		1% ?
tt		1% ?
bb	0.42%	
τ τ	0.54%	
cc	0.71%	
ss	H→Vγ, in progr.	
μμ	6.4%	2% ?
uu,dd	H→Vγ, in progr.	
ee	e^+e^-→H, in progr.	
HH		5% ?
BR_{exo}	0.45%	$<10^{-3}$

Γ_{tot} 1%

	σ	N / 10ab^{-1}
gg→H	740 pb	7.4 G
VBF	82 pb	0.8 G
WH	16 pb	160 M
ZH	11 pb	110 M
ttH	38 pb	380 M
gg→HH	1.4 pb	14 M

Zγ: → extrapolation from HL-LHC estimates

tt: → from ttH/ttZ arXiv:1507.08169

FCC-hh ambitious but possible targets?

μμ: → extrapolation from HL-LHC estimates

HH: → from HH → bb γγ

BR_{exo}: $<10^{-3}$ for specific channels, like H→eμ, ...

NB

- Statistics allows to bring the precision in the measurement of BR ratios to sub-% level (e.g. B($\rightarrow\gamma\gamma$)/B(H$\rightarrow$ZZ*). Relying on the sub-% measurement of benchmark BR's from FCC-ee, FCC-hh can export this precision to other channels it has access to.

- Experimental feasibility, and theoretical implications, of these measurements are under study

- Several of these new ideas can be already explored at HL-LHC

Higgs physics

NLO rates

$$R(E) = \sigma(E\ TeV)/\sigma(14\ TeV)$$

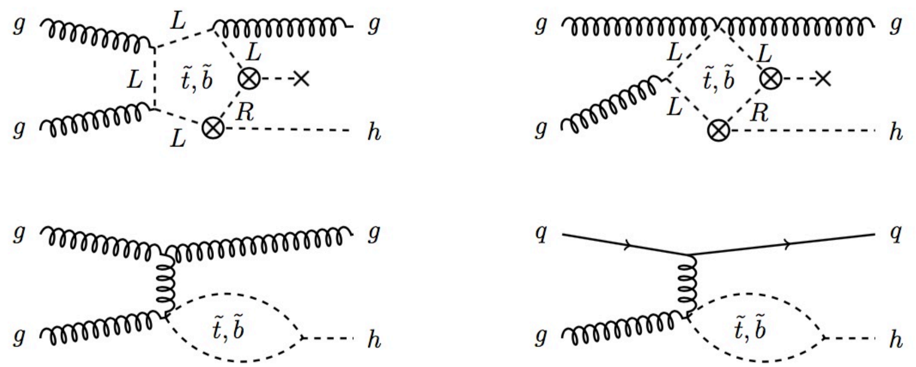
	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

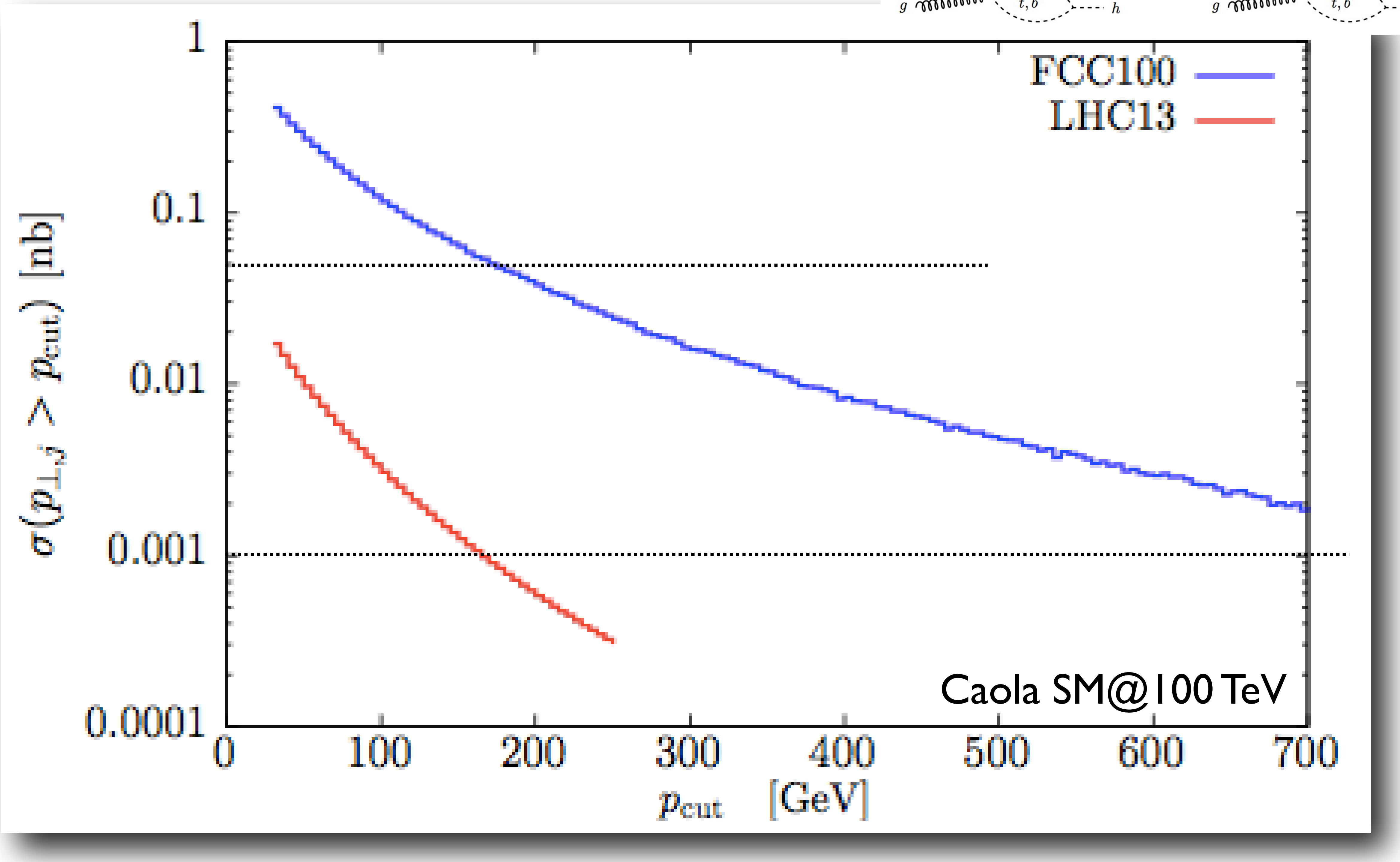
In several cases, the gains in terms of "useful" rate are much bigger.
E.g. when we are interested in the large-invariant mass behaviour of the final states:

$\sigma(ttH, p_T^{top} > 500\ GeV) \Rightarrow R(100) = 250$

gg→H + jet

Huge rates for Higgs Production at high p_T





High-pt H for BR ratios measurements

1 pb rate (i.e. 10^7 events) with $p_T(H) > 1$ TeV

Exploit:

- Improved S/B for many final states at large p_T
- Reduced TH and exp systematics?
- More robust measurement/modeling of BR ratios between different channels, eg:
  + $B(H\to\mu\mu)/B(H\to\gamma\gamma)$, $B(H\to\tau\tau)/B(H\to\gamma\gamma)$, $B(H\to WW)/B(H\to\gamma\gamma)$, $B(H\to Z\gamma)/B(H\to\gamma\gamma)$

Example: $H\to\mu\mu$ statistical precision vs $p_T^{min}(\mu)$ vs $\Delta m_{\mu\mu}$ resolution (Bkg=off-shell DY)

LO only, no K factors

$\sqrt{B}/S$ for $10ab^{-1}$ — $\Delta m_{\mu\mu} = \pm\ 2.5$ GeV

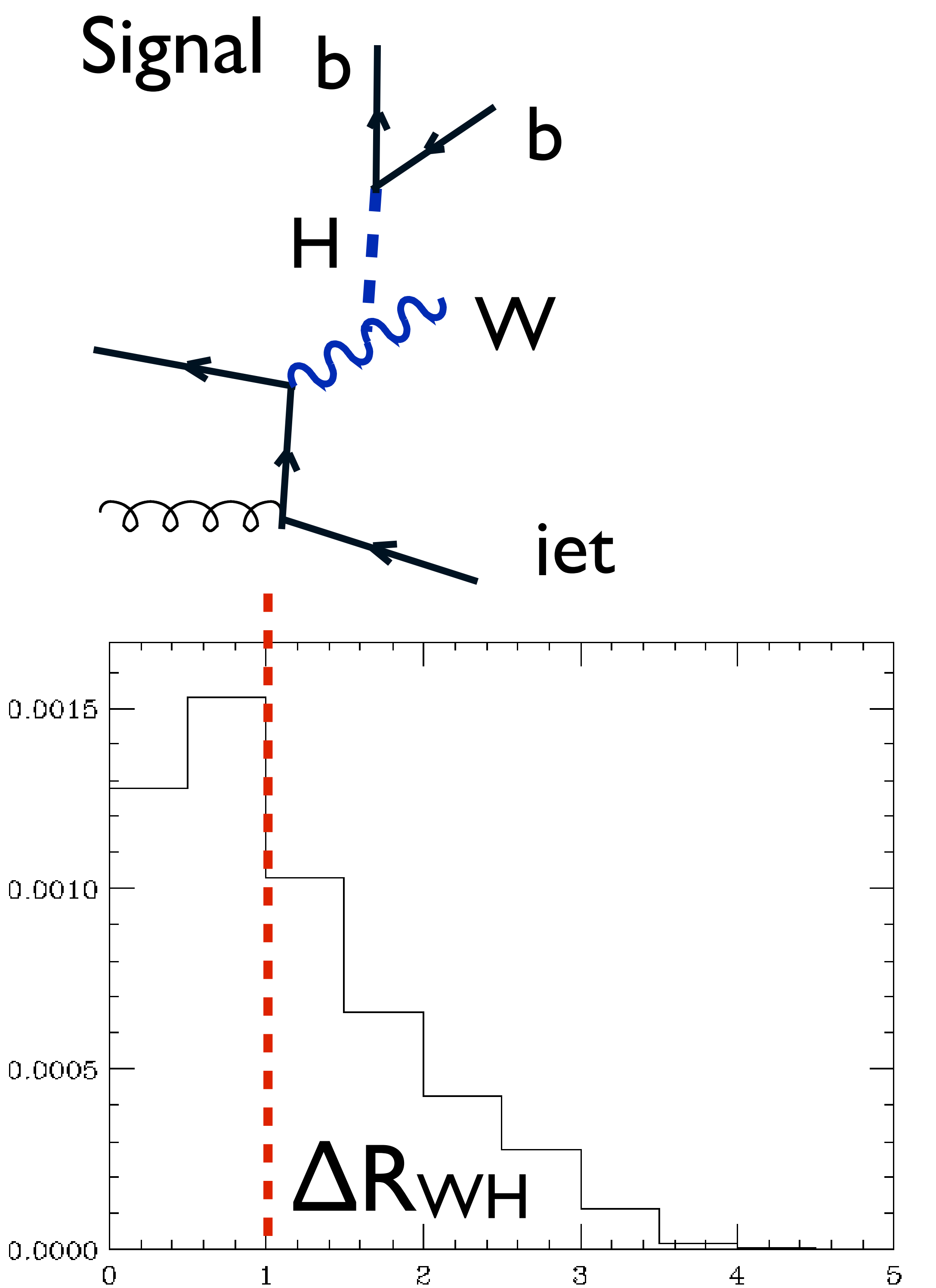
pt mu min \ *pt H min*	30	50	100	150	200
20.00	0.141E-01	0.160E-01	0.185E-01	0.197E-01	0.206E-01
30.00	0.149E-01	0.170E-01	0.193E-01	0.201E-01	0.209E-01
40.00	0.165E-01	0.185E-01	0.201E-01	0.206E-01	0.212E-01
50.00	0.194E-01	0.204E-01	0.209E-01	0.213E-01	0.218E-01
75.00	0.235E-01	0.235E-01	0.234E-01	0.232E-01	0.233E-01
100.00	0.254E-01	0.254E-01	0.254E-01	0.254E-01	0.252E-01

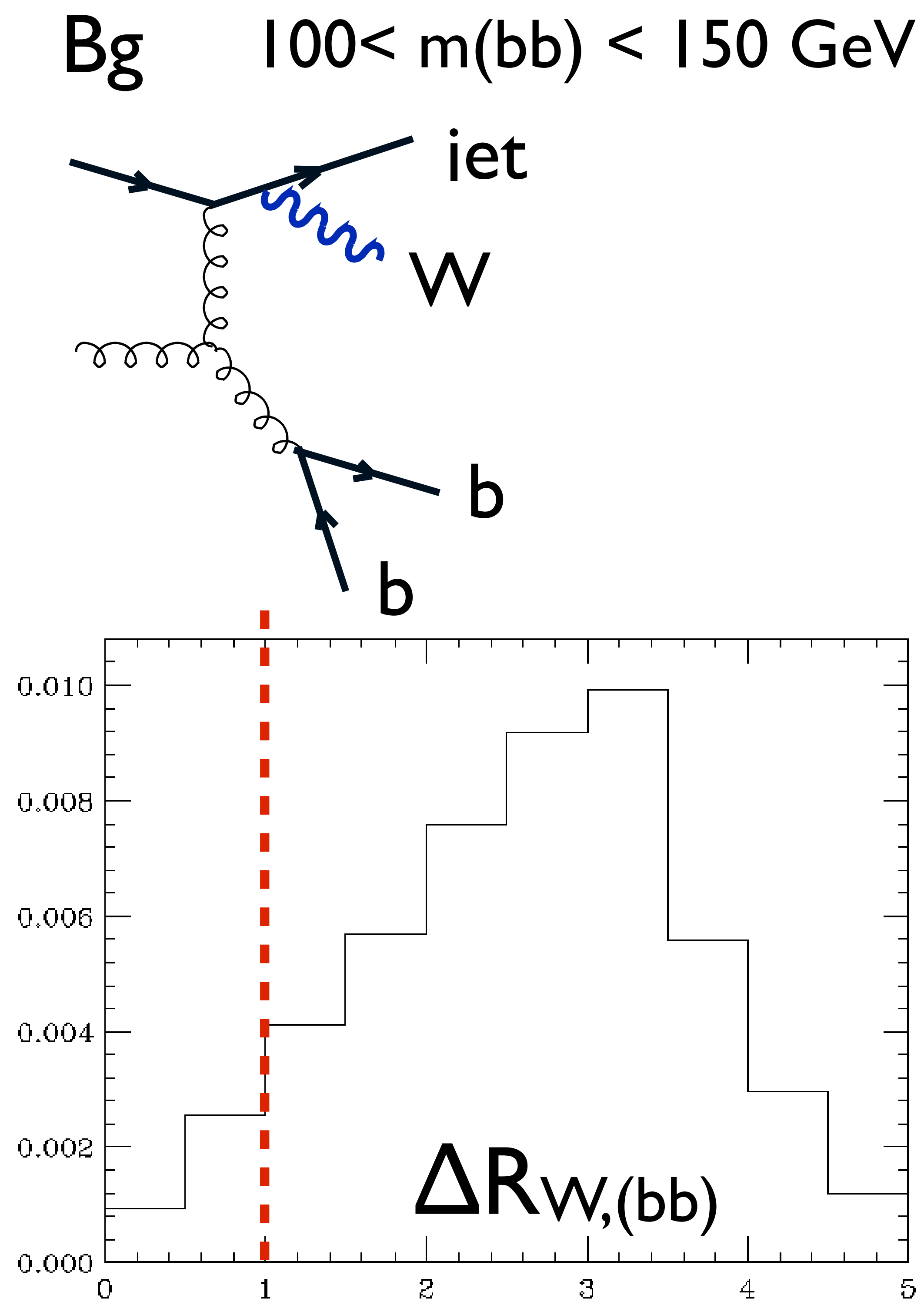
$\sqrt{B}/S$ for $10ab^{-1}$ — $\Delta m_{\mu\mu} = \pm\ 1$ GeV

pt mu min \ *pt H min*					
20.00	0.902E-02	0.102E-01	0.119E-01	0.128E-01	0.135E-01
30.00	0.953E-02	0.109E-01	0.124E-01	0.130E-01	0.137E-01
40.00	0.105E-01	0.119E-01	0.129E-01	0.134E-01	0.139E-01
50.00	0.124E-01	0.131E-01	0.135E-01	0.139E-01	0.143E-01
75.00	0.153E-01	0.153E-01	0.153E-01	0.152E-01	0.153E-01
100.00	0.168E-01	0.168E-01	0.168E-01	0.168E-01	0.167E-01

Ex. WH→e ν bb at large p_T(WH)

p_T(jet) > 500 GeV





σ=5fb → $\sigma(\Delta R<1)$=2.8fb

σ=50fb → $\sigma(\Delta R<1)$=3.5fb

S/B: 1/10 → ~1/1 with 60% efficiency !

ttH/ttZ at 100 TeV as a probe of y_{top}

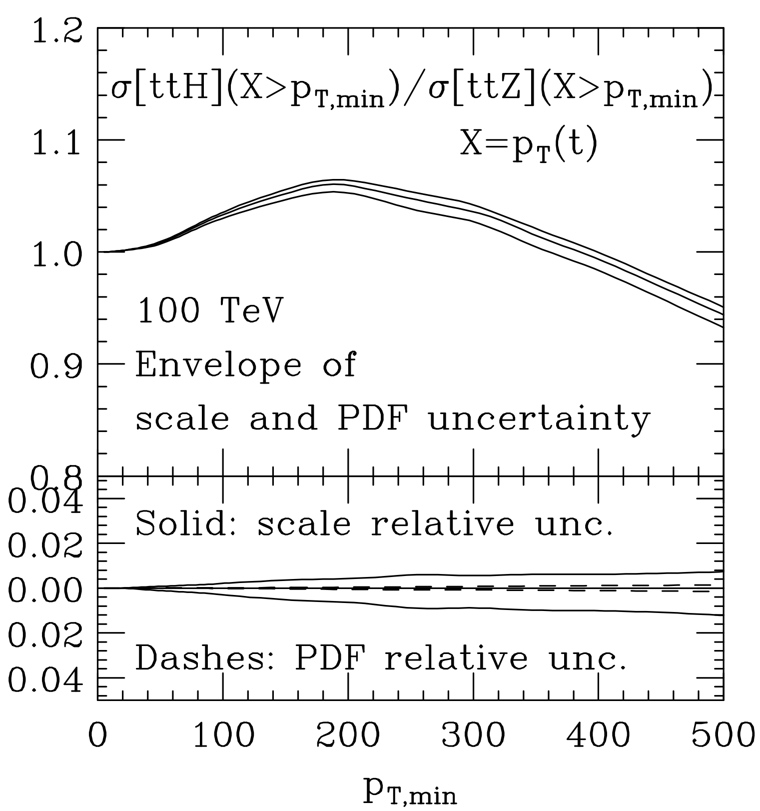
etal, Plehn, Reimitz, Shell, Shao, arXiv:1507.08169

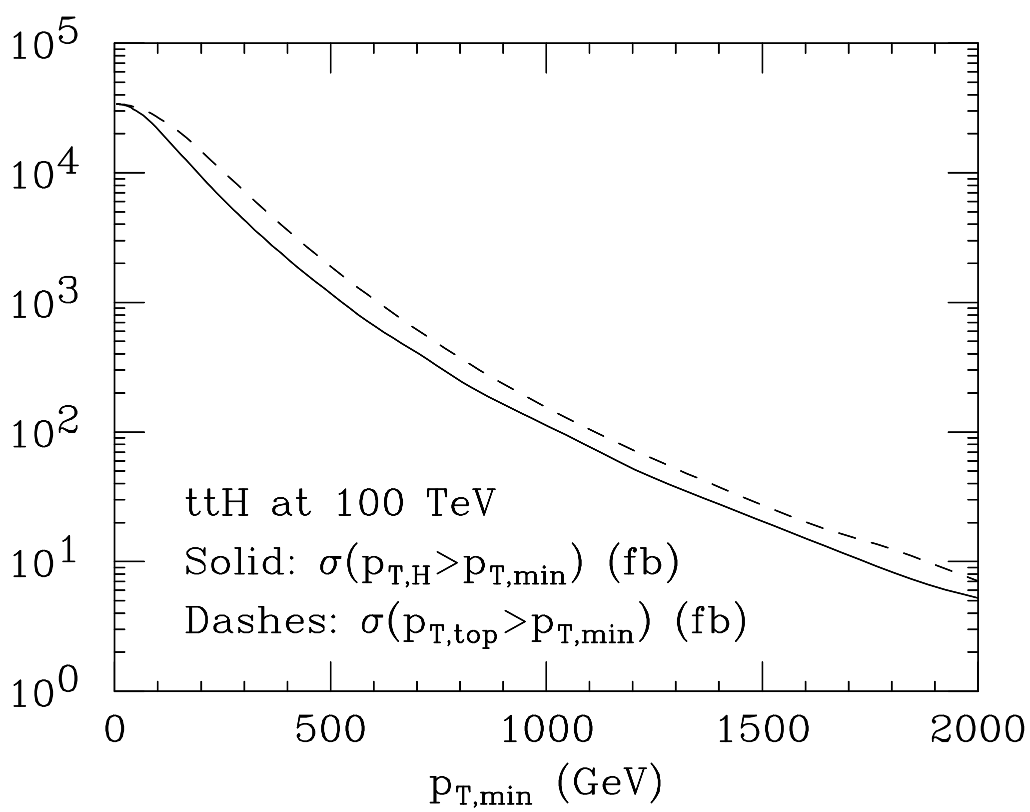
Strong correlations between the two processes in terms of:

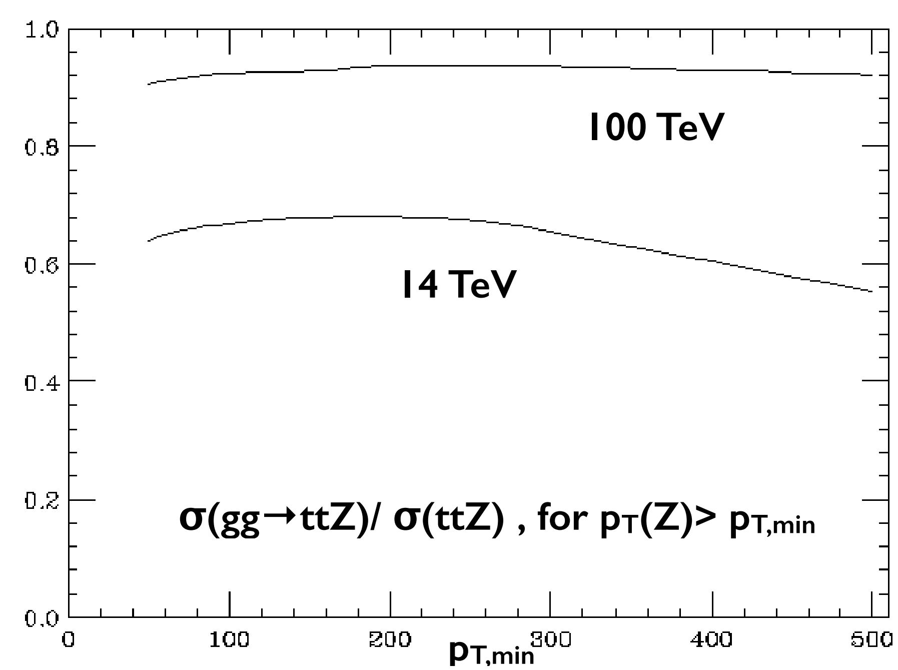
- production dynamics, radiative corrections (⇒reduced scale dependence, MC modeling)
- kinematics ($m_H \sim m_Z$) (⇒reduced PDF systematics, reduced m_{top} systematics, modeling, ...)

At 100 TeV:

- greater dominance of gg initial state w.r.t. 14 TeV ⇒ ttH closer to ttZ
- huge production rates (ttH rate@100 TeV ~ 60 x ttH rate@14 TeV)
- large rate at very high $p_T(H)$ and $p_T(top)$ ⇒ effective use of boosted techniques, reduced combinatorial bg, systematics)
- access to “clean” final states (H→γγ, H→WW*)





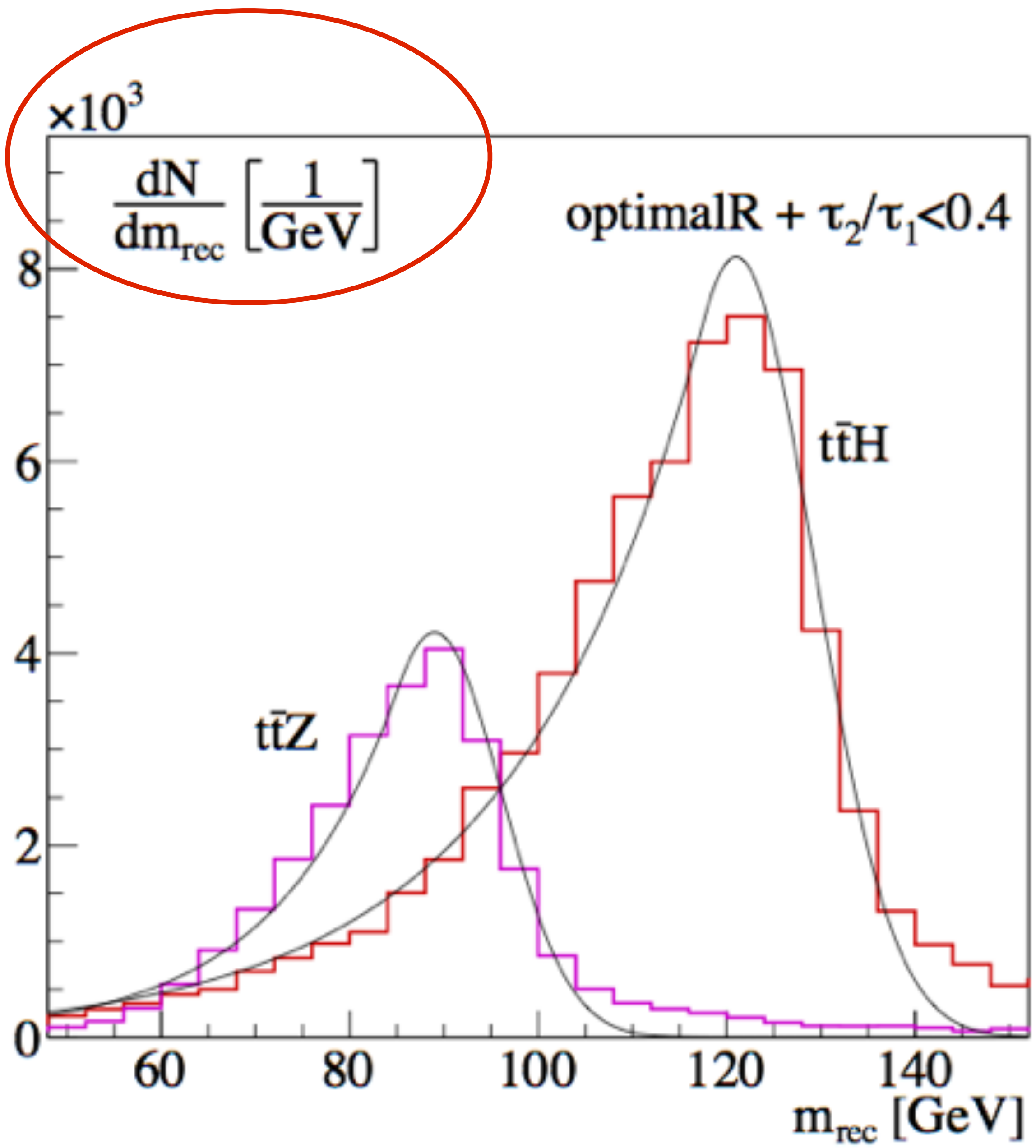


	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

Scale + PDF uncert.

N(events) w. 20 ab^{-1}, tt→e/μ + jets

$H \to 4\ell$	$H \to \gamma\gamma$	$H \to 2\ell 2\nu$	$H \to b\bar{b}$
$2.6 \cdot 10^4$	$4.6 \cdot 10^5$	$2.0 \cdot 10^6$	$1.2 \cdot 10^8$



Top fat C/A jet(s) with R = 1.2, |y| < 2.5, and $p_{T,j}$ > 200 GeV

1% precision on y_{top} within reach

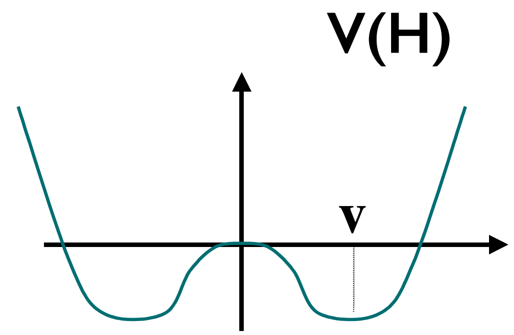
(assuming B(H→bb) known)

arXiv:1507.08169

Higgs selfcouplings

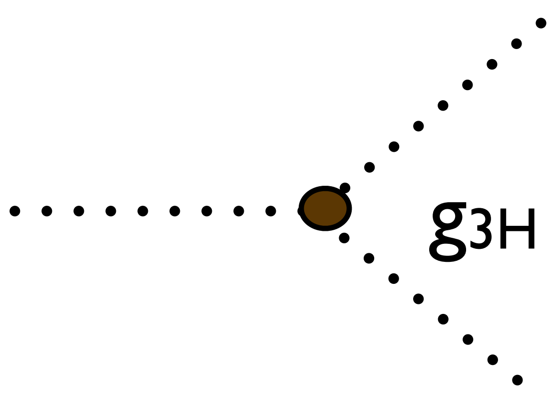
The Higgs sector is defined in the SM by two parameters, **μ** and **λ**:

$$V_{SM}(H) = -\mu^2 \, |H|^2 + \lambda \, |H|^4$$

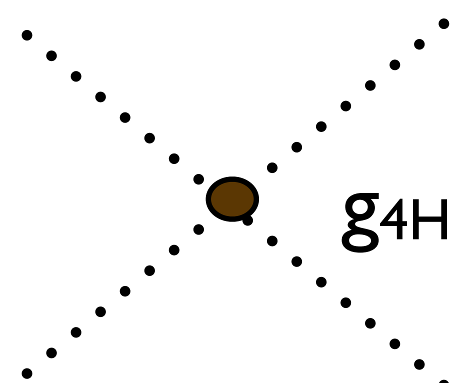


$$\frac{\partial V_{SM}(H)}{\partial H}\Big|_{H=v} = 0 \quad \text{and} \quad m_H^2 = \frac{\partial^2 V_{SM}(H)}{\partial H \partial H^*}\Big|_{H=v} \quad \Rightarrow \quad \begin{aligned} \mu &= m_H \\ \lambda &= \frac{m_H^2}{2v^2} \end{aligned}$$

These relations uniquely determine the strength of Higgs selfcouplings in terms of m_H



$g_{3H} \Rightarrow 6\lambda \, v = \frac{3m_H^2}{v}$ ~$O(m_{top})$



$g_{4H} \Rightarrow 6\lambda = \frac{3m_H^2}{v^2}$ ~$O(1)$

Testing these relations is therefore an important test of the SM nature of the Higgs mechanism

Higgs selfcouplings: pp→HH

- gg→HH (most promising?) , qq→HHqq (via VBF)
- Reference benchmark process: HH→bb γγ
- Goal: 5% (or better) precision for SM selfcoupling

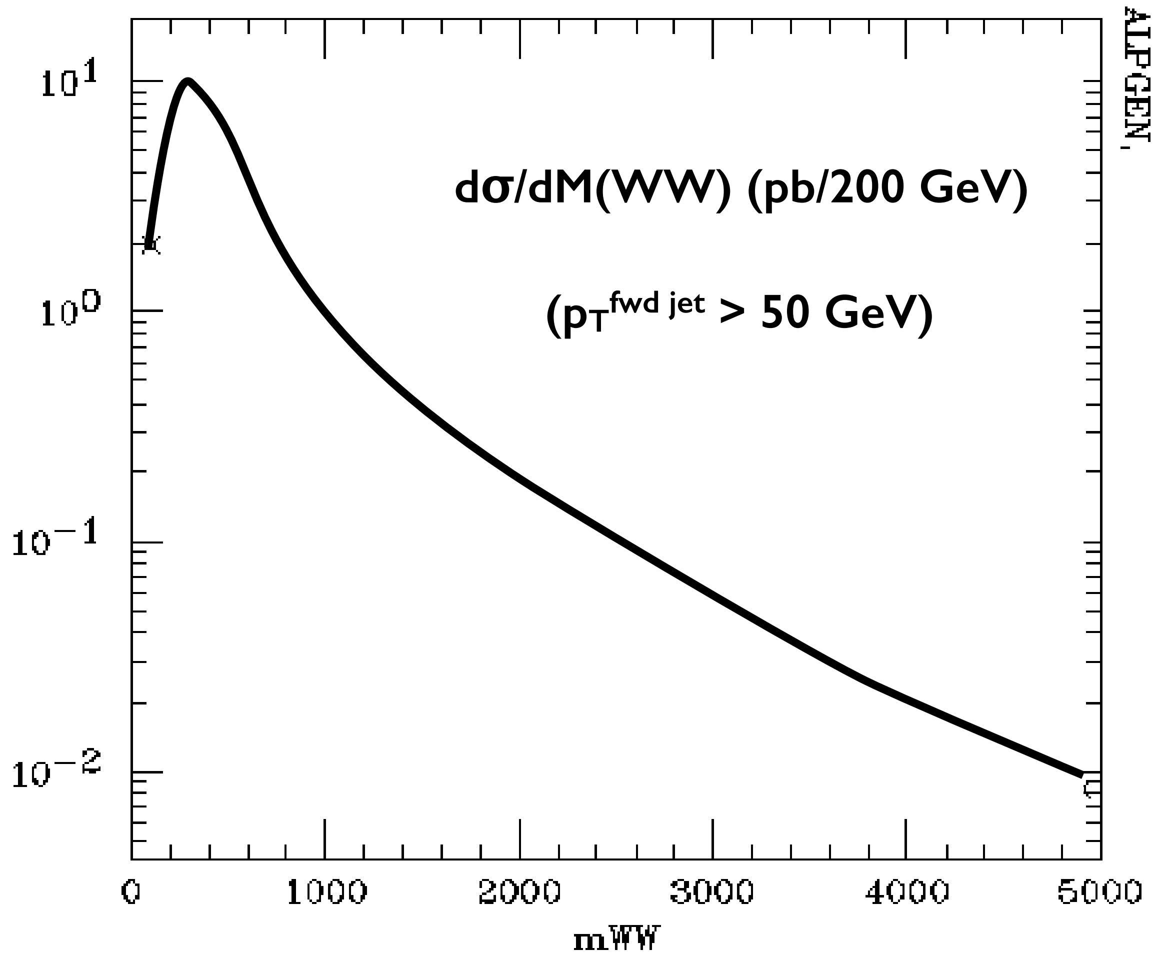
$HH \to b\bar{b}\gamma\gamma$	Barr,Dolan,Englert,Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren, Yao (follow-up of Snowmass study)
FCC$_{@100TeV}$ 3/ab	30~40%	30%	15%
FCC$_{@100TeV}$ 30/ab	10%	10%	5%
$S/\sqrt{B}$	8.4	15.2	16.5
Details	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ✓ Background systematics ○ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach ○ No $c \to b$ & $j \to \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet /W_{had} veto	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV

Work in progress to compare studies, harmonize performance assumptions, optimize, etc
⇒ ideal benchmarking framework

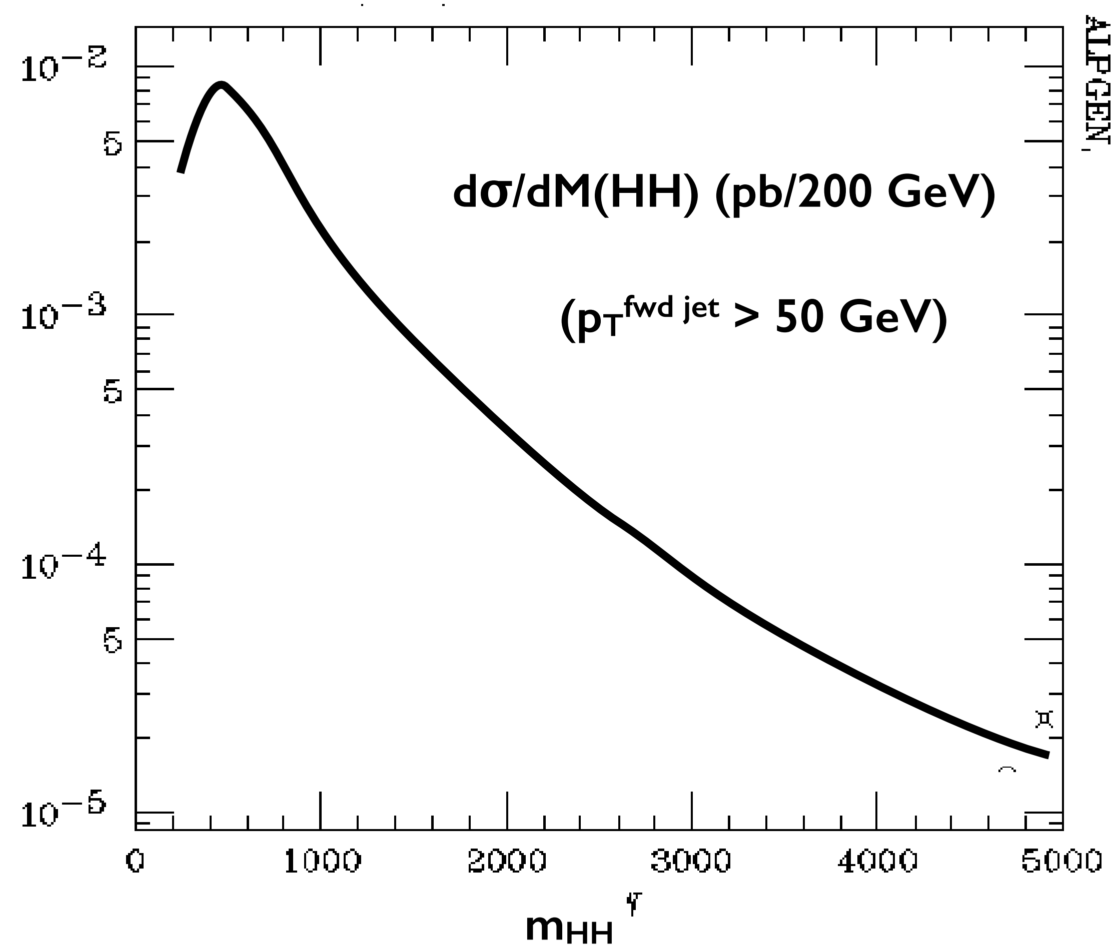
M.Son, HH summary at FCC week

EWSB probes: high mass WW/HH in VBF

SM rates at 100 TeV

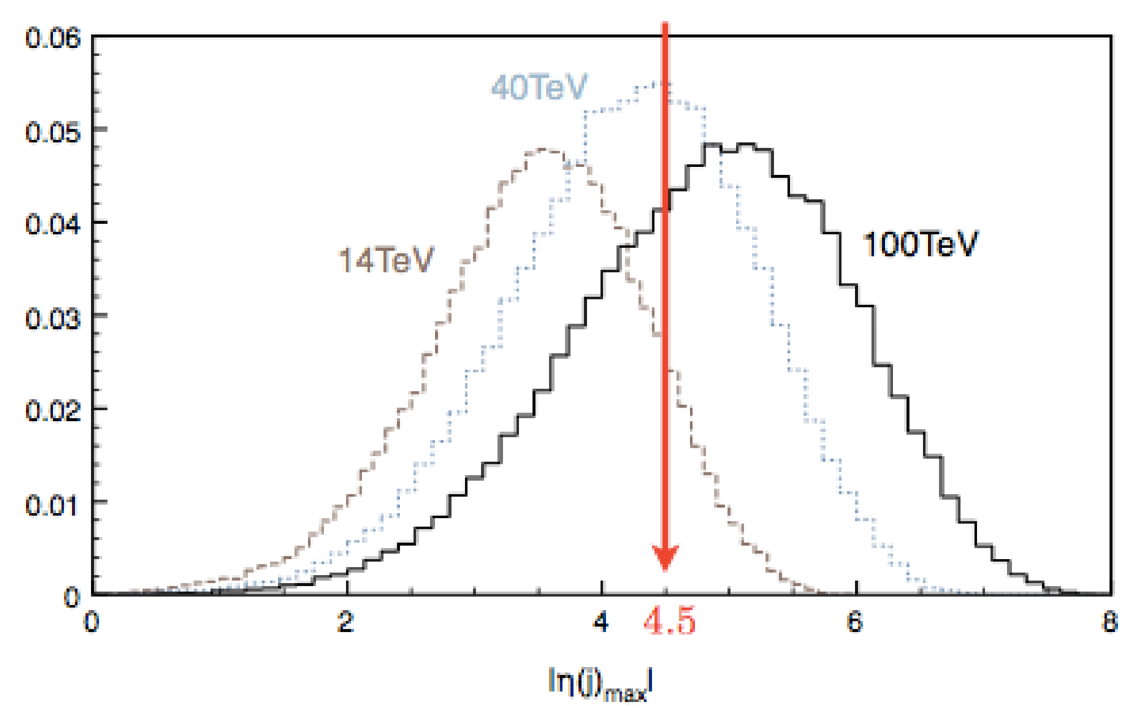


100 fb with M(WW) ≳ 3 TeV

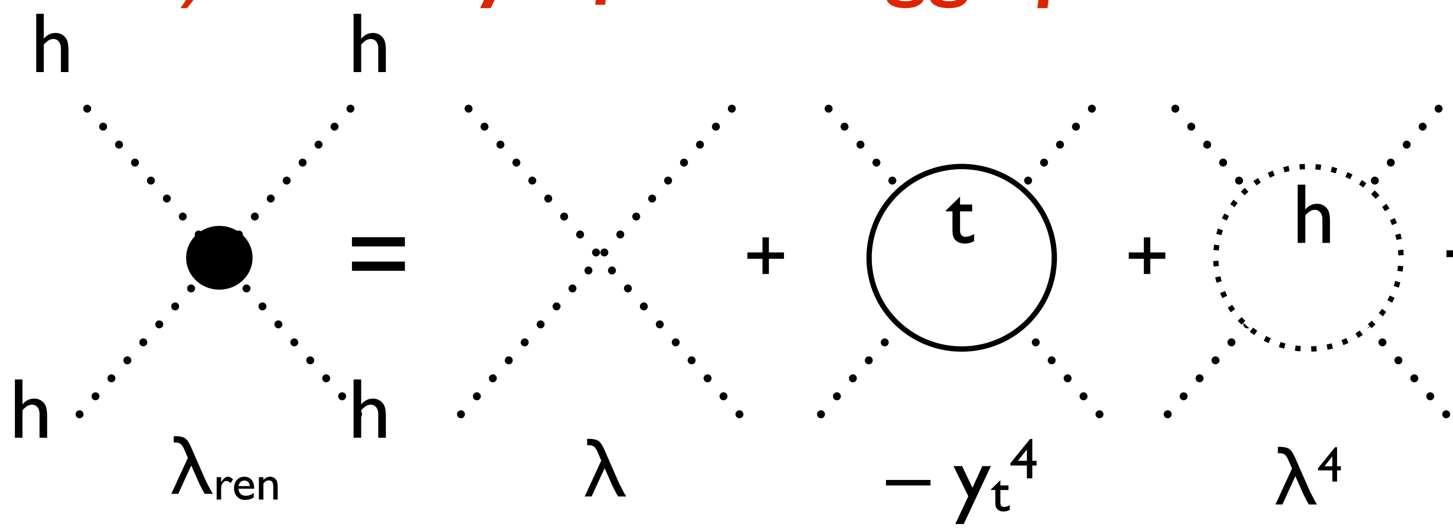


1 fb with M(HH) ≳ 2 TeV

Fwd jet η spectrum



(meta)Stability of the Higgs potential

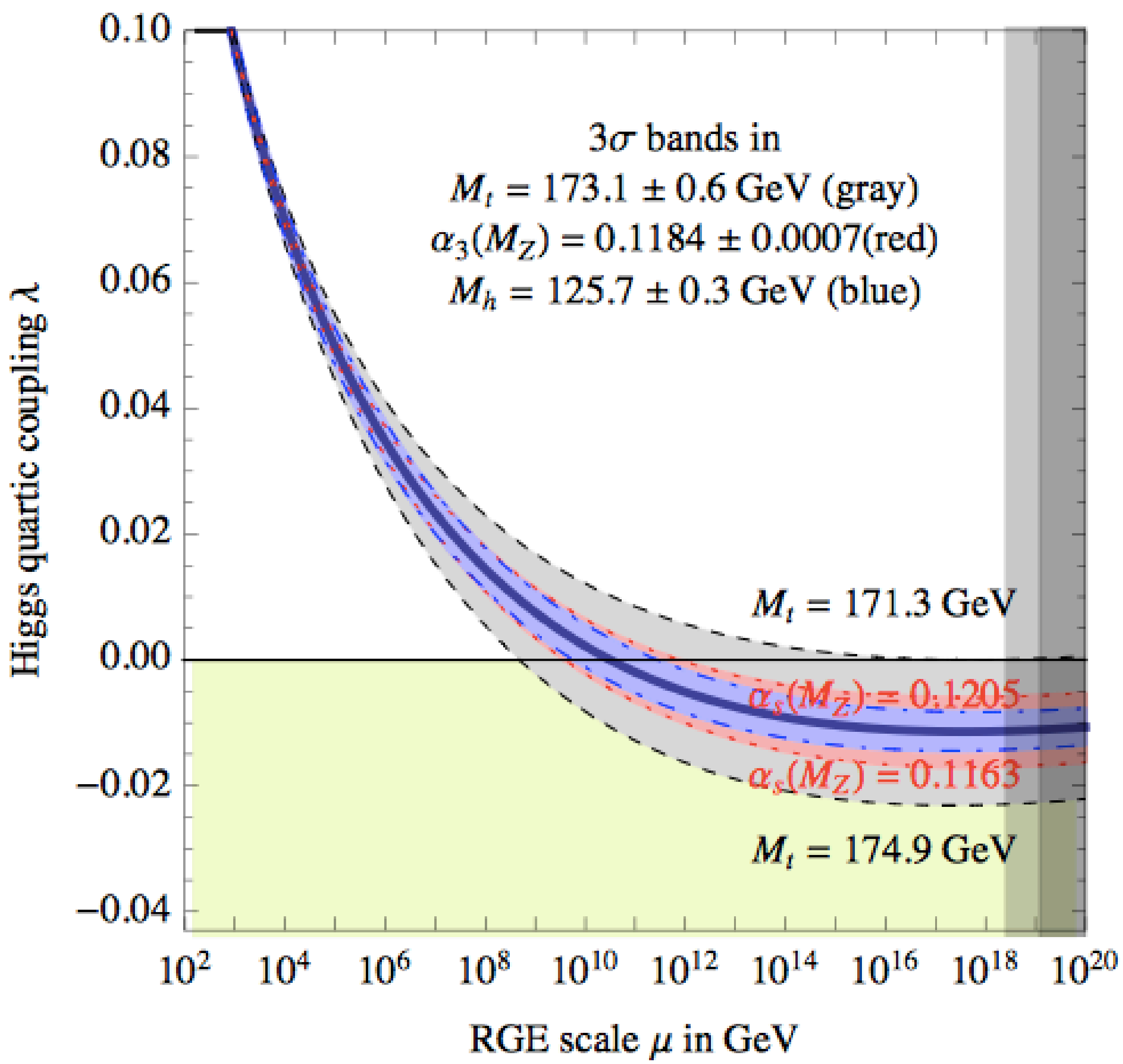


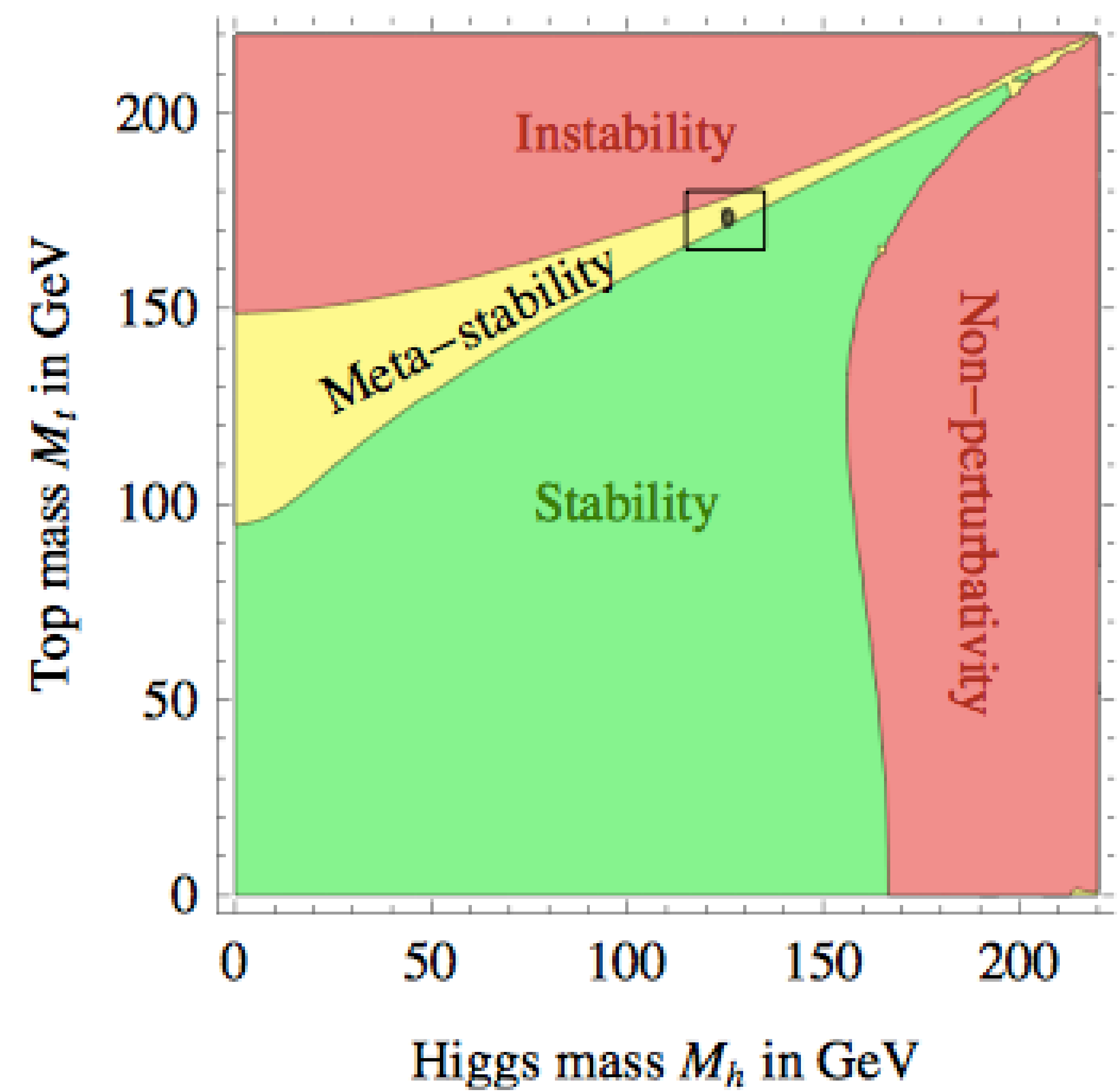
$$\Rightarrow \frac{d\lambda}{d\log\mu} \propto \lambda^4 - y_t^4$$

$$\propto a\, m_H^4 - b\, m_t^4$$

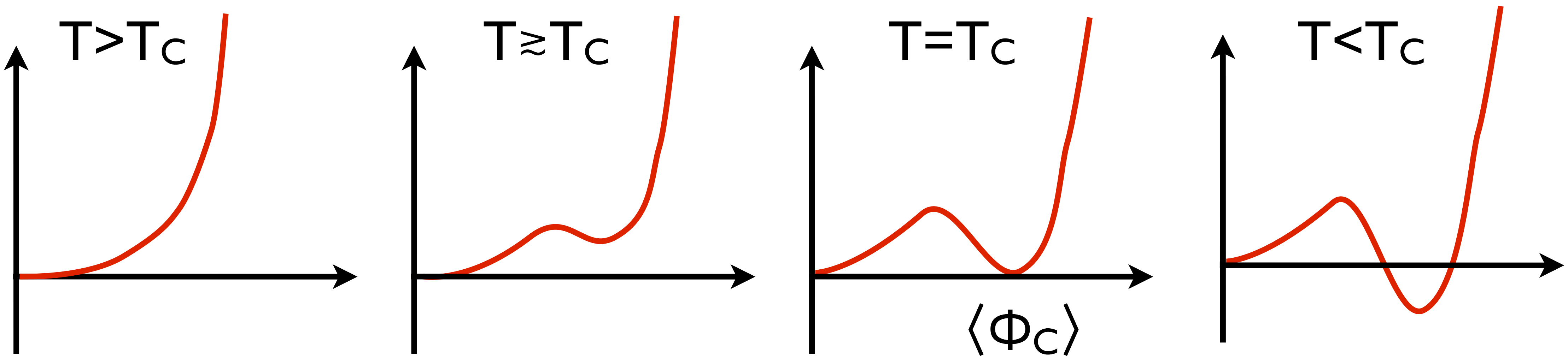
Higgs selfcoupling and coupling to the top are the key elements to define the stability of the Higgs potential

Degrassi et al, http://arxiv.org/pdf/1205.6497



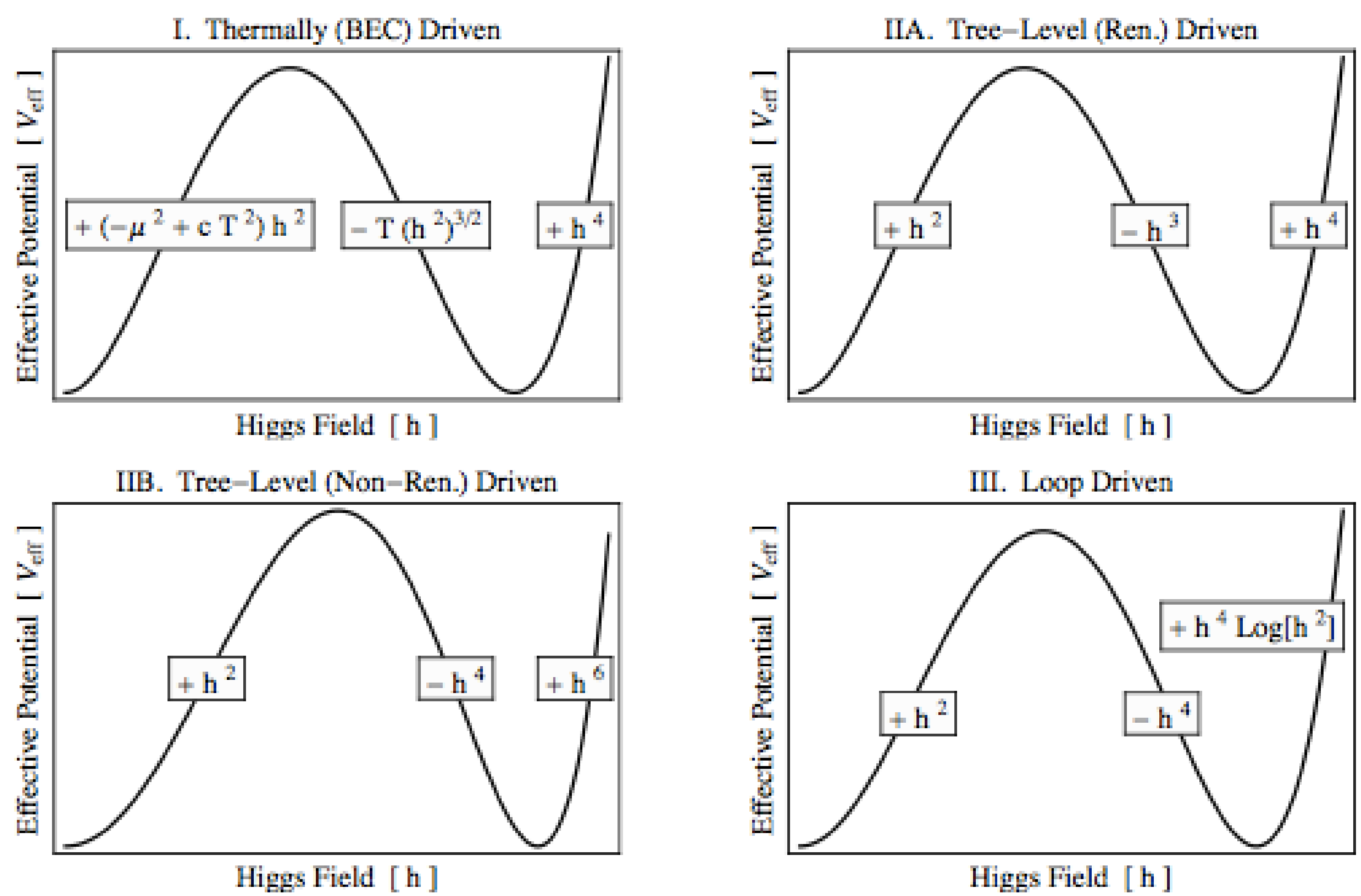


The nature of the EW phase transition



Strong 1st order phase transition $\Rightarrow \langle \Phi_C \rangle > T_C$

In the SM this requires $m_H \lesssim 80$ GeV $\Rightarrow$ new physics, coupling to the Higgs and effective at scales O(TeV), must modify the Higgs potential to make this possible

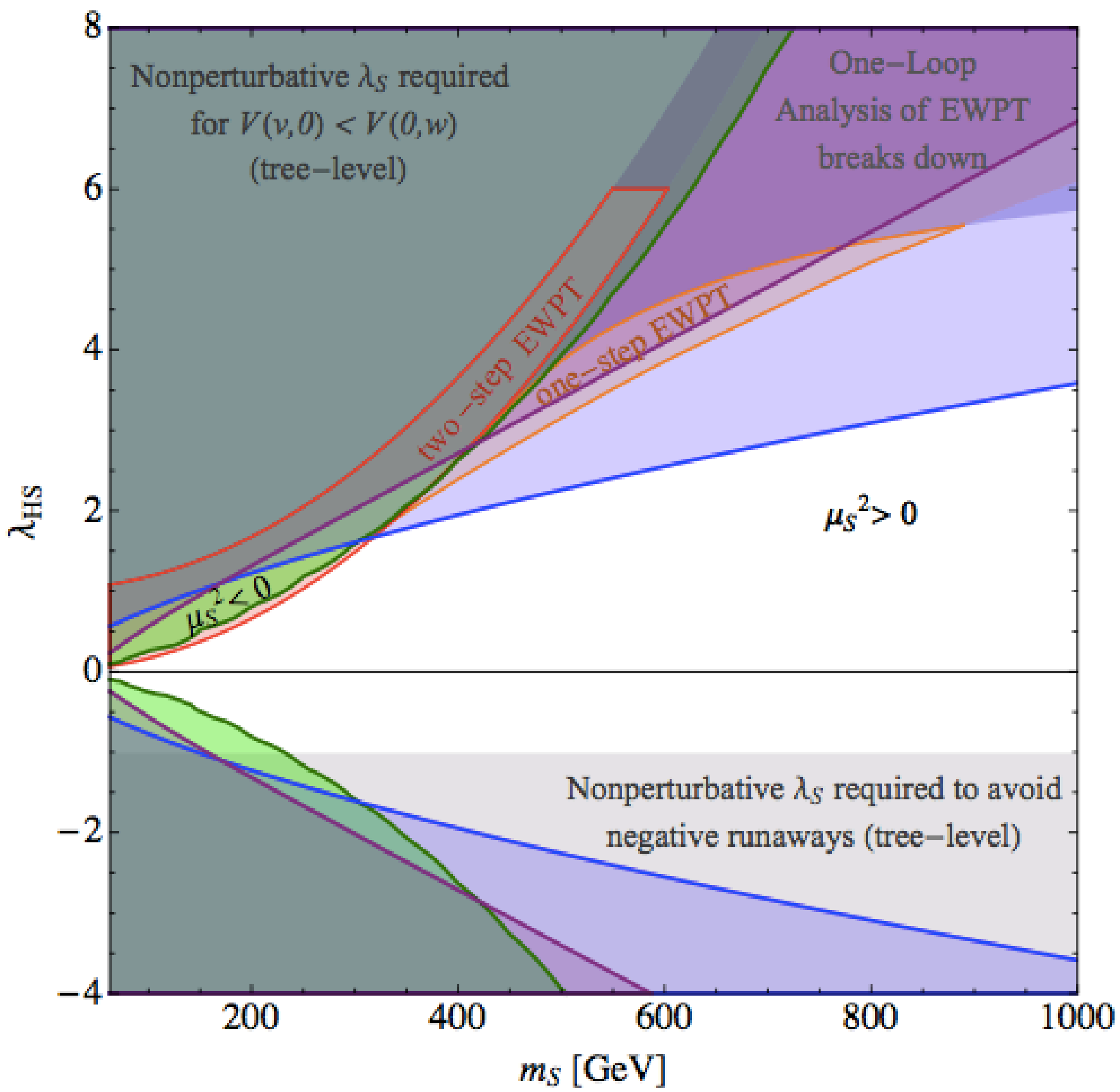


Minimal stealthy model for a strong EWPT

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4$$

D.Curtin @ FCC week

Unmixed SM+S. No exotic higgs decays, no higgs-singlet mixing, no EWPO, ...



Two regions with strong EWPT

Only Higgs Portal signatures:
- $h^* \to SS$ direct production
- Higgs cubic coupling
- $\sigma(Zh)$ deviation (> 0.6% @ TLEP)

100 TeV collider could cover *entire* parameter space.

TLEP (super ILC) can cover *some* of parameter space.

Potential complimentarily!

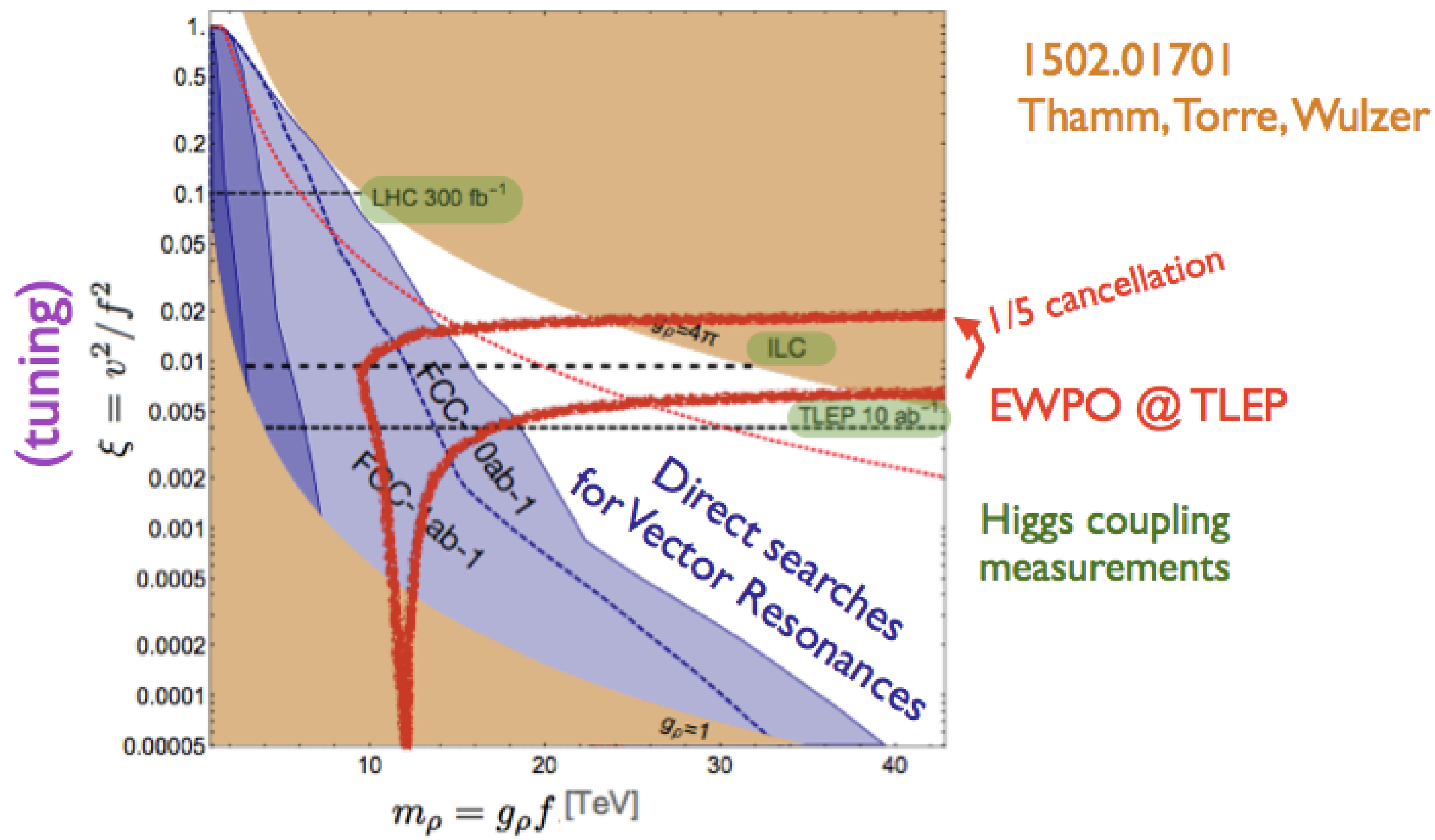
1409.0005 DC, Patrick Meade, Tien-Tien Yu

⇒ Appearance of first “**no-lose**” arguments for classes of compelling scenarios of new physics

Composite Higgs Models

Want Lepton colliders to probe Higgs coupling deviations & EWPO

Want 100 TeV to produce vector resonances of strongly coupled sector (as well as top partners)



Interplay of EW precision tests (Tera-Z@FCC-ee), Higgs BR measurements (H@FCC-ee) and direct resonance searches (10-30 TeV, @ FCC-hh)

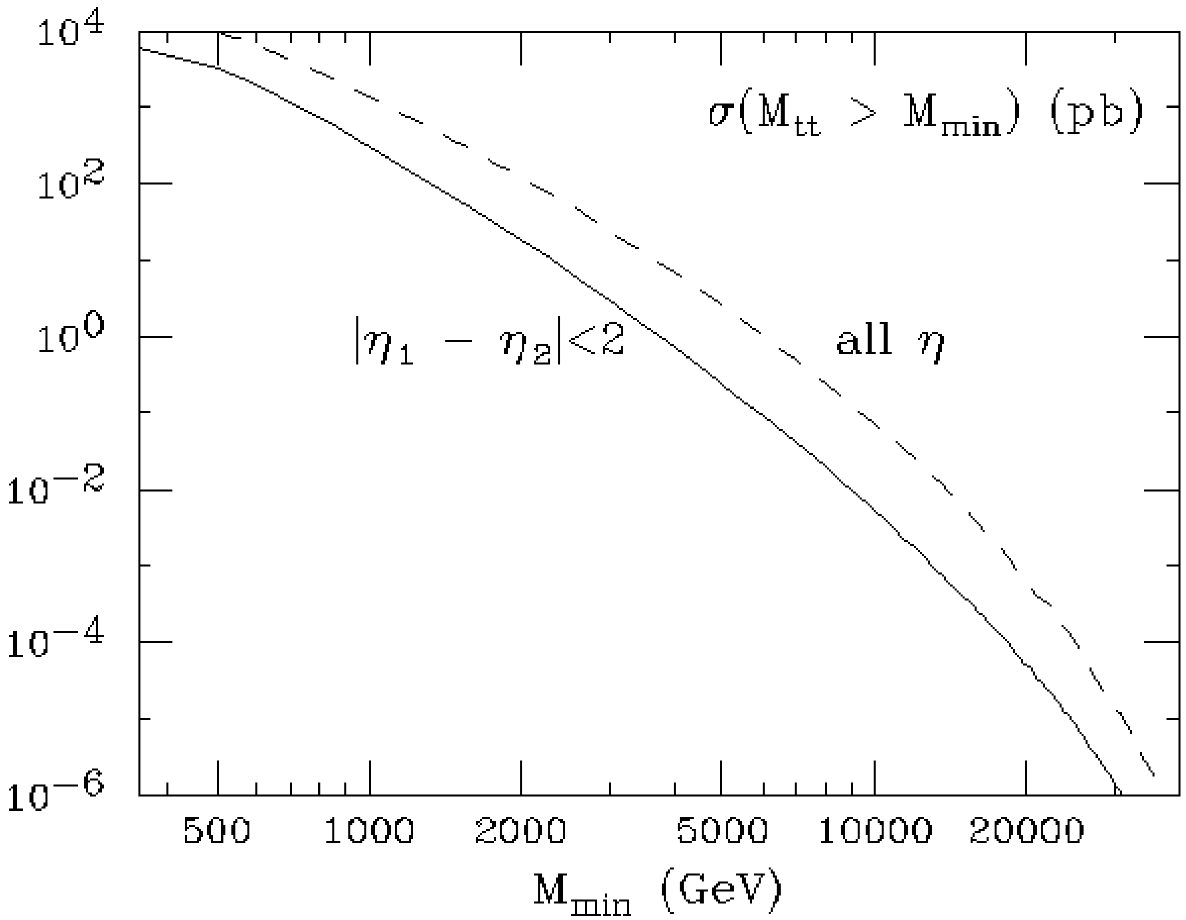
Inclusive top quark production

- Top quark production $\sigma_{100\,\text{TeV}}$ (tt)~30 nb ~ 30 x $\sigma_{14\,\text{TeV}}$ (tt)

LO (CT14lo): sigma_tot = 21.7 + 4.8 (22 %) - 3.6 (17 %) [nb].
NLO (CT14nlo): sigma_tot = 32.1 + 3.6 (11 %) - 3.3 (10 %) [nb].
NNLO (CT14nnlo): sigma_tot = 34.7 + 1.0 (2.9 %) - 1.6 (4.8 %) [nb].
NNLO (NNPDF30_nnlo_as_0118): sigma_tot = 34.8 + 1.0 (2.9 %) - 1.6 (4.7 %) [nb]. *Mitov et al*

- ⇒ about 10^{12} top quarks produced in 10 ab^{-1}
  - rare and forbidden top decays
  - 10^{12} fully inclusive W decays, triggerable by "the other W"
    - rare and forbidden W decays
    - 3 10^{11} W→charm decays
    - 10^{11} W→tau decays
  - 10^{12} fully charge-tagged b hadrons

Inclusive top quark production



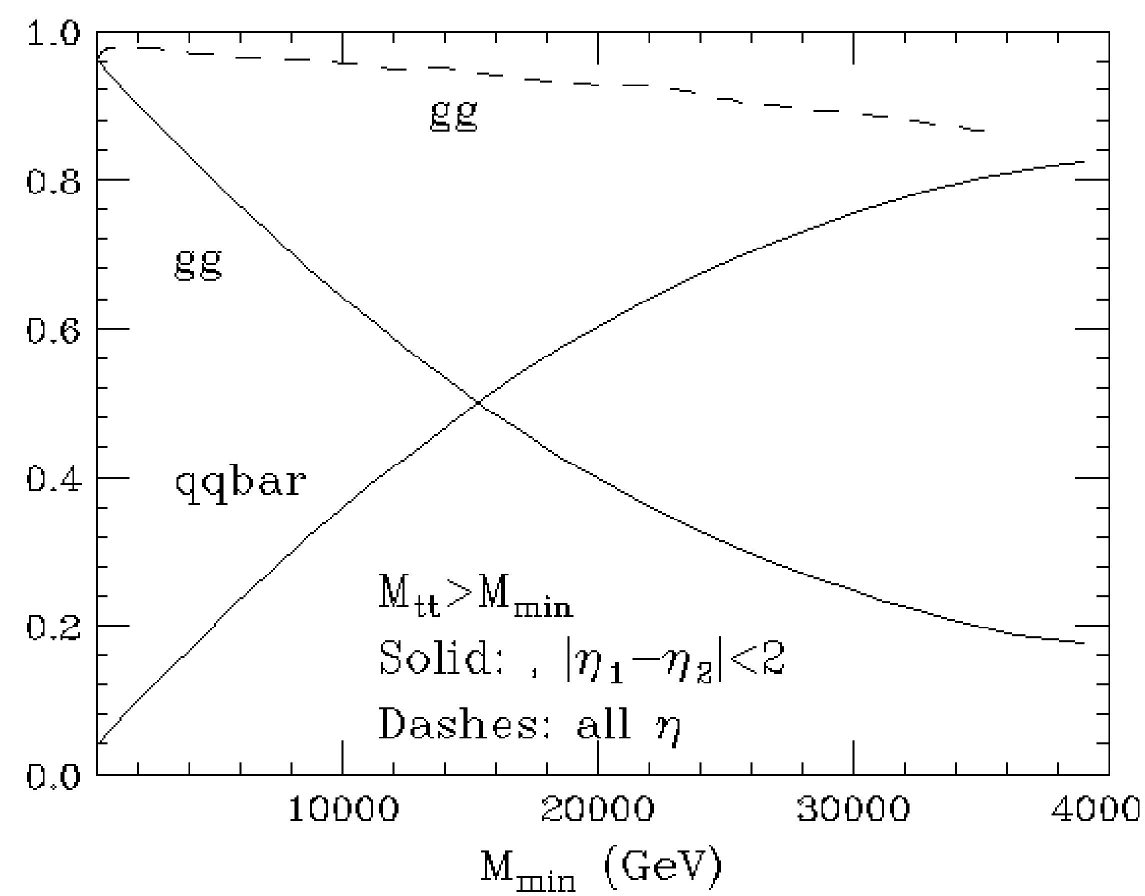
Ex: integrated rates as a function of t-tbar invariant mass for centrally (inclusive) produced tops

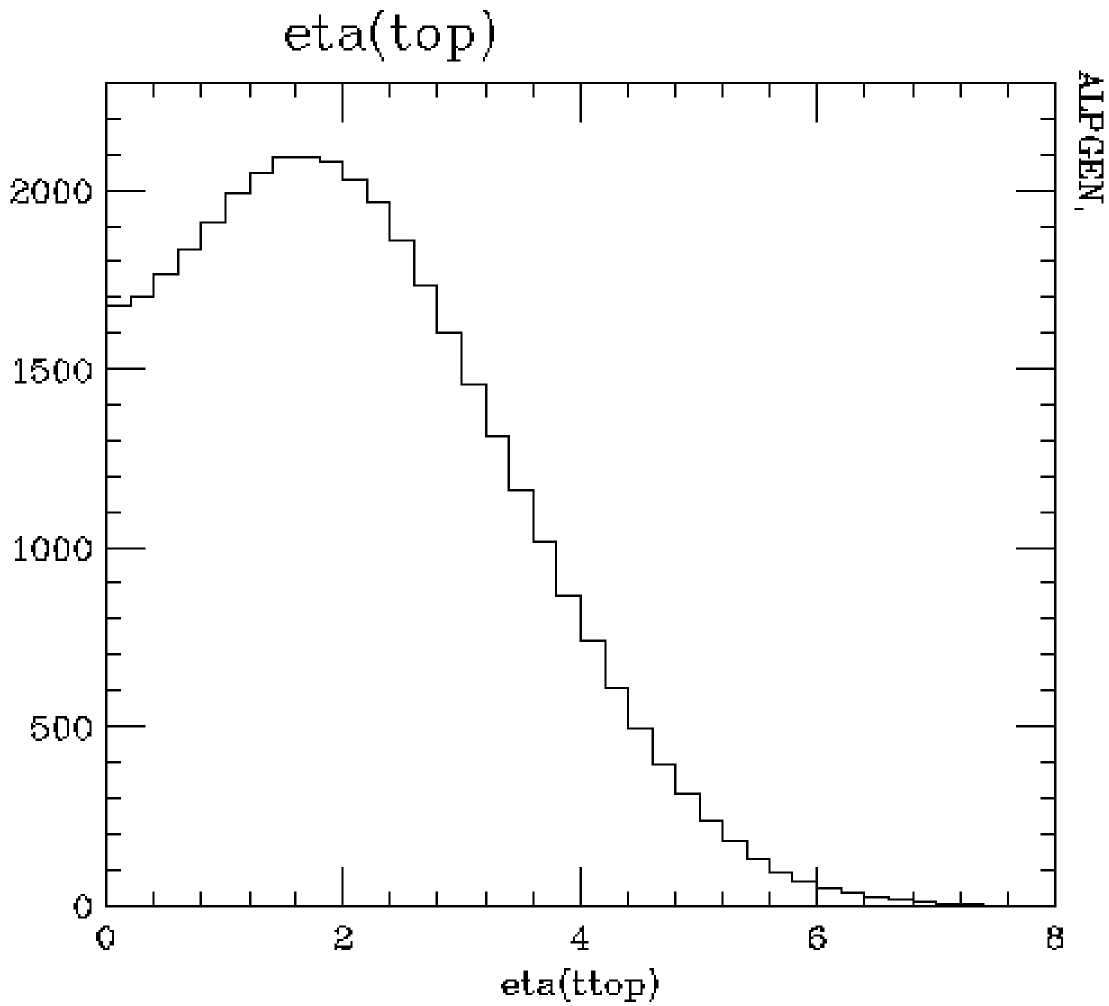
Statistics out to over 30 TeV with 10ab^{-1}
Inclsuive rate ~ 10 times larger at highest mass

Ex: gg initial state content for central (vs inclusive) t-tbar pairs, vs M(tt)

In central production, dominated by gg up to ~ 15 TeV. Still 20% gg at the kinematic edge of ~ 30 TeV

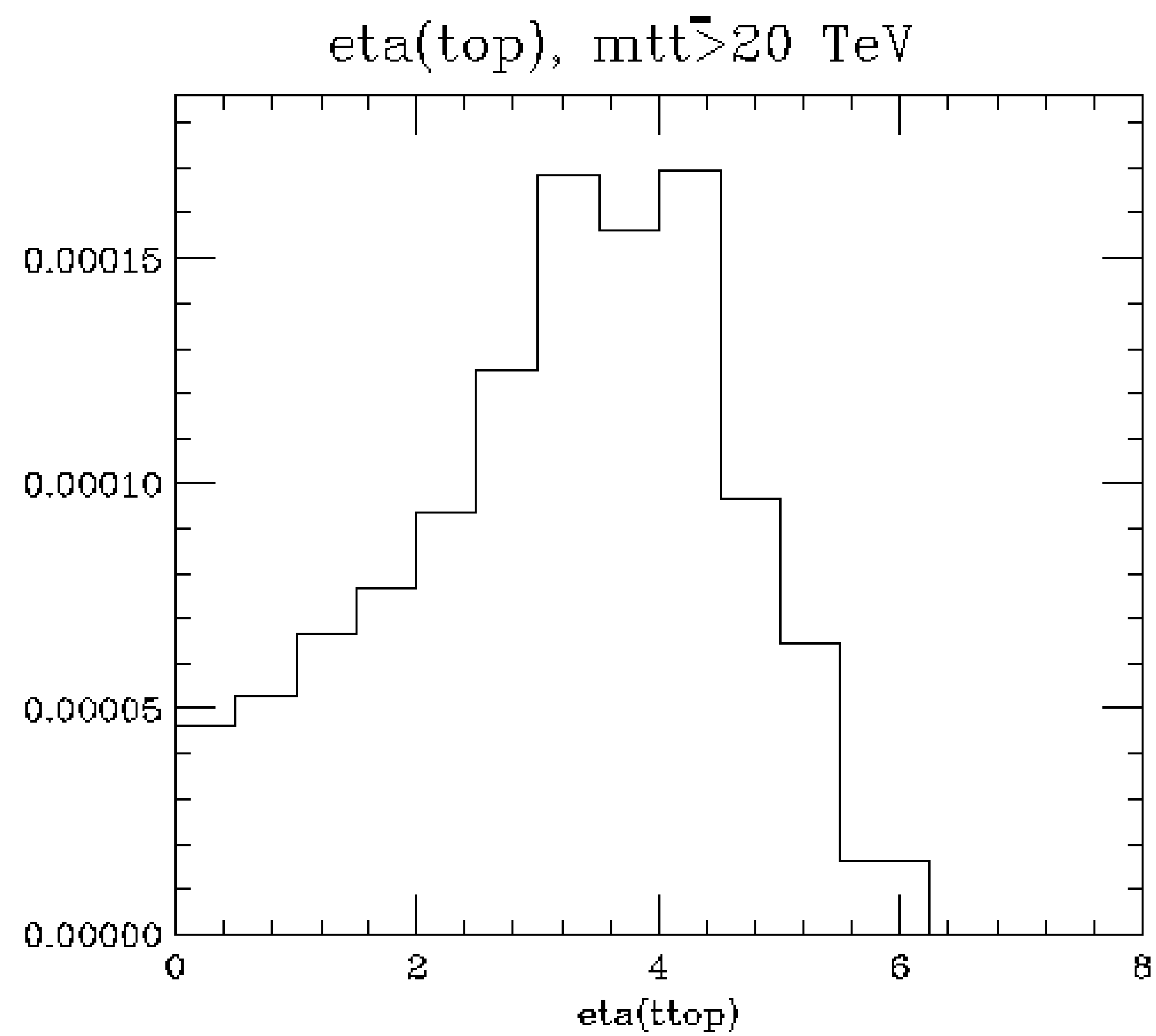
For inclusive prodution, >90% gg!





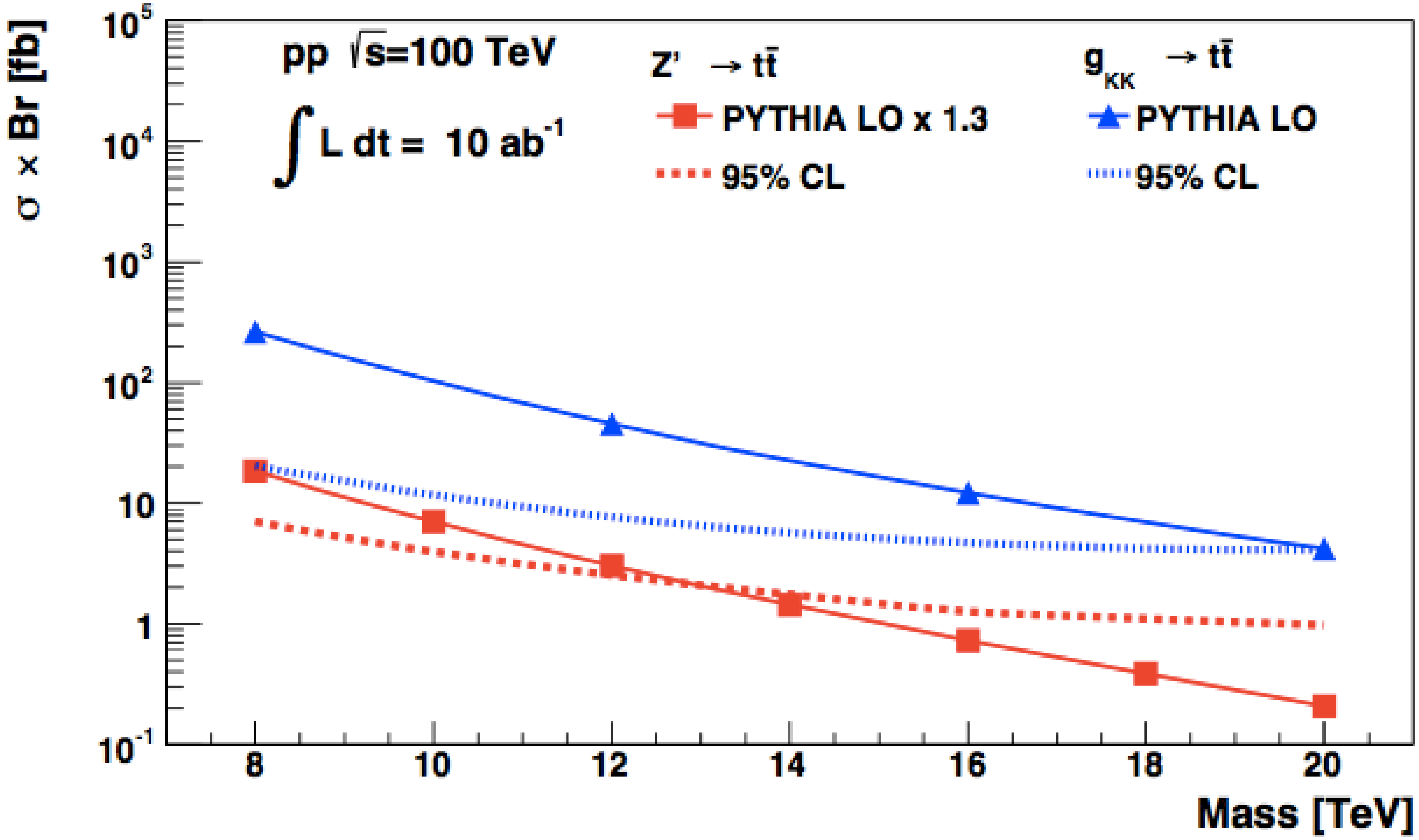
<u>Ex: eta spectrum for m(tt)>350 GeV</u>

<u>Ex: eta spectrum for m(tt)>20 TeV</u>



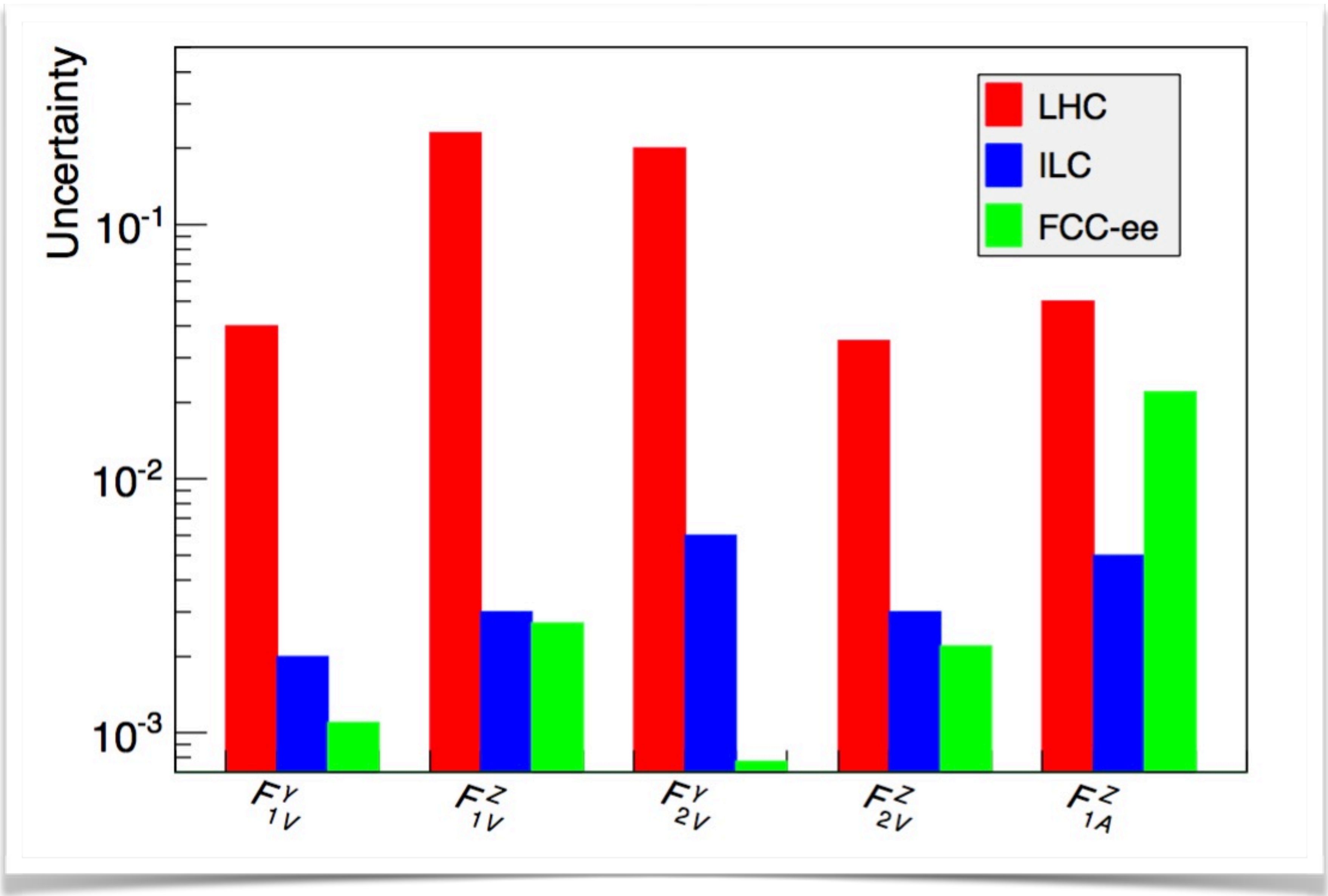
Sensitivity to ttbar resonances

Auerbach, Chekanov, Proudfoot, Kotwal, arXiv:1412.5951



Top EW couplings at FCC-ee

$$\Gamma_{\mu}^{ttX} = -ie\left\{\gamma_{\mu}\left(F_{1V}^{X} + \gamma_5 F_{1A}^{X}\right) + \frac{\sigma_{\mu\nu}}{2m_t}(p_t + p_{\bar{t}})^{\nu}\left(iF_{2V}^{X} + \gamma_5 F_{2A}^{X}\right)\right\}$$



ILC: 500 fb^{-1} at $\sqrt{s}$ = 500 GeV with beam polarizations of P = ±0.8, P′ = ∓0.3

FCC-ee: 2.4ab^{-1} at $\sqrt{s}$ = 365 GeV (no beam polarization)

LHC: 300fb^{-1} at $\sqrt{s}$ = 14 TeV

Top anomalous chromomagnetic moments at FCC-hh

J-A Aguilar-Saavedra, Fuks, etal, arXiv:1412.6654

$$\mathcal{L}_{\rm tg} = -g_s \bar{t}\gamma^\mu \frac{\lambda_a}{2} t\, G^a_\mu + \frac{g_s}{m_t}\bar{t}\sigma^{\mu\nu}(d_V + i d_A \gamma_5)\frac{\lambda_a}{2} t\, G^a_{\mu\nu}$$

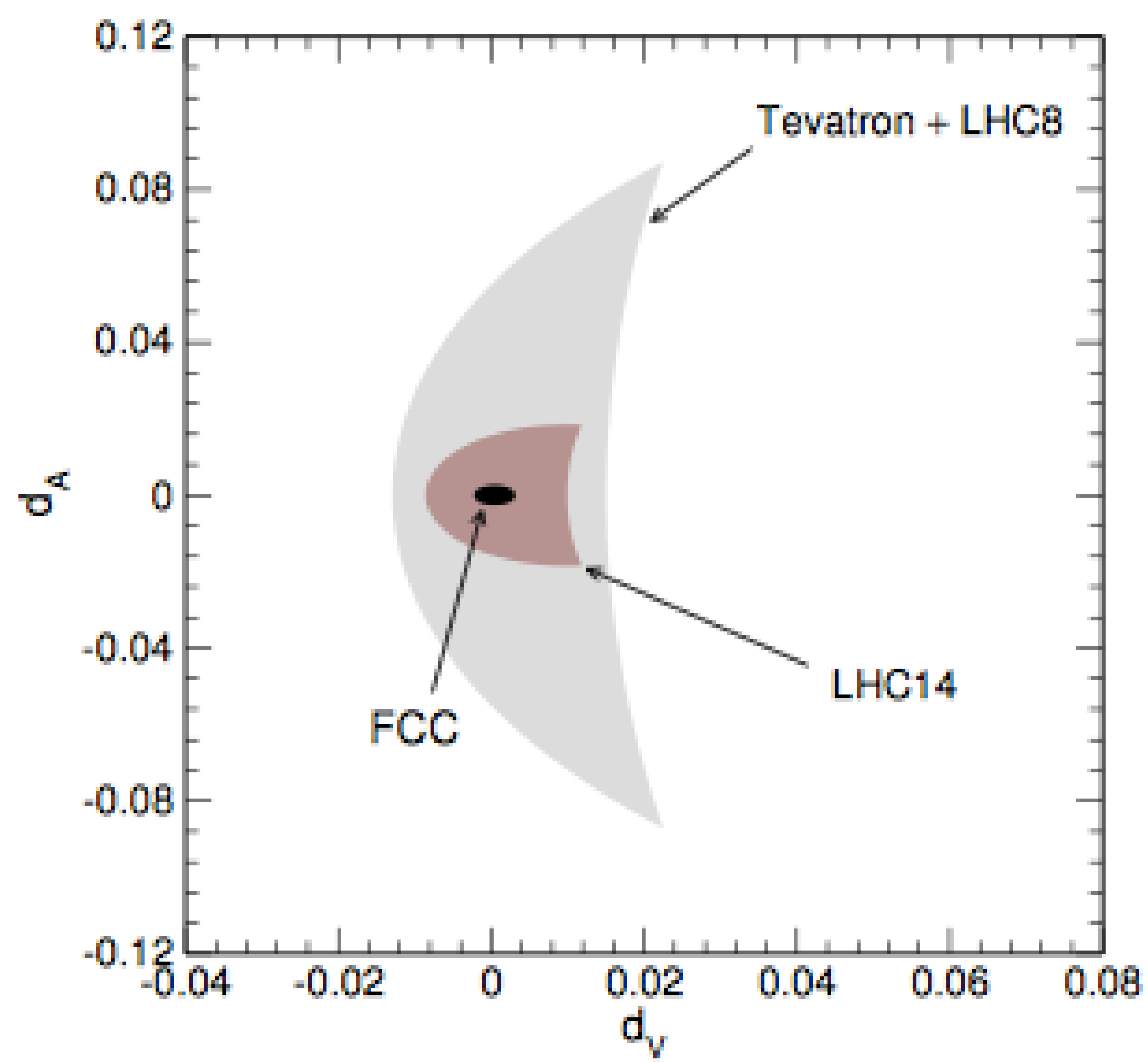
$$O^{33}_{uG\phi} = (\bar{q}_{L3}\lambda_a \sigma^{\mu\nu} t_R)\tilde{\phi}\, G^a_{\mu\nu} \quad \Rightarrow \quad d_V = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} \mathrm{Re}\, C^{33}_{uG\phi}\,, \quad d_A = \frac{\sqrt{2} v m_t}{g_s \Lambda^2} \mathrm{Im}\, C^{33}_{uG\phi}$$

At 100 TeV, constraints from event rate at $M_{tt} > 10$ TeV:

$$-0.0022 \leq d_V \leq 0.0031$$

$$|d_A| \leq 0.0026$$

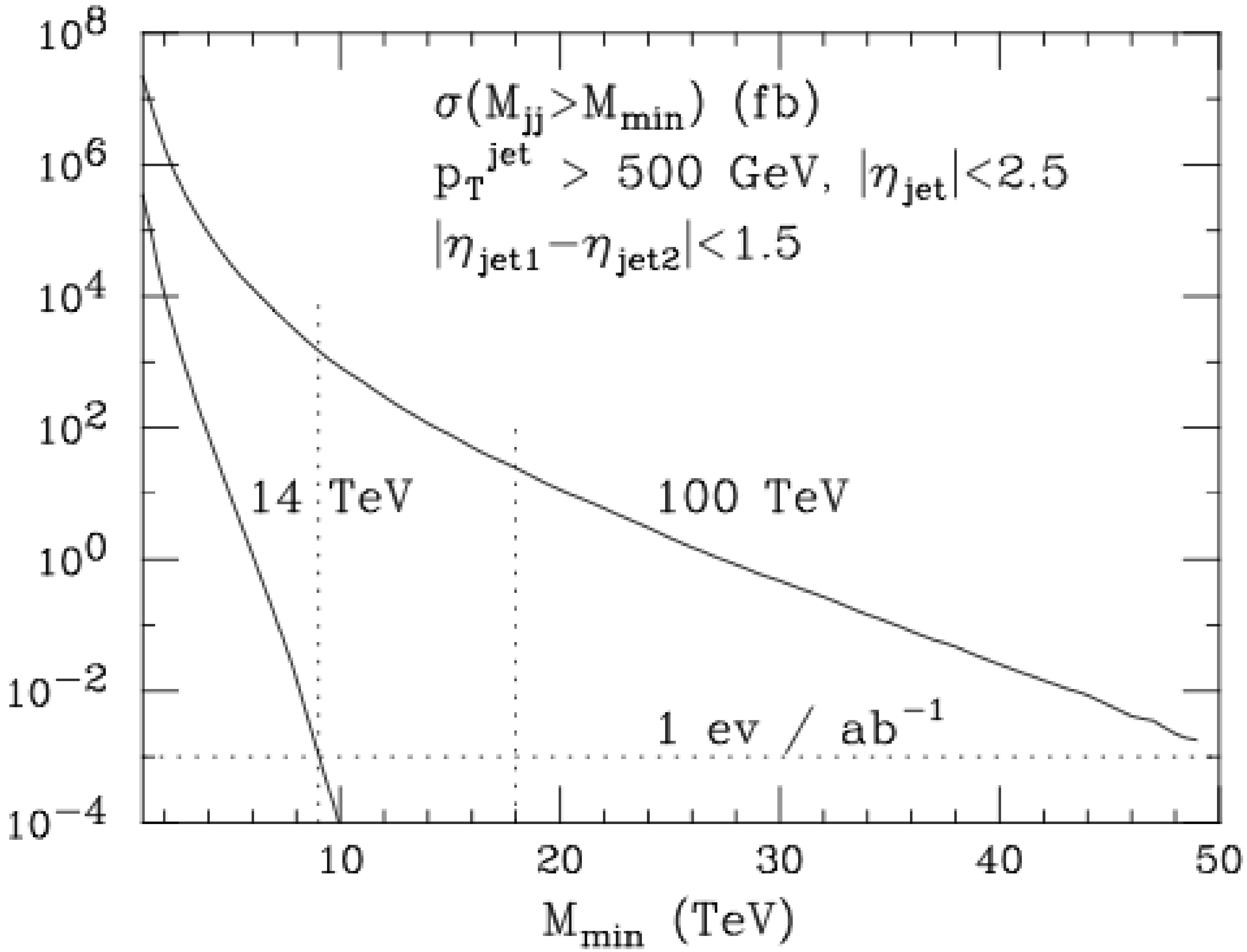
$$\Rightarrow \Lambda \gtrsim 17 \text{ TeV}$$



High-Q^2 phenomena

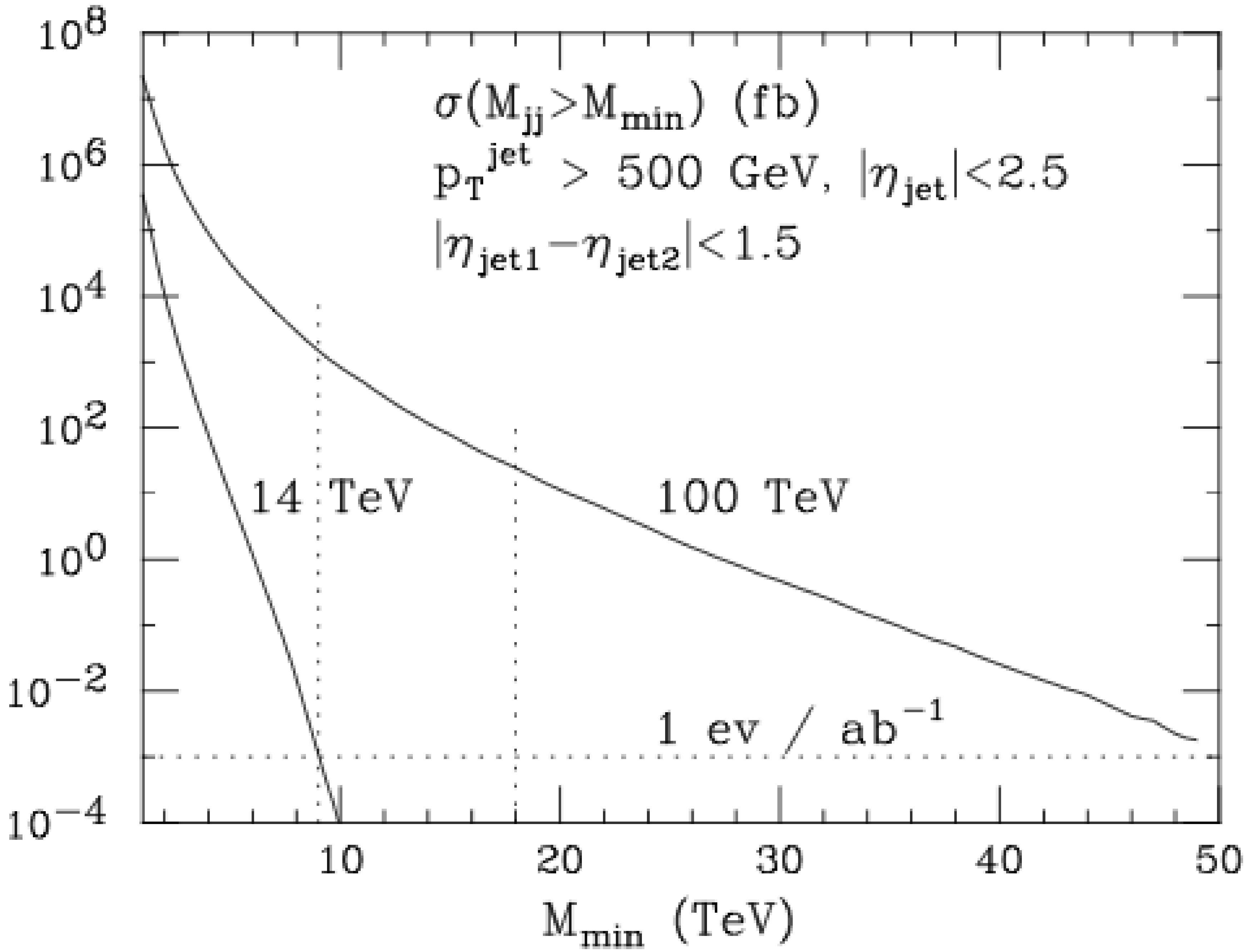
Exploring the shortest distances with jets at 100 TeV

(dijet resonances, quark compositeness, ...)



Exploring the shortest distances with jets at 100 TeV

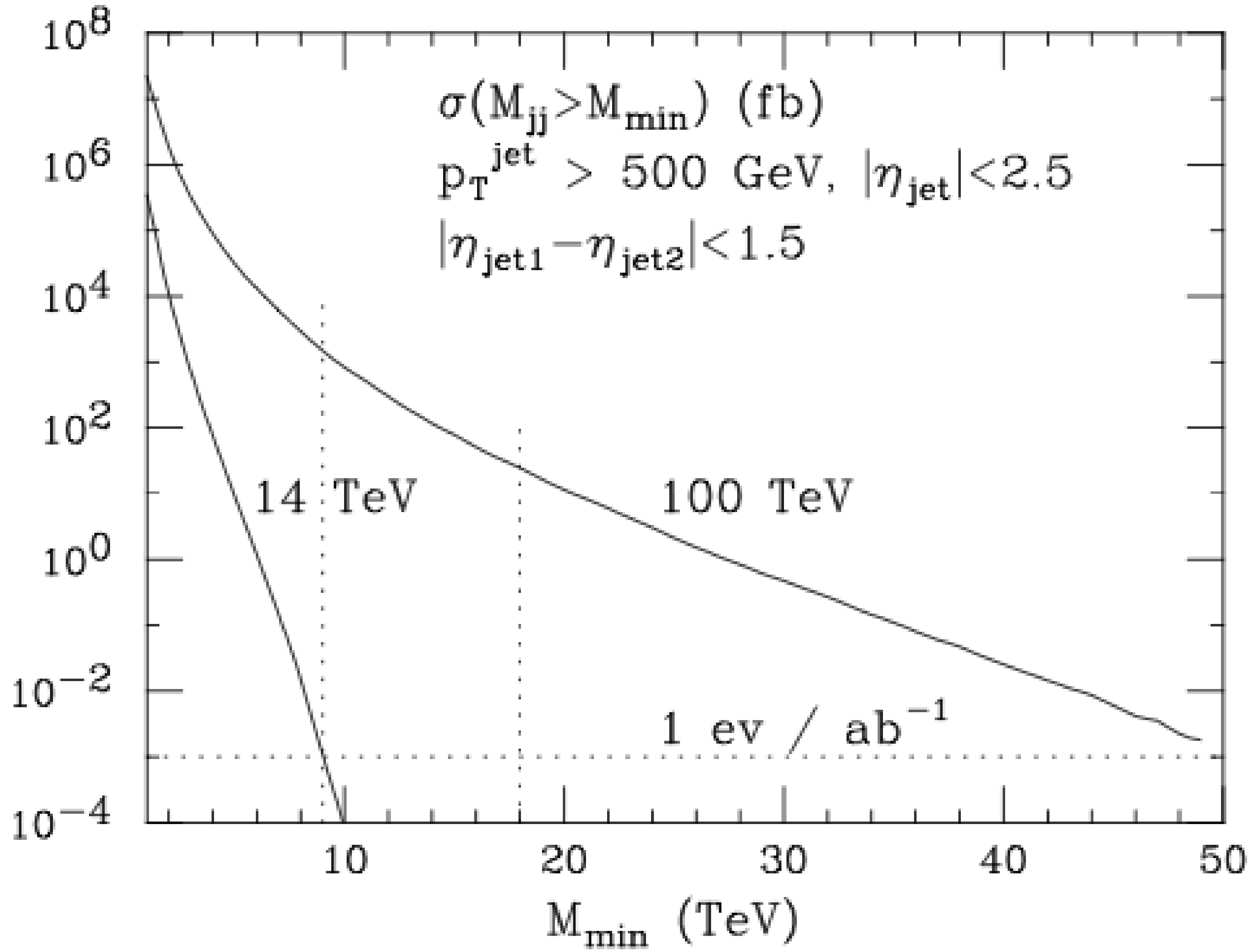
(dijet resonances, quark compositeness, ...)



- 1 pb^{-1} to recover sensitivity of HL-LHC ⇒< 1 day @ 10^{32}

Exploring the shortest distances with jets at 100 TeV

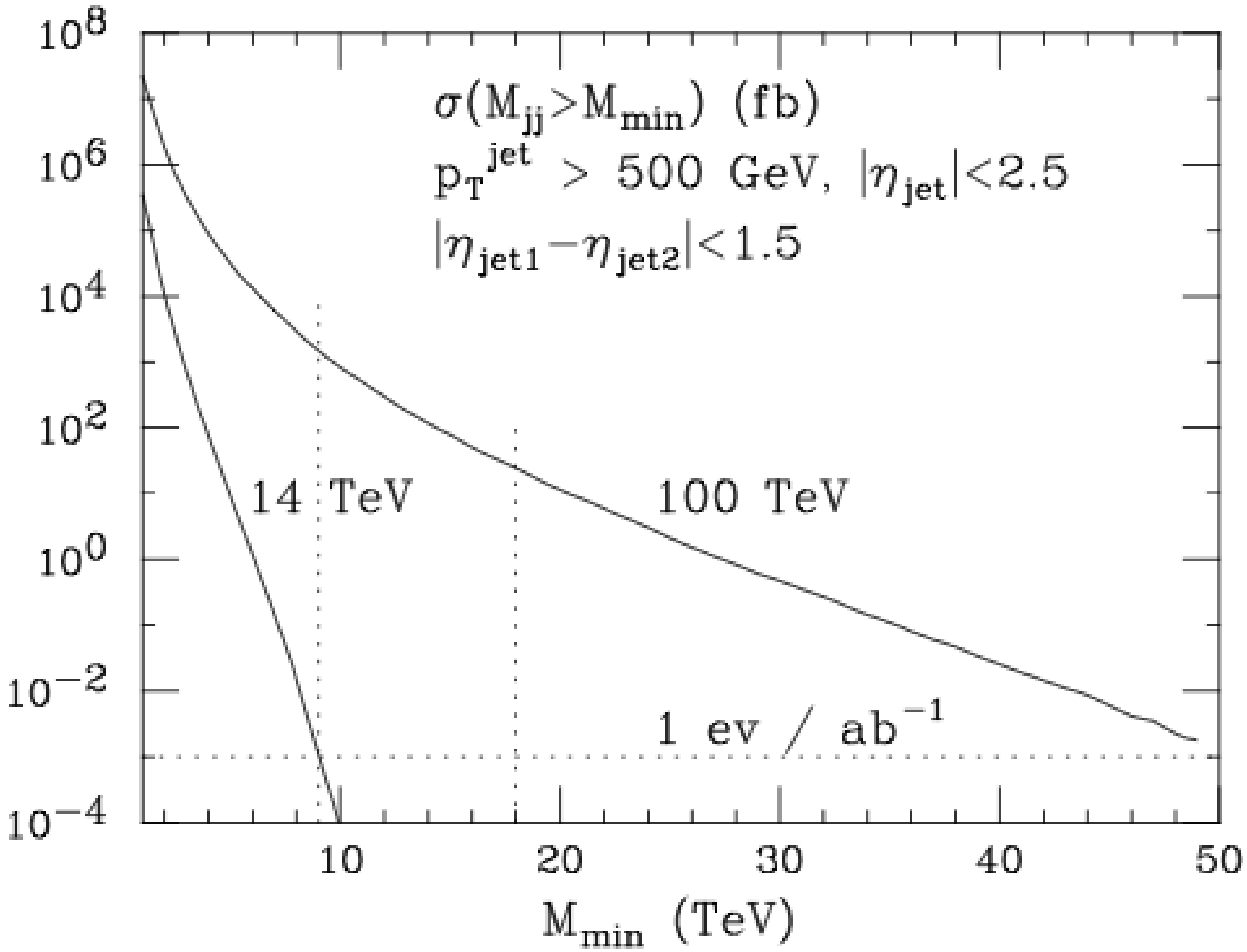
(dijet resonances, quark compositeness, ...)



- 1 pb^{-1} to recover sensitivity of HL-LHC ⇒< 1 day @ 10^{32}
- 50pb^{-1} to 2x the sensitivity of HL-LHC ⇒< 1 month @ 10^{32}

Exploring the shortest distances with jets at 100 TeV

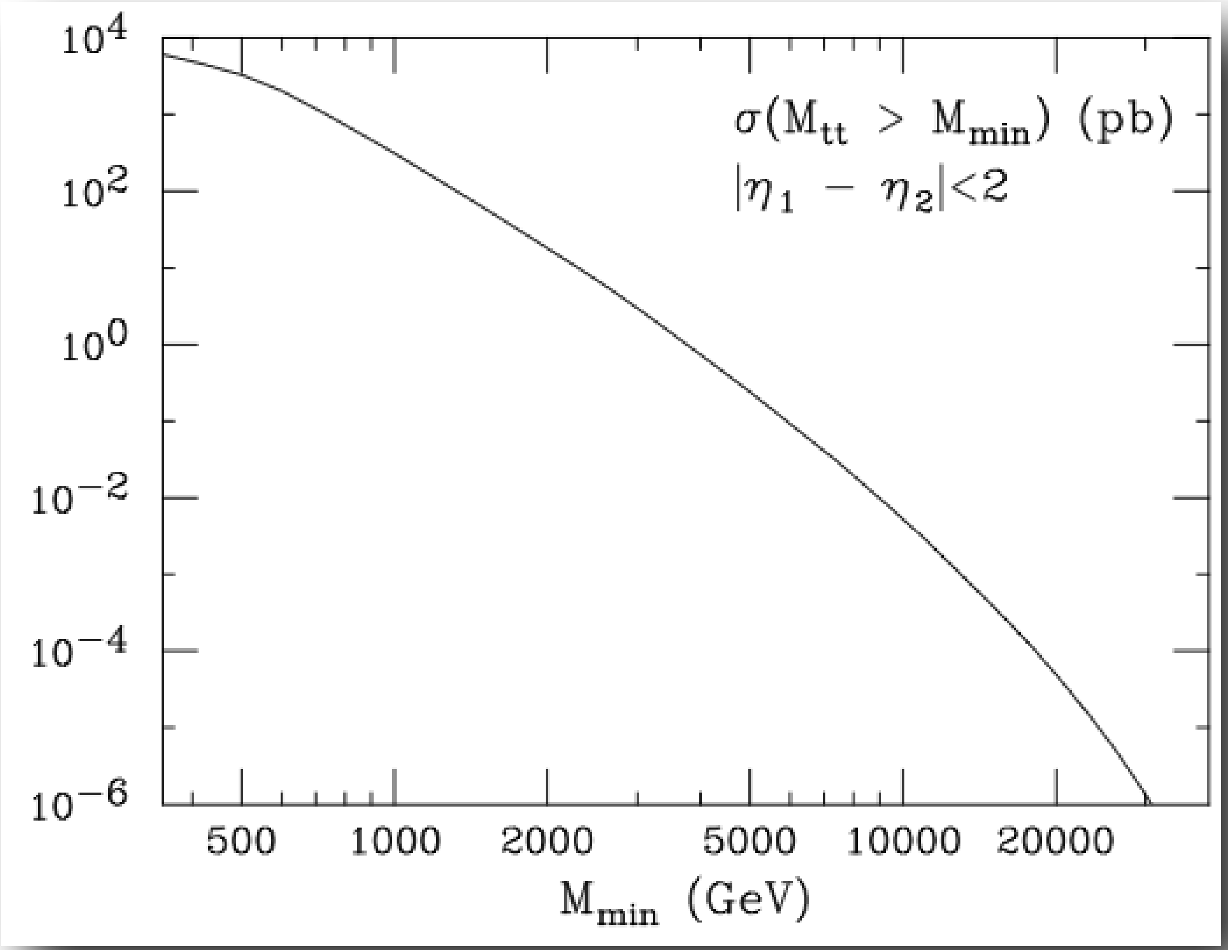
(dijet resonances, quark compositeness, ...)



- 1 pb^{-1} to recover sensitivity of HL-LHC ⇒< 1 day @ 10^{32}
- 50pb^{-1} to 2x the sensitivity of HL-LHC ⇒< 1 month @ 10^{32}
- 1fb^{-1} to 3x the sensitivity of HL-LHC ⇒< 1 year @ 2x10^{32}

Exploring the shortest distances with ...

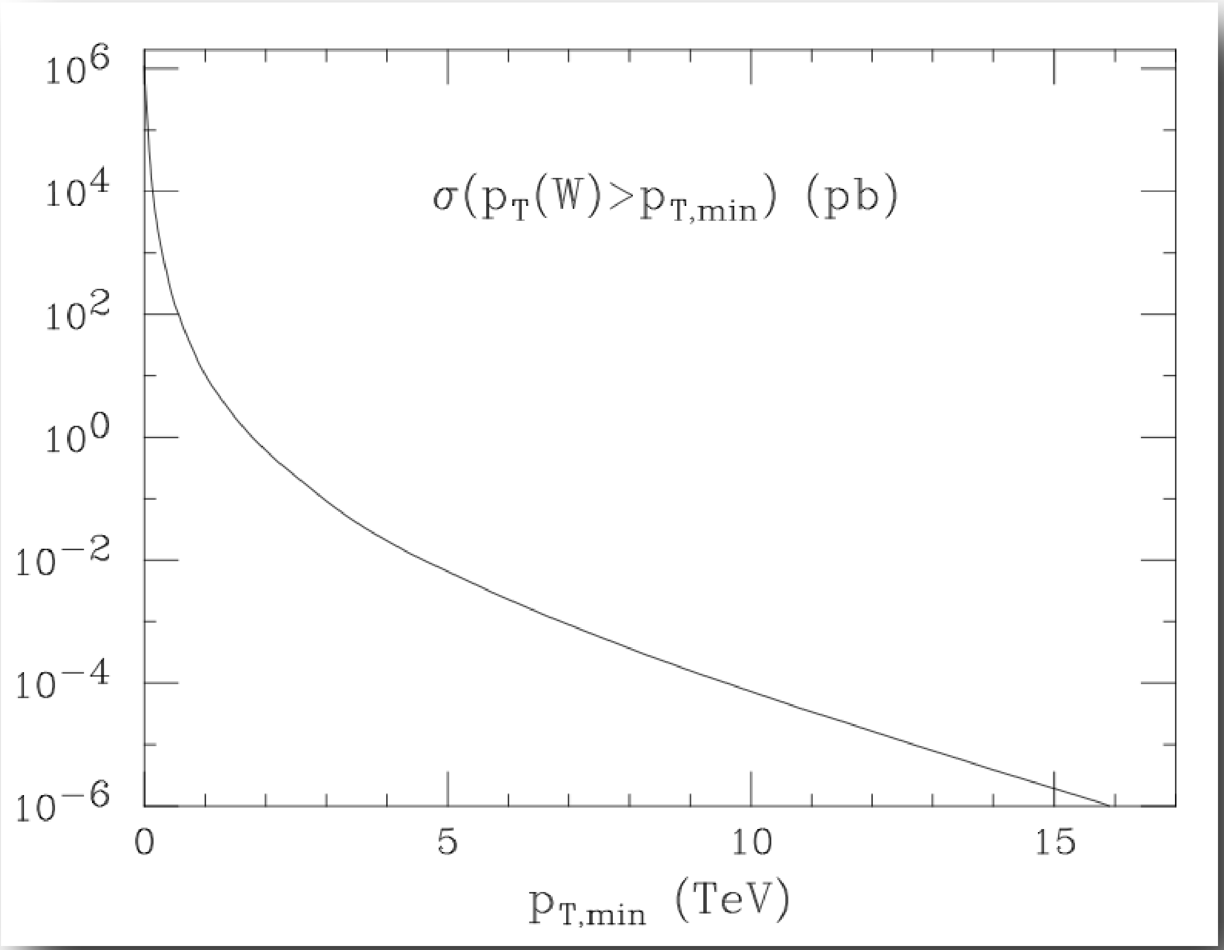
top quarks



(⇒ top tagging at ~10 TeV?)

(dijet resonances, anomalous top couplings, contact interactions, ...)

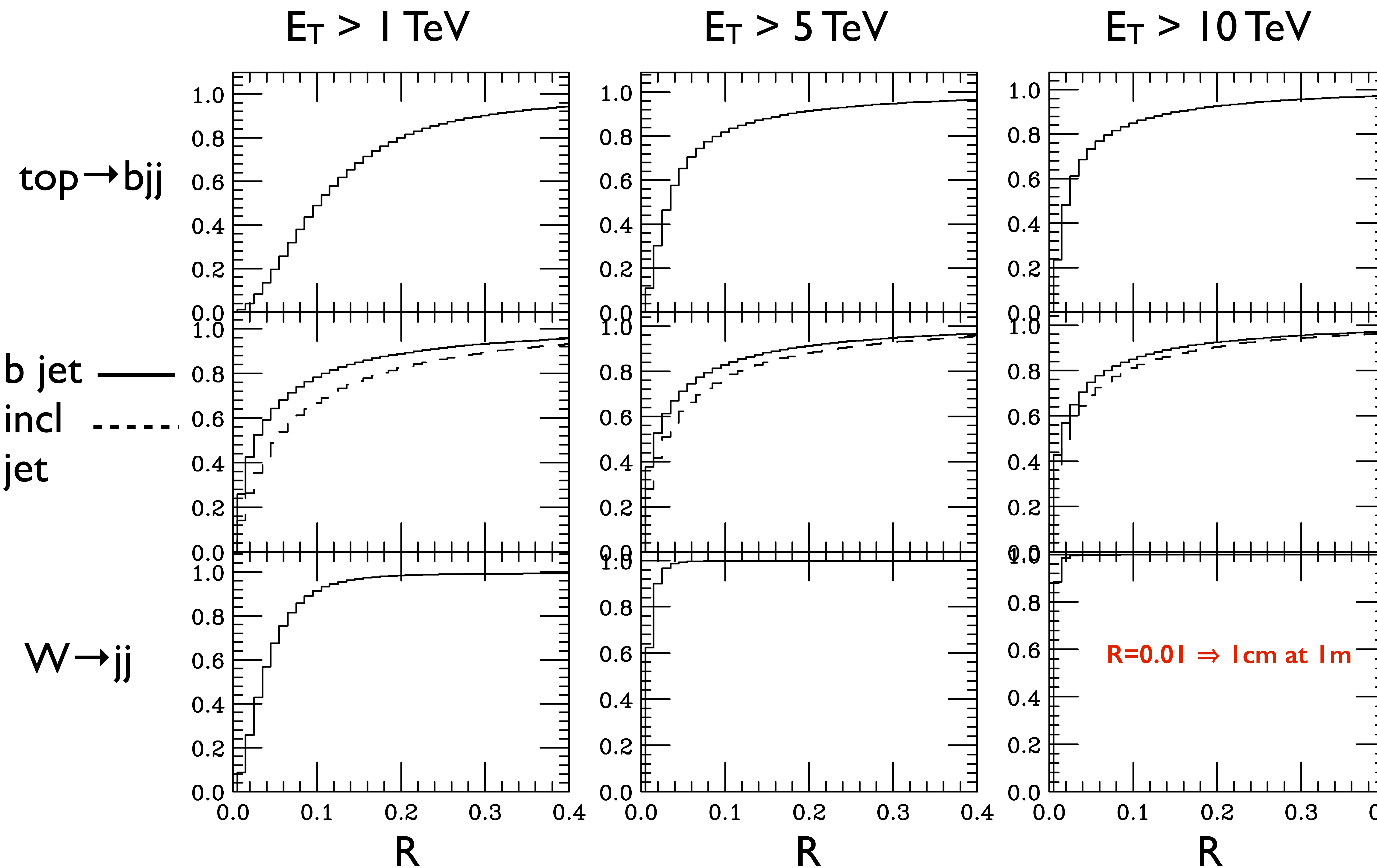
W bosons



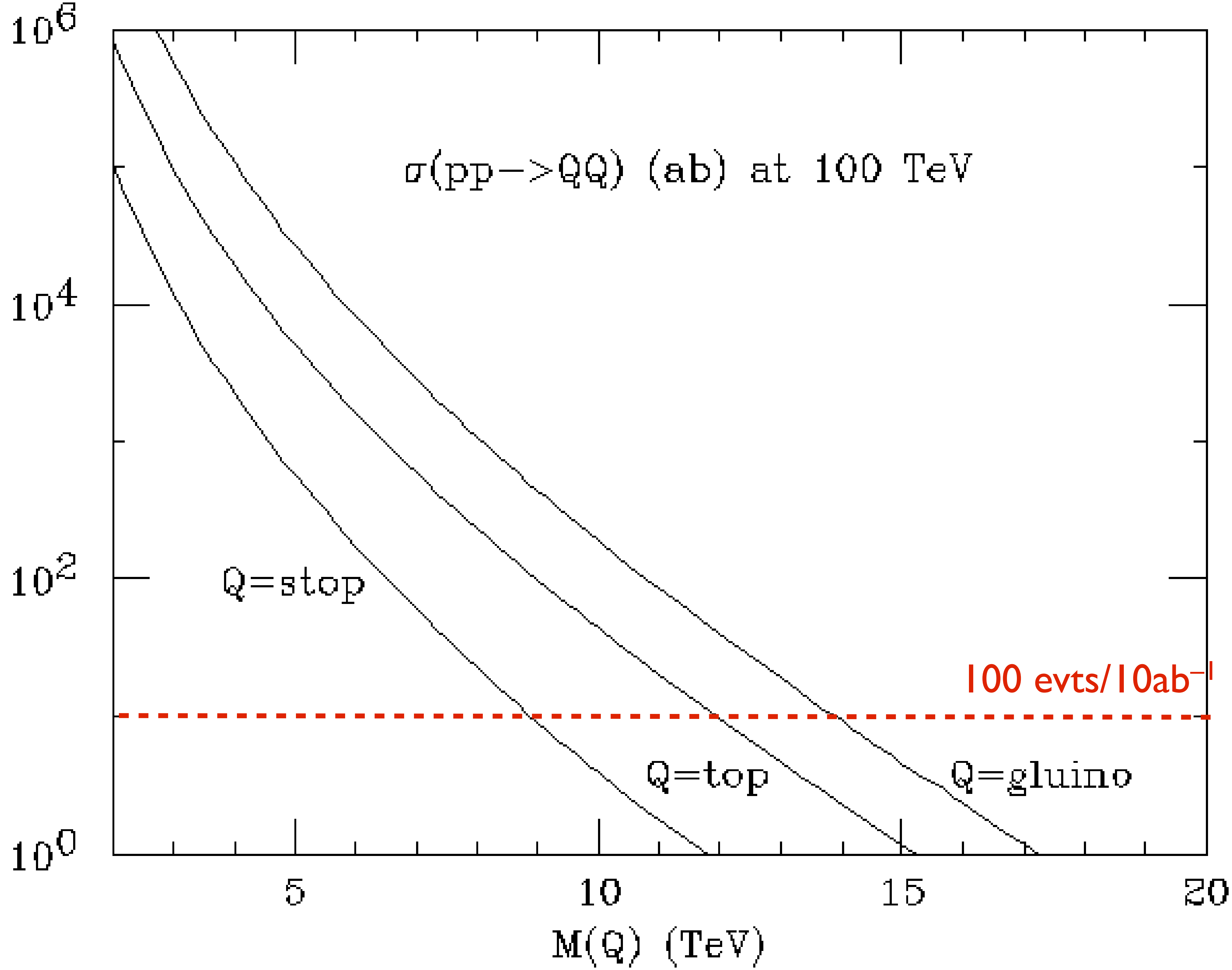
(⇒ W tagging at ~10-15 TeV?)

Jets' energy shape: E(r<R) / E(r<1)

(⇒ calorimeter granularity, tracker)



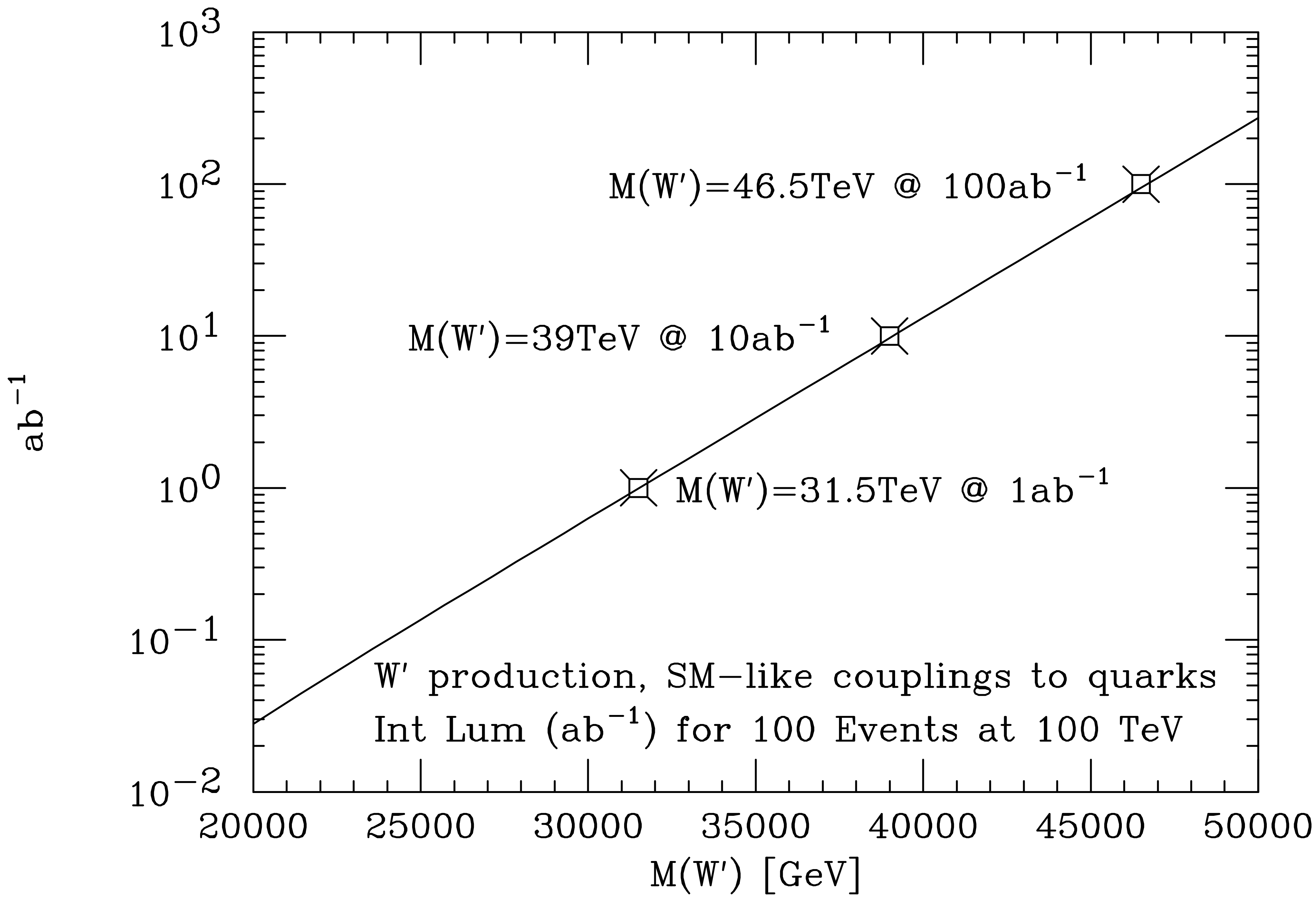
Discovery reach for pair production of strongly-interacting particles



New gauge bosons discovery reach

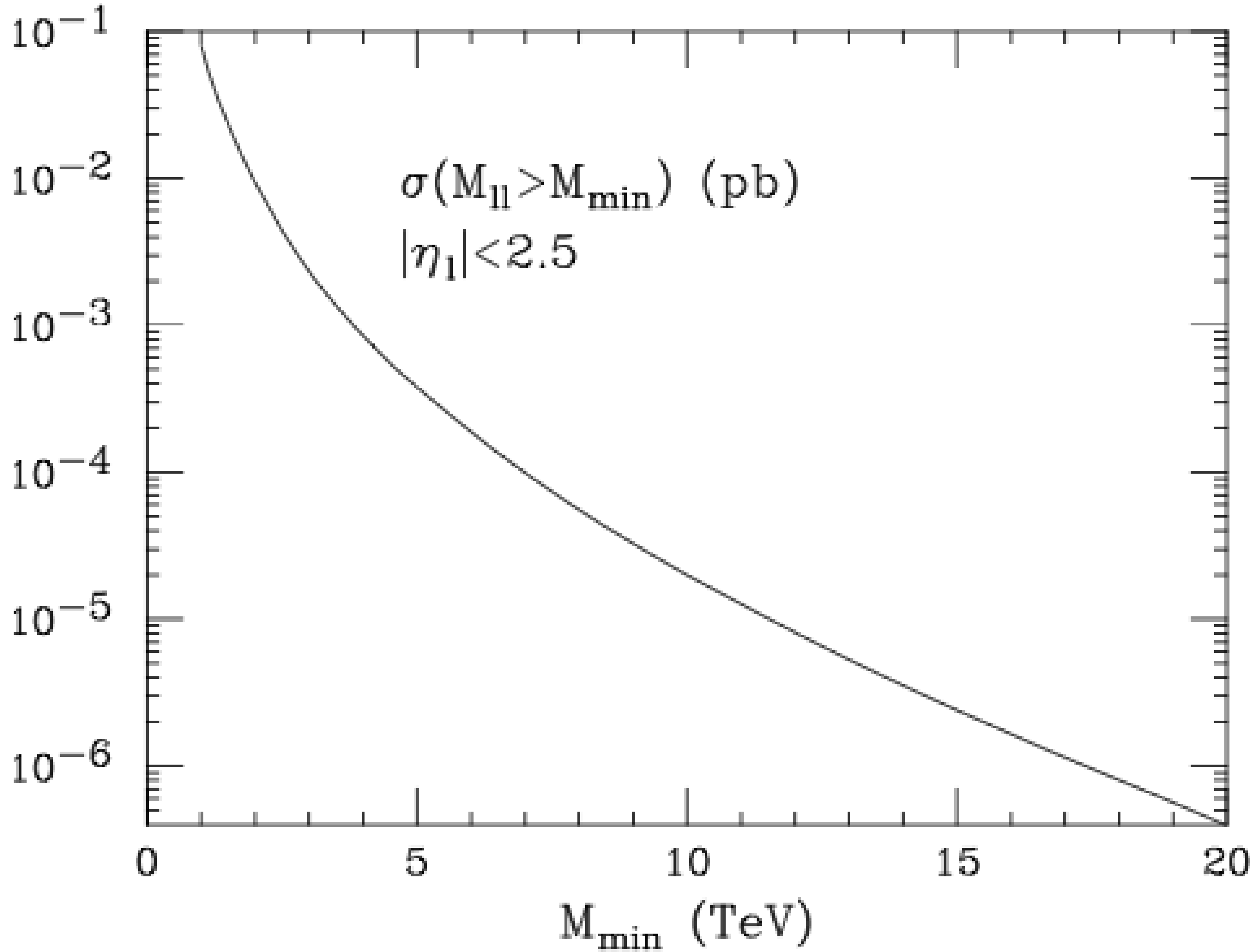
Example: **W' with SM-like couplings**

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



At L=O(ab^{-1}), Lum x 10 ⇒ ~ M + 7 TeV

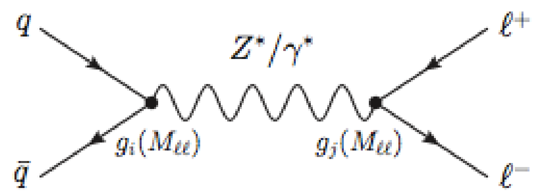
SM DY mass spectrum



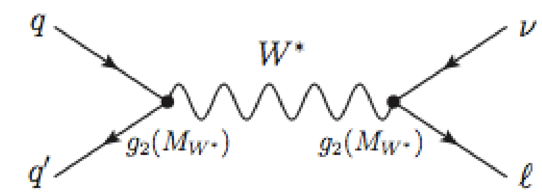
=> rate (i.e. background to searches for new Z' resonances) out to M ~ 20 TeV

Running Electroweak Couplings as a Probe of New Physics

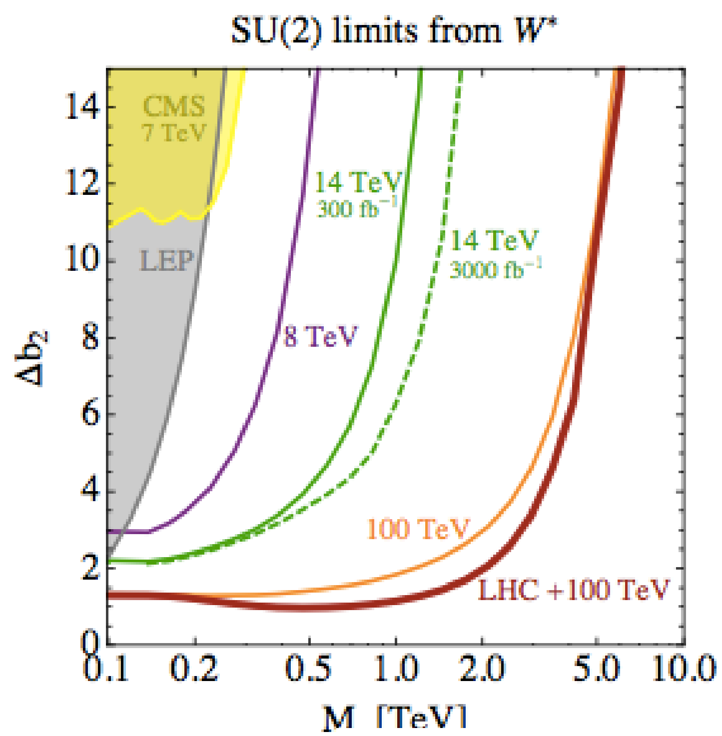
D.Alves, J. Galloway, J.Ruderman, J.Walsh *arXiv:1410.6810*

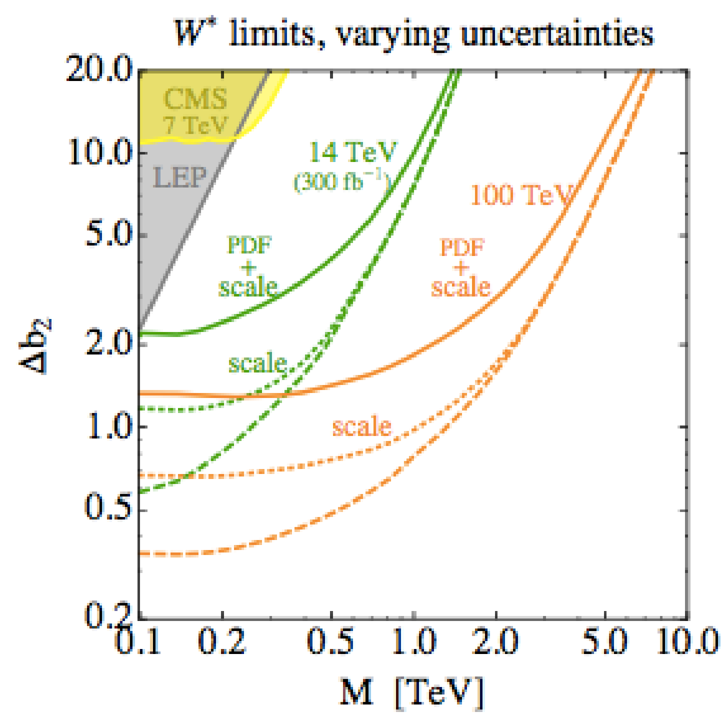


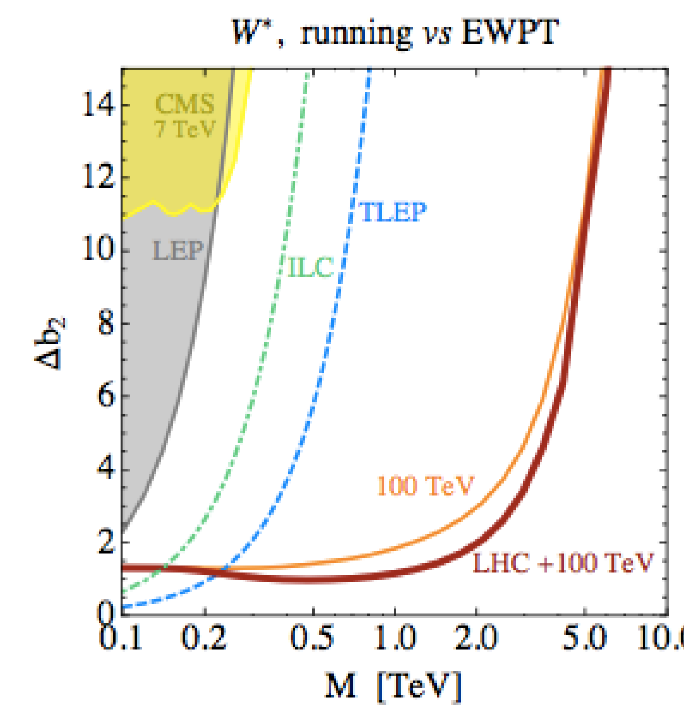
$$\frac{d\sigma}{dm_{ll}} \Rightarrow \alpha_{1,2}(q)$$

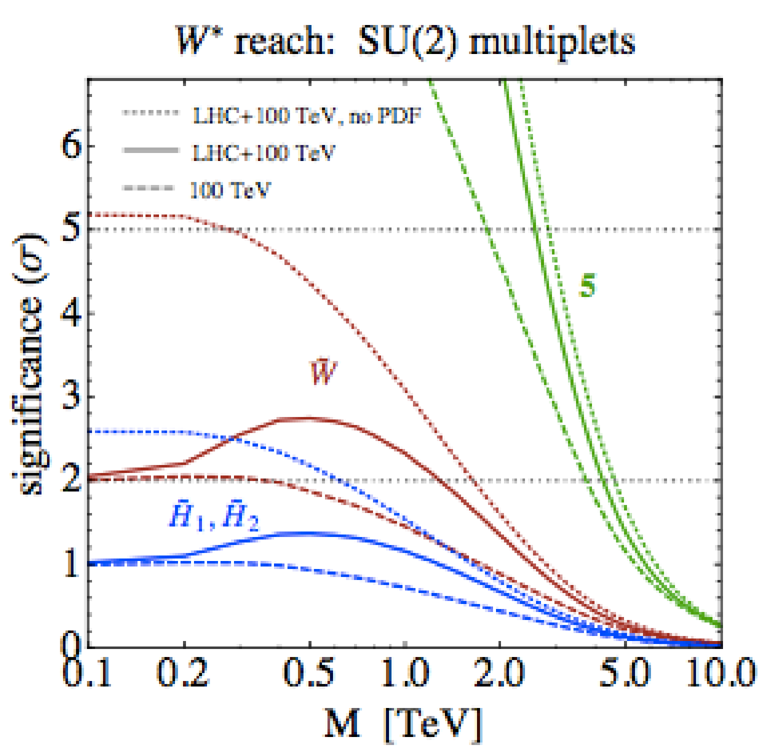


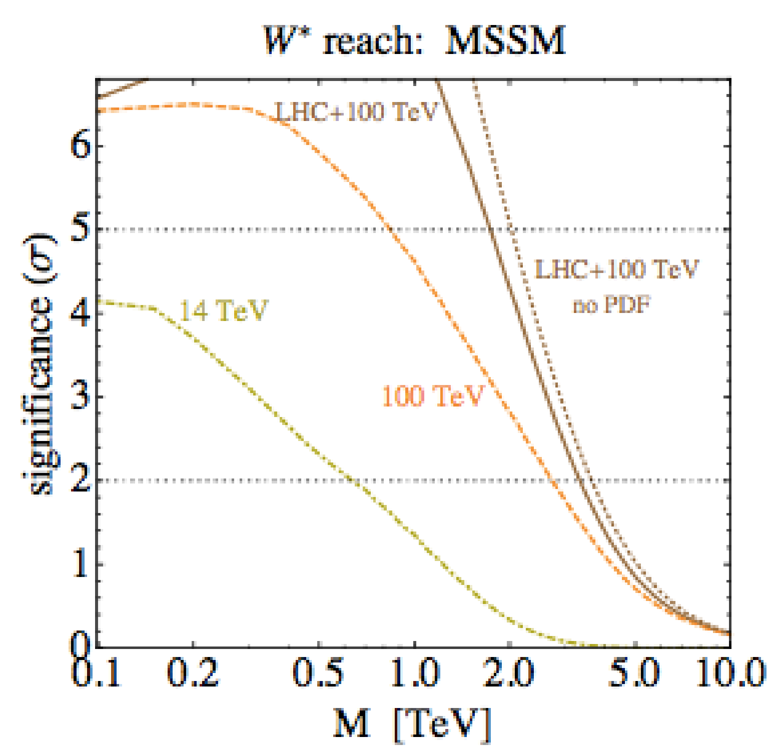
$$\frac{d\sigma}{dM_T} \Rightarrow \alpha_2(q)$$



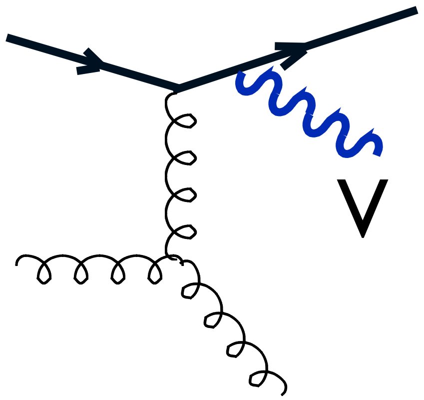




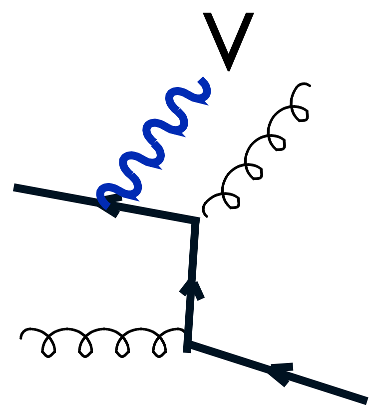




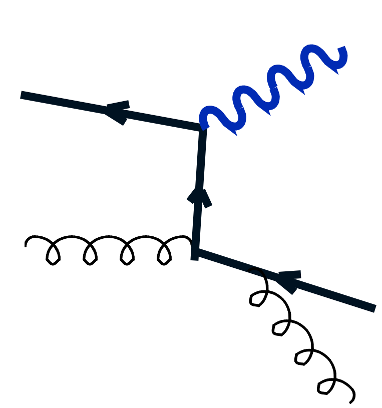
V emission in events with very large E_T jets



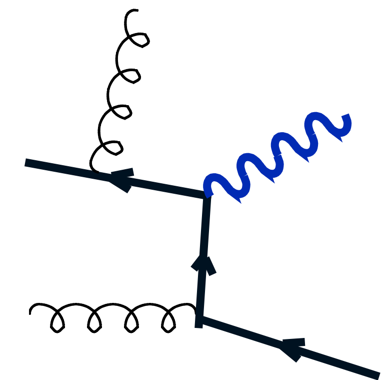
Large EW logs,
V correlated to jet



Large EW logs,
V not correlated to jet



Radiative correction to V+jet, no EW log



Radiative correction to V+jet, no EW log

Study σ(jet jet + V) / σ(jet jet) vs $E_T^{(\text{leading jet})}$

EW interactions at multi-TeV energy

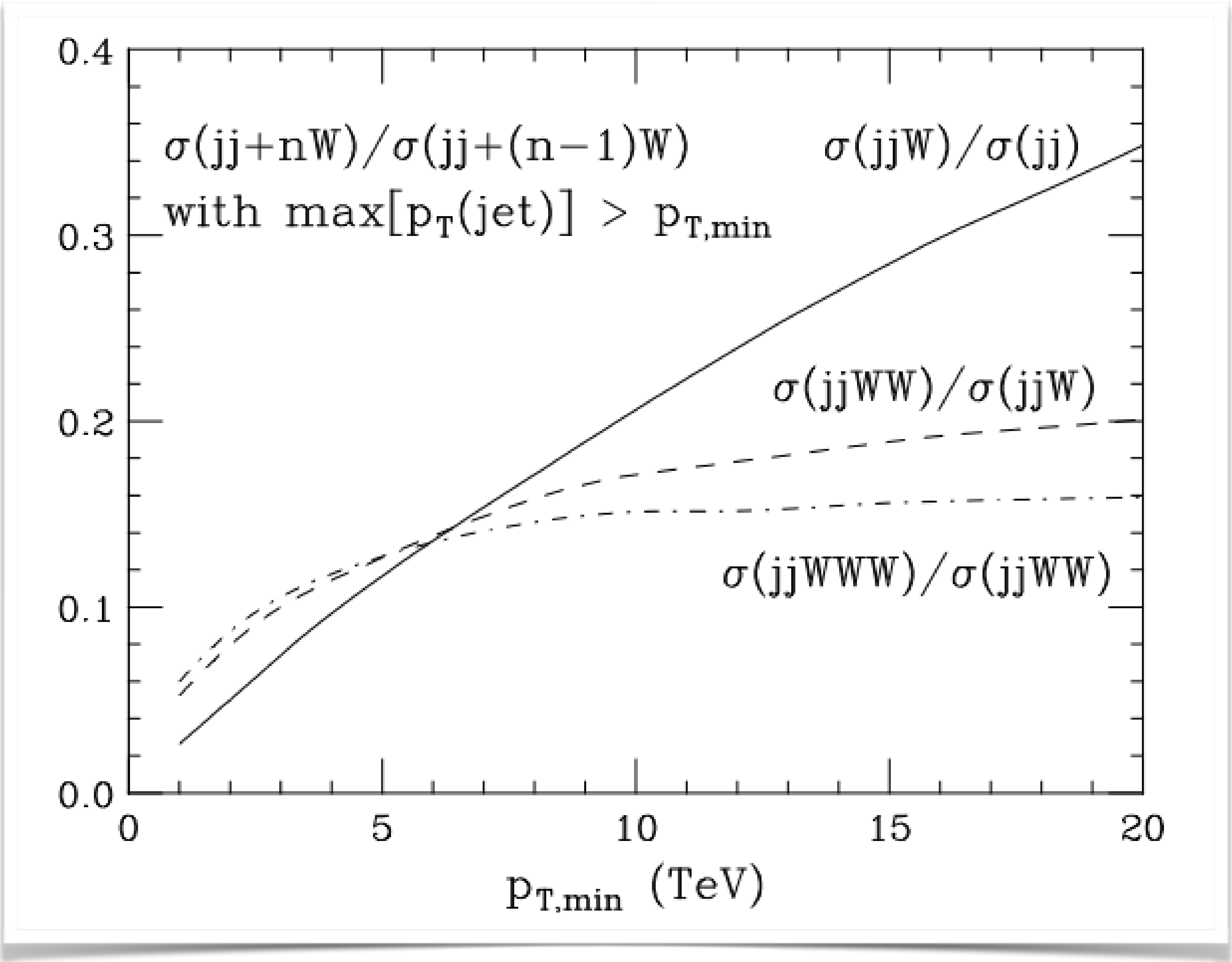
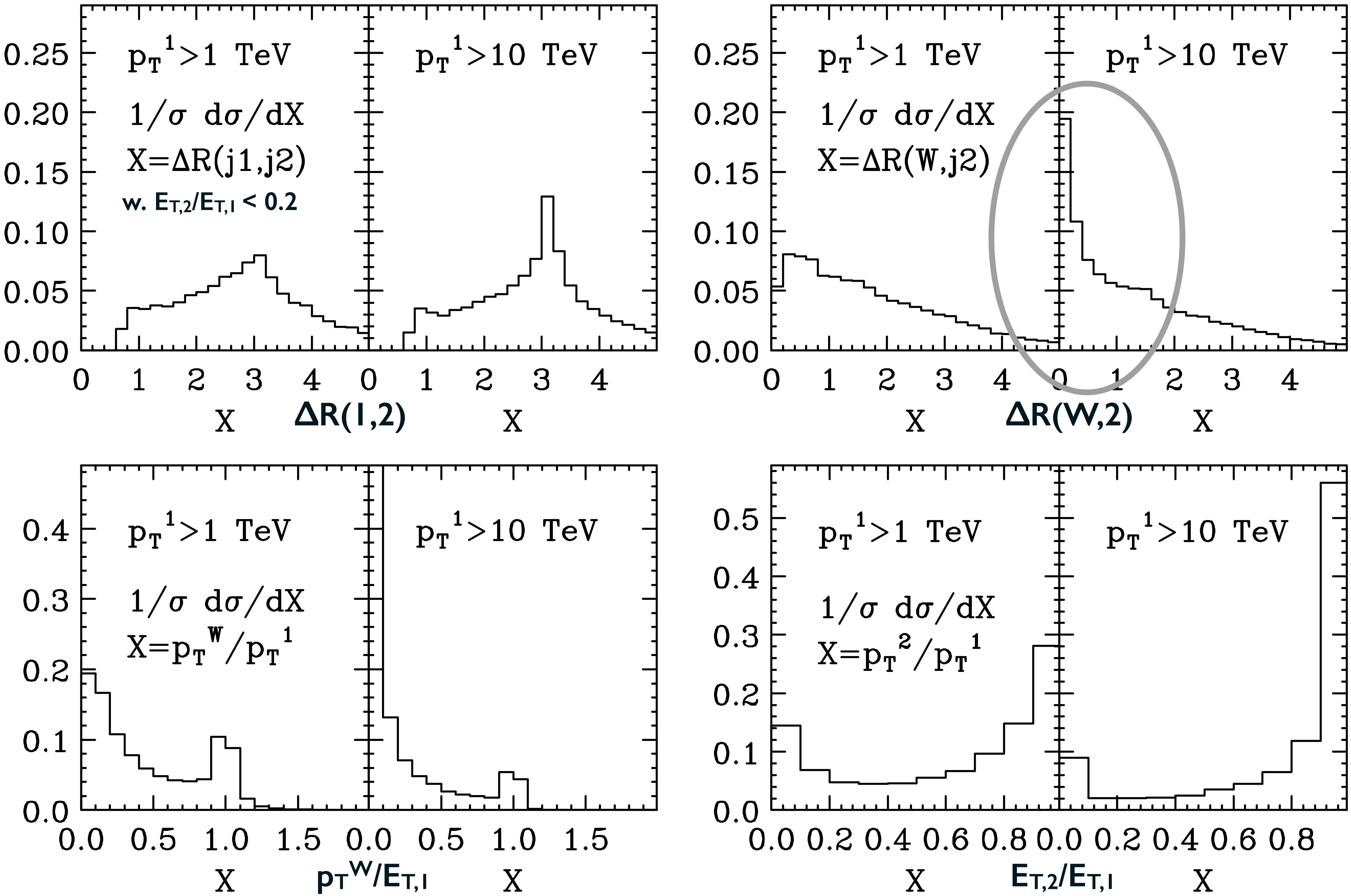
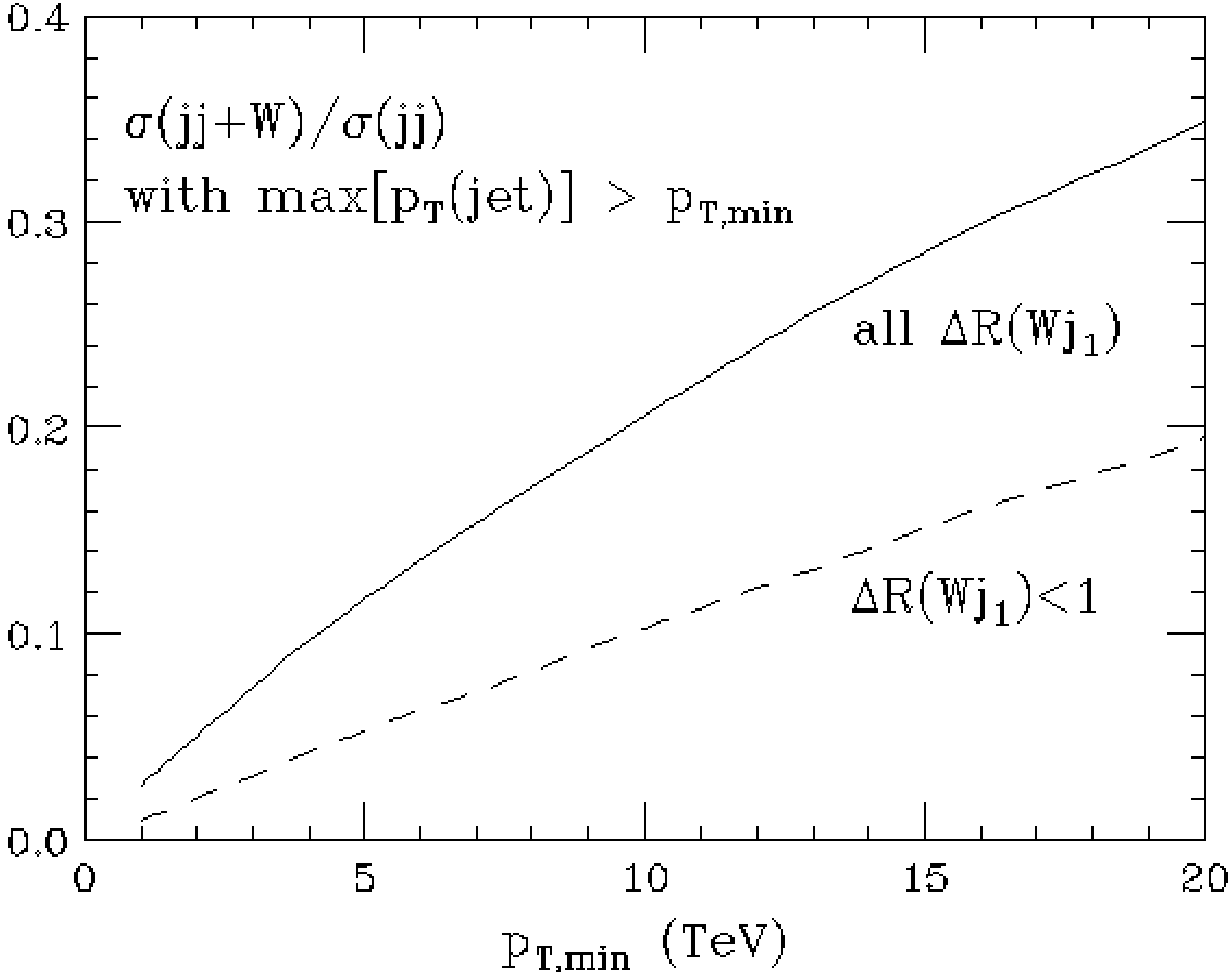


Fig. 15: Emission probability for additional W bosons in dijet events at large p_T.

W emission distributions

which fraction of Ws can be associated to radiation off the jet, vs ISR or ISR/FSR interference?





Possible implications:

- 10-20% probability of q→qW ⇒ may need b-tagging to separate top jet above 1- TeV from ordinary light-q jet?

NB: inclusive emission probabilities for additional V bosons ~ O(α)

Proc	WWW	WWZ	WZZ	ZZZ
σ(fb)	4.3×10^3	4.0×10^3	1.4×10^3	2.6×10^2

Proc	$WWWW$	$WWWZ$	$WWZZ$	$WZZZ$	$ZZZZ$
σ(fb)	41	60	33	7.1	0.8

NB: the leading source of multi-W final states is anyway tt production

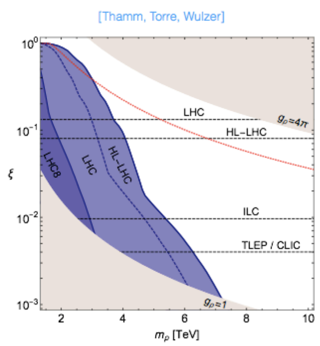
	$t\bar{t}$	$t\bar{t}t\bar{t}$	$t\bar{t}W^\pm$	$t\bar{t}Z^0$	$t\bar{t}WW$	$t\bar{t}W^\pm Z$	$t\bar{t}ZZ$
σ(pb)	$3.2 \cdot 10^4$	4.9	16.8	56.3	1.1	0.17	0.16

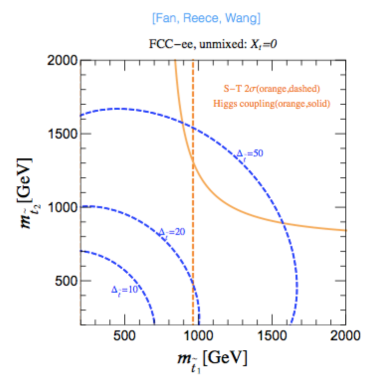
N.Craig

Colorful naturalness

Probing at a Higgs factory:

Look for **O**(loop*v/m) [SUSY] or **O**(v/f) [global] Higgs coupling deviations; precision electroweak corrections.





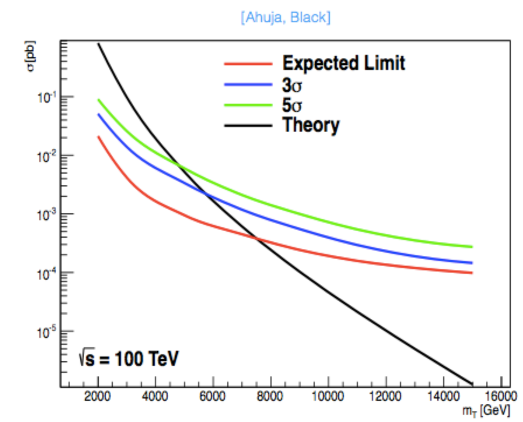
Where we'll be @ Higgs factory:
Sensitive to kinematic holes at LHC.

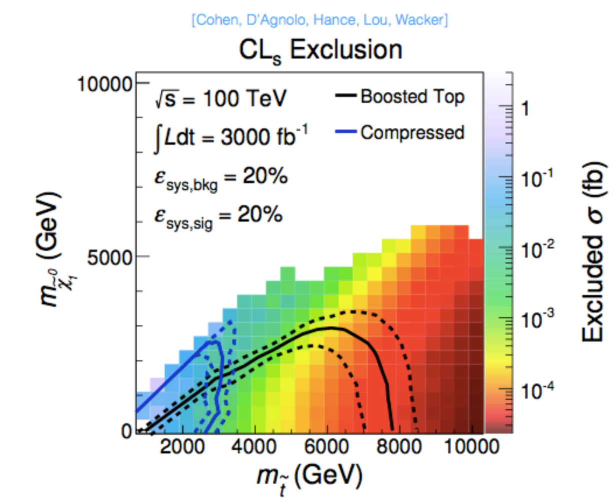
~1-2% level

Colorful naturalness

Probing at 100 TeV:

Look for the light partner states





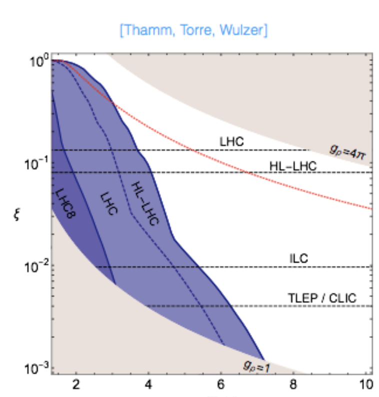
Where we'll be @ 100 TeV: "generically"

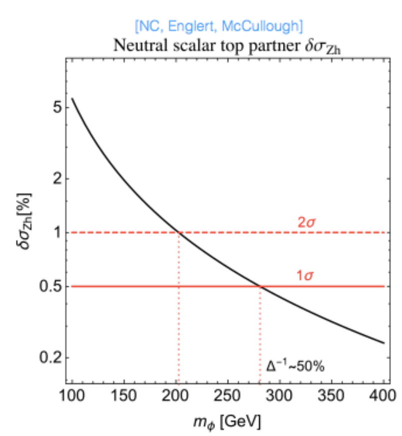
~.05% level

Neutral naturalness

Probing at a Higgs factory:

Look for **O**(loop*v/m) oblique [SUSY] or **O**(v/f) [global] Higgs coupling deviations.





Where we'll be @ Higgs factory:

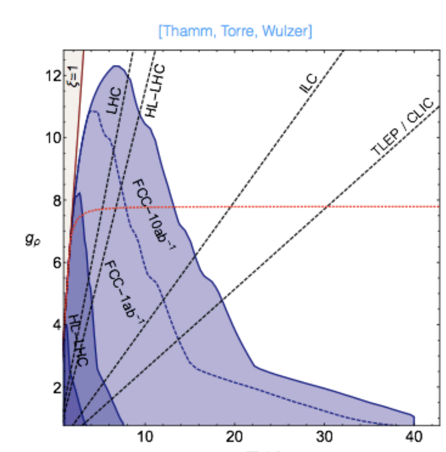
~1% level (global)
~50% level (SUSY)

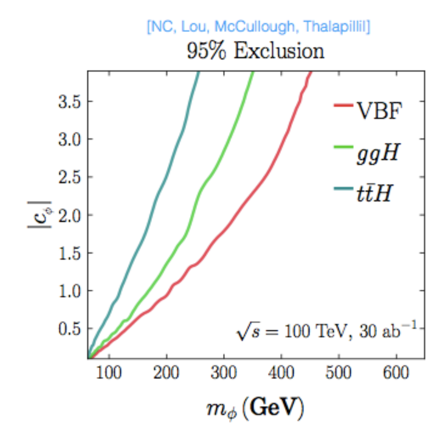
Even if the light natural states are neutral, there are heavier states with SM charges

Neutral naturalness

Probing at 100 TeV

Look for the UV completion, or probe light states via the Higgs portal.





Where we'll be @ 100 TeV:

~1% level

Dark Matter

For ~complete discussion, see ”Dark Matter at a future hadron collider” Workshop,

FNAL Dec 4-6, http://indico.cern.ch/event/445743/

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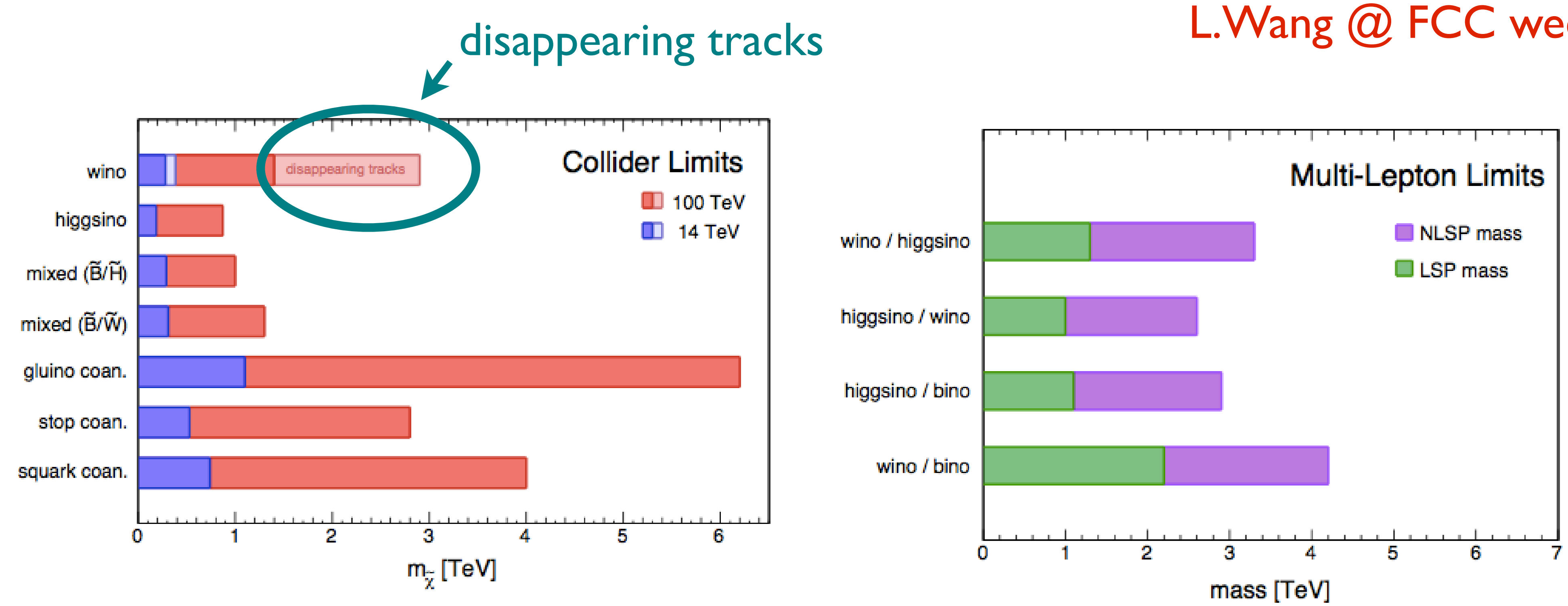
  - can WIMPS, detectable in direct and indirect (DM annihilation) experiments, be discovered at future colliders?
  - what are the opportunities w.r.t. new DM scenarios (e.g. interacting DM, asymmetric DM, ...)?

DM chapter of the report (in preparation) on "Physics at 100 TeV"

Towards no-lose arguments for Dark Matter scenarios:

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.

Final remarks

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  - ....

- Future developments in any of the points above will allow to sharpen and focus the assessment of the role of future pp colliders

backup slides

Reference literature

NB: click on underlined documents to access relevant URLs

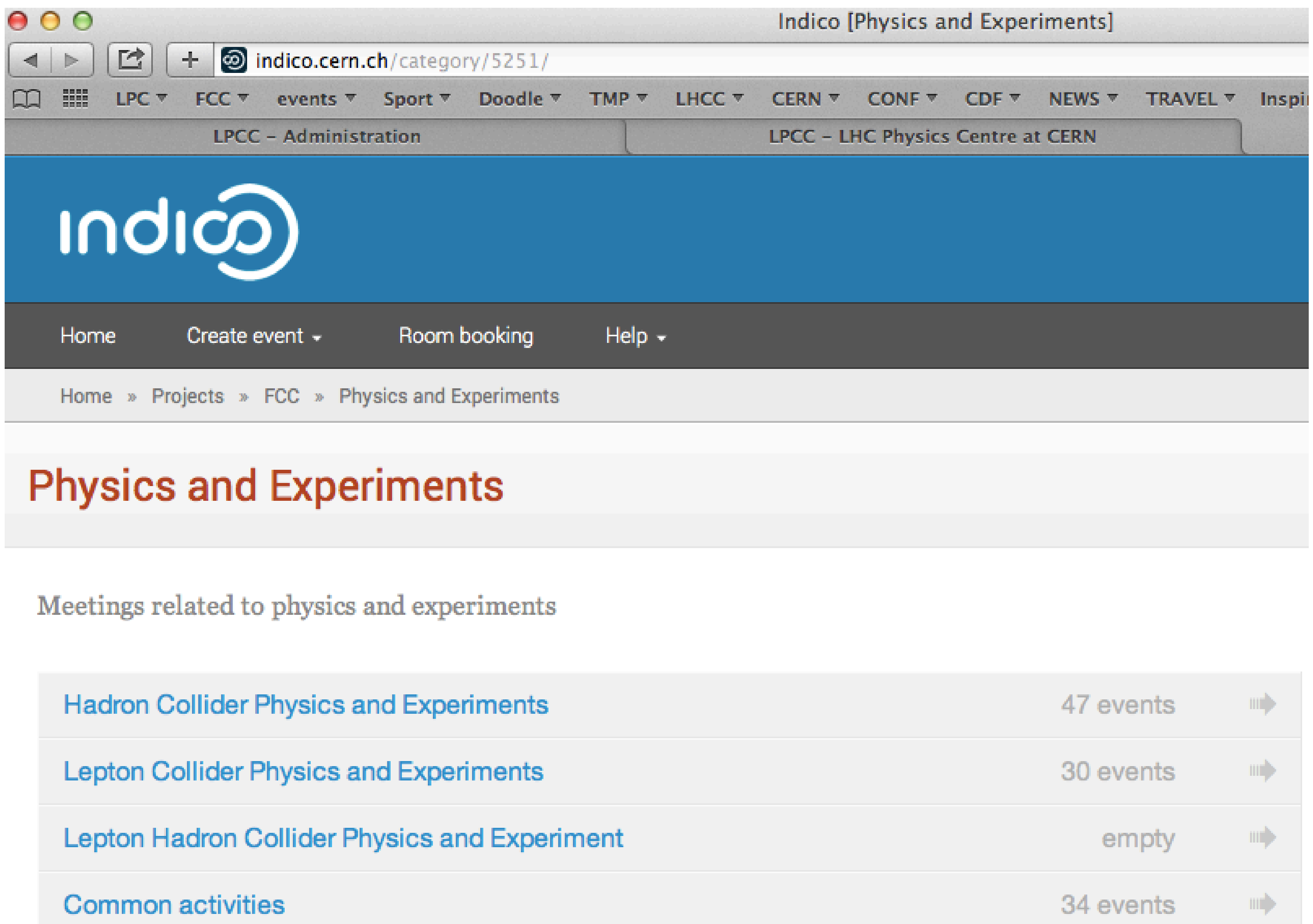
- **FCC-ee**: "First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164
- **FCC-eh**: no document as yet, see however
  - "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", J.Phys. G39 (2012) 075001
- **FCC-hh**: report on Physics at 100 TeV by March 2016
- **CEPC/SPPC**: Physics and Detectors pre-CDR:
  - http://cepc.ihep.ac.cn/preCDR/volume.html

See also:

- Physics Briefing Book to the European Strategy Group (ESG 2013)
- Planning the Future of U.S. Particle Physics (Snowmass 2013): Chapter 3: Energy Frontier, arXiv:1401.6081

FCC Physics coordination

FCC-ee	FCC-hh	FCC-eh
Alain Blondel	Austin Ball	Max Klein
Patrick Janot	Werner Riegler	Monica D'Onofrio
John Ellis	Joe Incandela	
Christophe Grojean	Michelangelo Mangano	



FCC Software twiki:

https://twiki.cern.ch/twiki/bin/view/FCC/WebHome

(must login with CERN account and must be registered on the FCC mailing list - see previous page)

Common tools for all FCC design studies

CommonTools

- FccComputing
- FccGenerators
- FccSoftware
  - FccCMakeGuide
  - FccPythiaDelphes
  - FccSoftwareEDM
  - FccSoftwareFramework
  - FccSoftwareFrameworkDelphes
  - FccSoftwareGit
  - FccSoftwareHeppy
  - FccSoftwareQA

FCC Pythia + Delphes Analysis (Tutorial)

Contents

See also slides https://indico.cern.ch/event/443015/

Delphes in FCC Software

The aim of this work is to integrate a delphes fast-sim inside the fccsw

List of presentations on the topic

https://indico.cern.ch/event/370378/contribution/2/material/slides/0.pdf
https://indico.cern.ch/event/375193/contribution/2/material/slides/0.pdf
https://indico.cern.ch/event/399484/contribution/0/material/slides/0.pdf

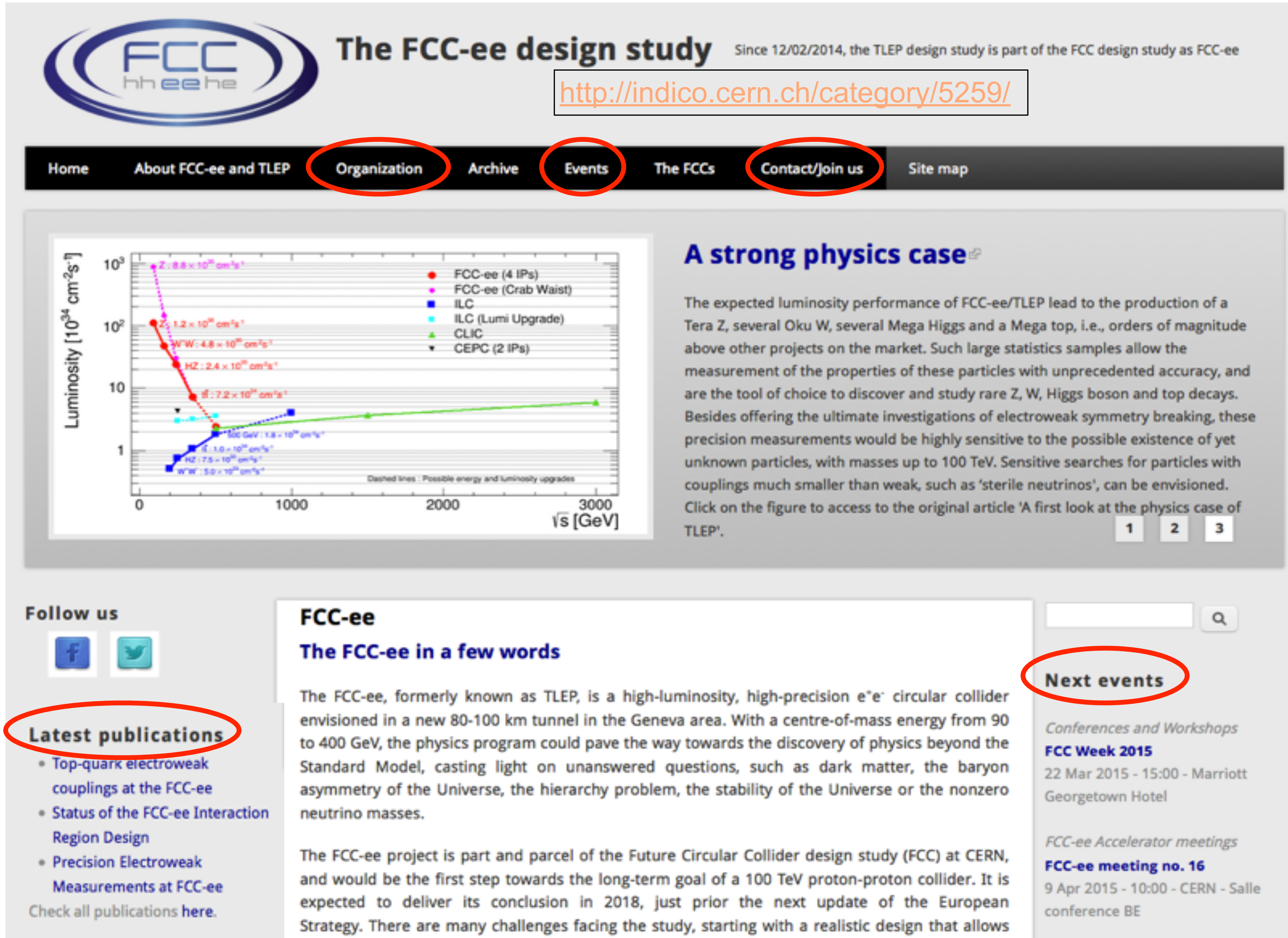
Contents

To follow FCC-hh physics activities

- Register with the FCC-hh mailing list for announcements:
  - http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=fcc-experiments-hadron
- Check agendas and contents of previous events at the following indico categories:
  - *Informal meetings of all **physics** subgroups (SM, Higgs, BSM):*
    - https://indico.cern.ch/category/6067/
  - *Workshops*
    - https://indico.cern.ch/category/6071/
  - *Physics with injectors:*
    - https://indico.cern.ch/category/6070/
  - *Heavy ion physics:*
    - https://indico.cern.ch/category/6068/
  - *Detector subgroup:*
    - https://indico.cern.ch/category/6069/
  - *Detector magnets subgroup:*
    - https://indico.cern.ch/category/6244/
  - *Software group (common with FCC-ee and FCC-eh):*
    - https://indico.cern.ch/category/5666/

FCC-ee : General documentation

- All relevant information gathered in http://cern.ch/fcc-ee (C. Martin Perez)



FCC-eh : Organization and documentation

- Overall coordination : Max Klein, Oliver Brüning
  - + coordination group

Physics Study Groups (Convenors)

PDFs, QCD	Fred Olness, Voica Radescu
Higgs	Uta Klein, Masahiro Khuze
BSM	Georges Azuelos, Monica D'Onofrio
Top	Olaf Behnke, Christian Schwanenberger
Nuclei	Nestor Armesto
Small x	Paul Newman, Anna Stasto
Software	Peter Kostka, Paul Laycock
Detector	Peter Kostka, Alessandro Polini

- Web page: http://www.lhec.cern.ch
  - LHeC conceptual design report: arXiV:1206.2913