Precision Higgs physics at 100 TeV

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- Higgs will soon become an analysis tool, if not a background, like W/Z and like the top quark
  - need to learn how to deal with and optimize the exploitation of large samples
- pp@100 TeV vs e^+e^- (LC or CC): complementarity, synergy and more ....

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- **Detector performance and systematics**. Ditto! (e.g. PU control, b-tagging, E-flow, 1MHz to HLT, 1kHz to tape, ...)

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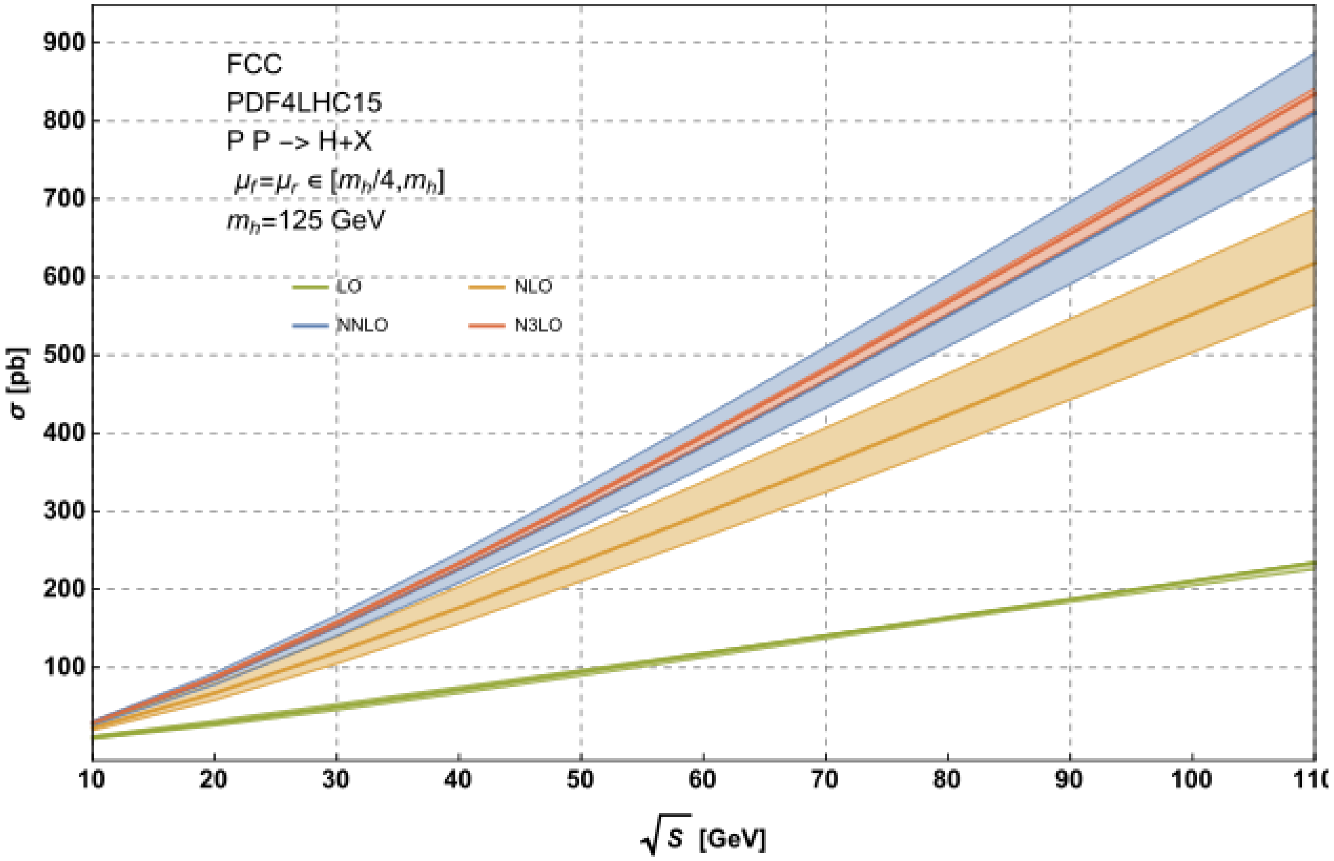
- **Statistics**.
  - Plenty at 100 TeV
  - Is it just a sqrt(N) scaling from LHC, till we hit LHC systematics? Or are there new features in the data that allows us to push beyond the systematics wall?

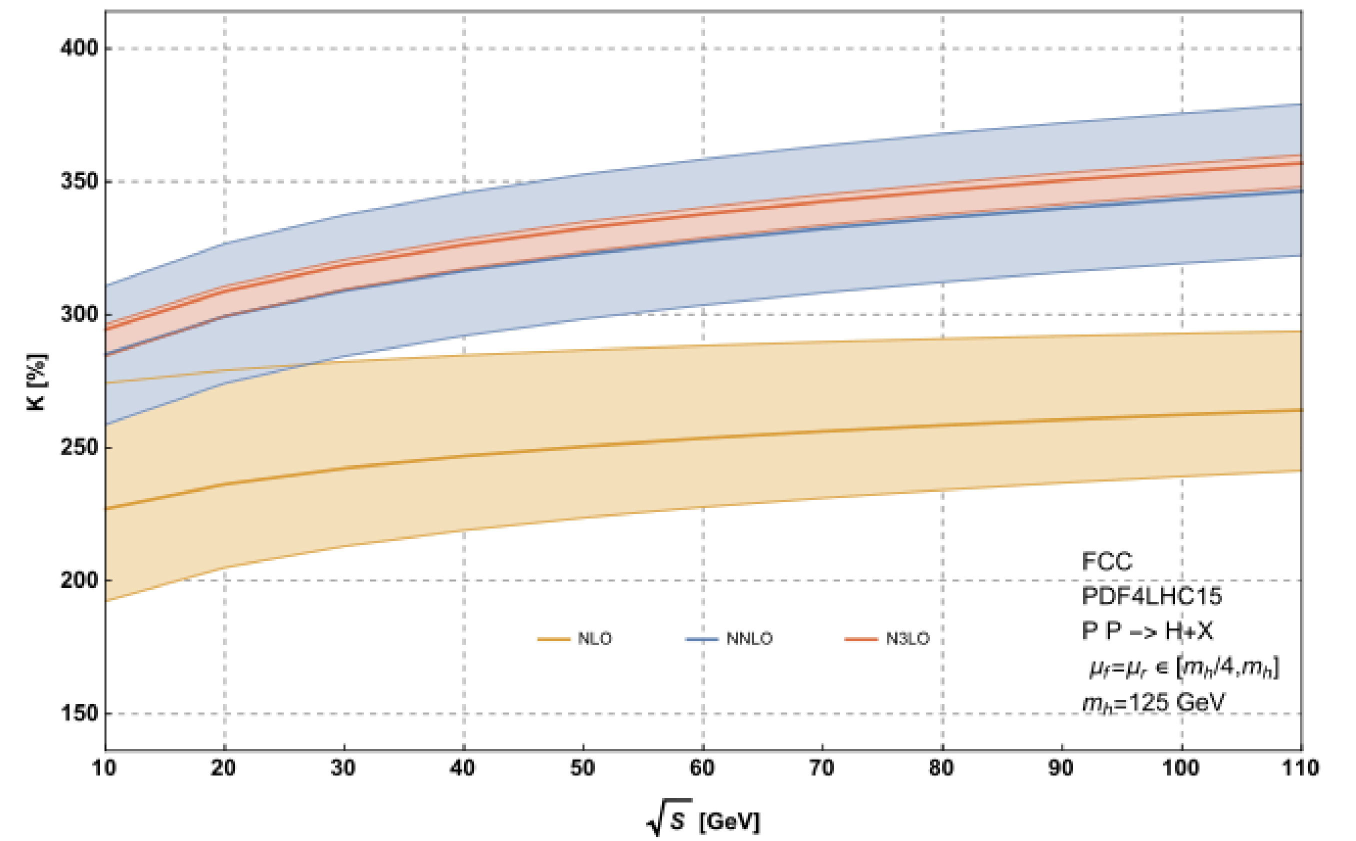
Guidelines for the exploration of measurement potential

- **Statistics**.
    - Plenty at 100 TeV
    - Is it just a sqrt(N) scaling from LHC, till we hit LHC systematics? Or are there new features in the data that allows us to push beyond the systematics wall?
- **Systematics.**
    - No point placing conservative constraints today
    - Account for irreducible bg's, but assume ideal performance to establish ideal reach, and take it from there to assess desirable performance benchmarks
    - Explore opportunities for validation and reduction of TH systematics (control samples, correlated measurements, ratios of observables, ...)

TH progress, an example

Anastasiou, Duhr, Dulat, Herzog, Mistlberger, arXiv:1503.06056
(100 TeV analysis to appear in FCC report on "Physics opportunties at 100 TeV", April 2016)





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

Table 3: Various sources of uncertainties of the inclusive gluon fusion Higgs production cross section at a 100 TeV proton-proton collider.

linear sum of all but PDF and α_S

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

Cross sections at 100 TeV

stays ~50 at N³LO

~800 at N³LO (16)

Process	√s = 14 TeV	√s = 33 TeV	√s = 40 TeV	√s = 60 TeV	√s = 80 TeV	√s = 100 TeV	8 TeV
ggF [a]	50.35 pb	178.3 pb (3.5)	231.9 pb (4.6)	394.4 pb (7.8)	565.1 pb (11.2)	740.3 pb (14.7)	**19 pb**
VBF [b]	4.40 pb	16.5 pb (3.8)	23.1 pb (5.2)	40.8 pb (9.3)	60.0 pb (13.6)	82.0 pb (18.6)	**1.6 pb**
WH [c]	1.63 pb	4.71 pb (2.9)	5.88 pb (3.6)	9.23 pb (5.7)	12.60 pb (7.7)	15.90 pb (9.7)	**0.7 pb**
ZH [c]	0.904 pb	2.97 pb (3.3)	3.78 pb (4.2)	6.19 pb (6.8)	8.71 pb (9.6)	11.26 pb (12.5)	**0.4 pb**
ttH [d]	0.623 pb	4.56 pb (7.3)	6.79 pb (11)	15.0 pb (24)	25.5 pb (41)	37.9 pb (61)	**0.13 pb**
bbH [e]	0.581 pb	2.13 pb (3.7)	2.77 pb (4.8)	4.69 pb (8.1)	6.65 pb (11)	8.64 pb (15)	**0.20 pb**
gg → HH[f]*(λ=1)*	33.8 fb	207 fb (6.1)	298 fb (8.8)	609 fb (18)	980 fb (29)	1.42 pb (42)	

PDF is NNLO(NLO) MSTW2008 set. Numbers in () parentheses are the cross-section ratio wrt 14 TeV.

a) NNLO+NNLL QCD + NLO EW corrections. QCD scale and PDF+α_s uncertainties remain constant about +-8% for both (D. de Florian).

b) NNLO QCD only with VBF@NNLO (M. Zaro).

c) NNLO QCD only with VH@NNLO (R. Harlander).

d) NLO QCD. (M. Spira).

e) NNLO QCD in 5FS (R. Harlander).

f) NLO QCD with HPAIR. The central scale is the invariant mass of the Higgs pair. The scale is varied by a factor 2 up and down. (M. Spira).

LHC Higgs XS WG https://cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy

Rate comparisons at 8, 14, 100 TeV

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16 G	4.2×10^4	110
VBF	1.6 G	5.1×10^4	120
WH	320 M	2.3×10^4	66
ZH	220 M	2.8×10^4	84
ttH	760 M	29×10^4	420
$gg \to HH$	28 M		280

$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$

$N_8 = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$

$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

Statistical precision:

- O(100 - 500) better w.r.t Run 1
- O(10 - 20) better w.r.t HL-LHC

Example, $H \to \gamma\gamma$ (fiducial, all channels)

8 TeV reference results from ATLAS, arXiv:1407.4222

Fiducial cross section for $|\eta_\gamma| < 2.37$, *with* $p_{T\,\gamma}^{max} / m_{\gamma\gamma} > 0.35$ *and* $p_{T\,\gamma}^{min} / m_{\gamma\gamma} > 0.25$

Signal dominated by $gg \to H$

Fiducial volume acceptance: $\varepsilon_{fid} \sim 3/4$

Detection efficiency within fiducial volume: $\varepsilon_{eff} \sim 2/3$

$\Rightarrow \mathbf{N_{signal}} \sim 3/4 * 2/3 * \sigma(pp \to H) * BR(H \to \gamma\gamma) * Lum \sim \mathbf{10^{-3}\,\sigma(pp \to H) * Lum}$

Observe 570 ± 130 signal events, over a bg of ~16000 events ($\mathbf{|\, m_{\gamma\gamma} - 125 \,| < 4\ GeV}$ *)*

Extract $\boldsymbol{\sigma_{FIDUCIAL}(pp \to H \to \gamma\gamma) = 43.2 \pm 9.4\ (stat.) + 3.2\ (syst.) \pm 1.2\ (lumi)\ fb}$

$\boldsymbol{\delta\,(\sigma \cdot B) / (\sigma \cdot B) \sim 22\%\ (stat.) + 7\%\ (syst.) \pm 3\%\ (lumi)}$

Example, $H\to\gamma\gamma$ (fiducial, all channels)

8 TeV 20 fb^{-1} $\delta(\sigma\cdot B)/(\sigma\cdot B) \sim 22\%$ (stat.) + 7% (syst.) ± 3% (lumi)

Extrapolations

(assume bg XS scales like signal, an overestimate since $gg\to\gamma\gamma$ is not the dominant process at 8 TeV ....)

14 TeV 300 fb^{-1} ($N_{14}/N_8 \sim 40$)

$\delta(\sigma\cdot B)/(\sigma\cdot B) \sim 3.5\%$ (stat.) + X_{14} % (syst.) ± 3% (lumi)

14 TeV 3000 fb^{-1} ($N_{14}/N_8 \sim 400$)

$\delta(\sigma\cdot B)/(\sigma\cdot B) \sim 1\%$ (stat.) + X_{14} % (syst.) ± 3% (lumi)

100 TeV 20 ab^{-1} ($N_{100}/N_8 \sim 40000$)

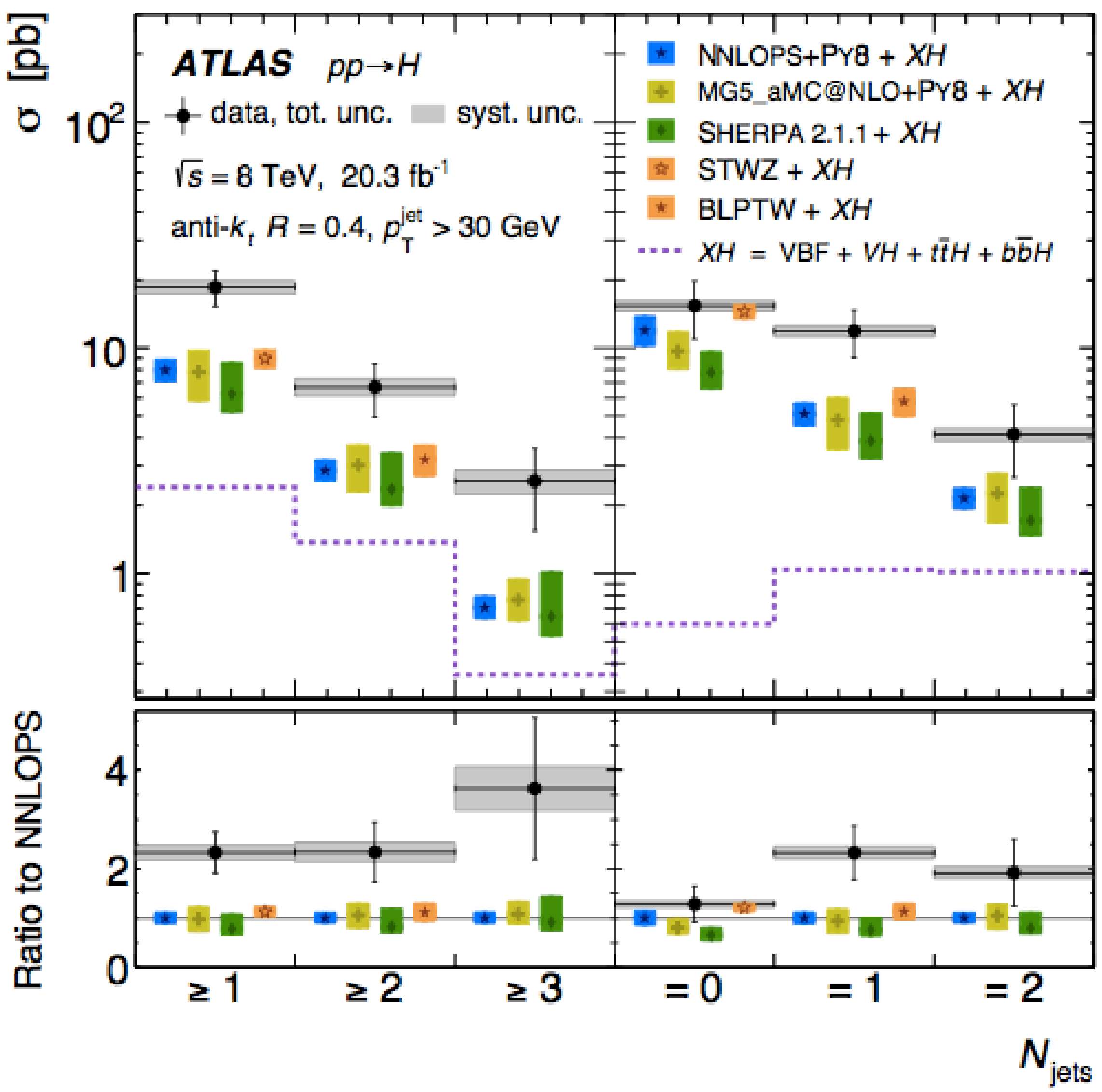
$\delta(\sigma\cdot B)/(\sigma\cdot B) \sim 0.1\%$ (stat.) + X_{100} % (syst.)

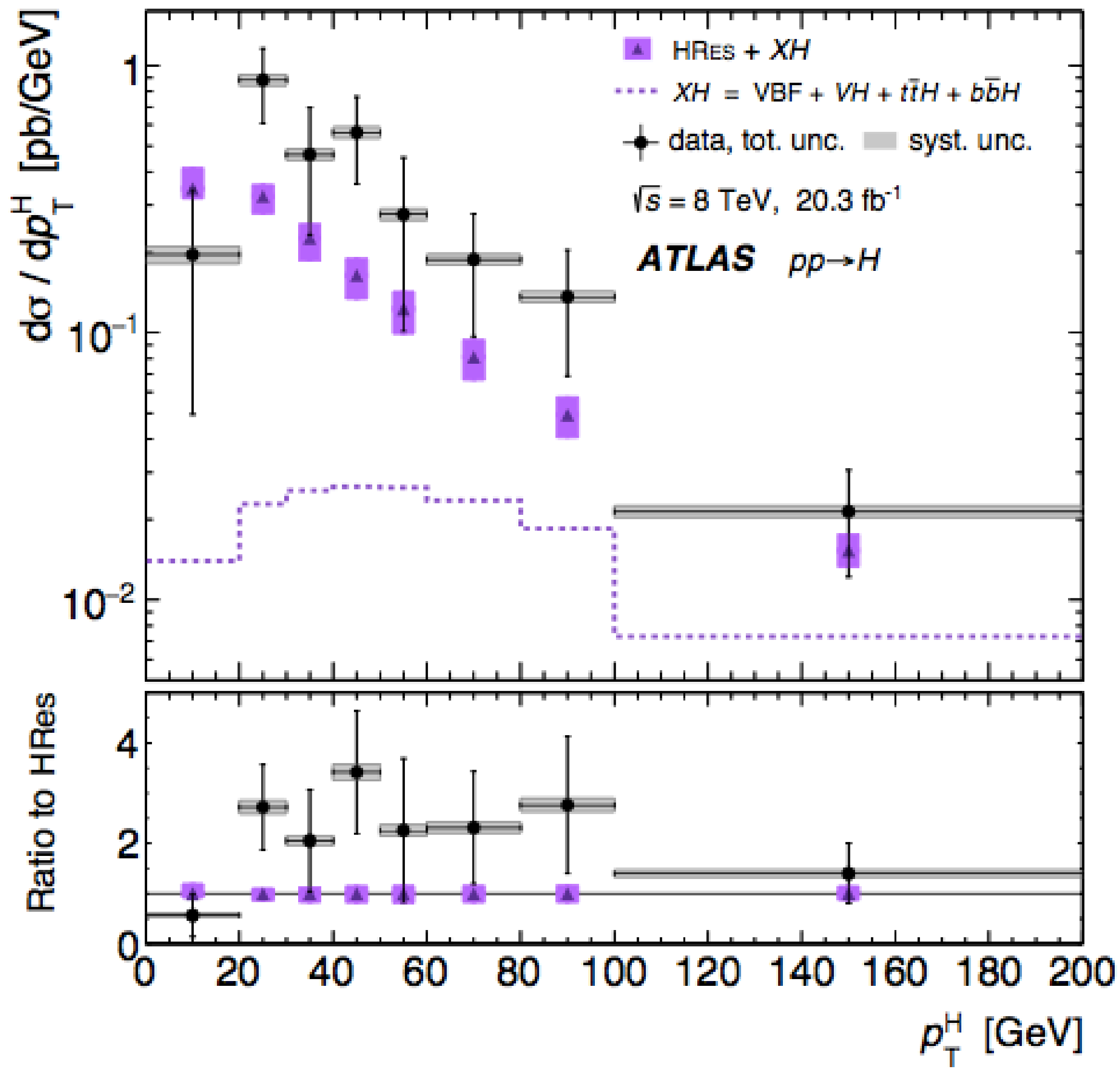
Cfr: ATLAS ATL-PHYS-PUB-2013-007 for TOTAL rate, not FIDUCIAL ....

$H\to\gamma\gamma$	with TH syst's	without TH syst's
300 fb^{-1}	15%	8.1%
3000 fb^{-1}	13%	4.0%

Examples of handles to improve on the modeling systematics with larger statistics

ATLAS, arXiv:1504.05833





Reduce all statistical uncertainties by ~ 200 !!

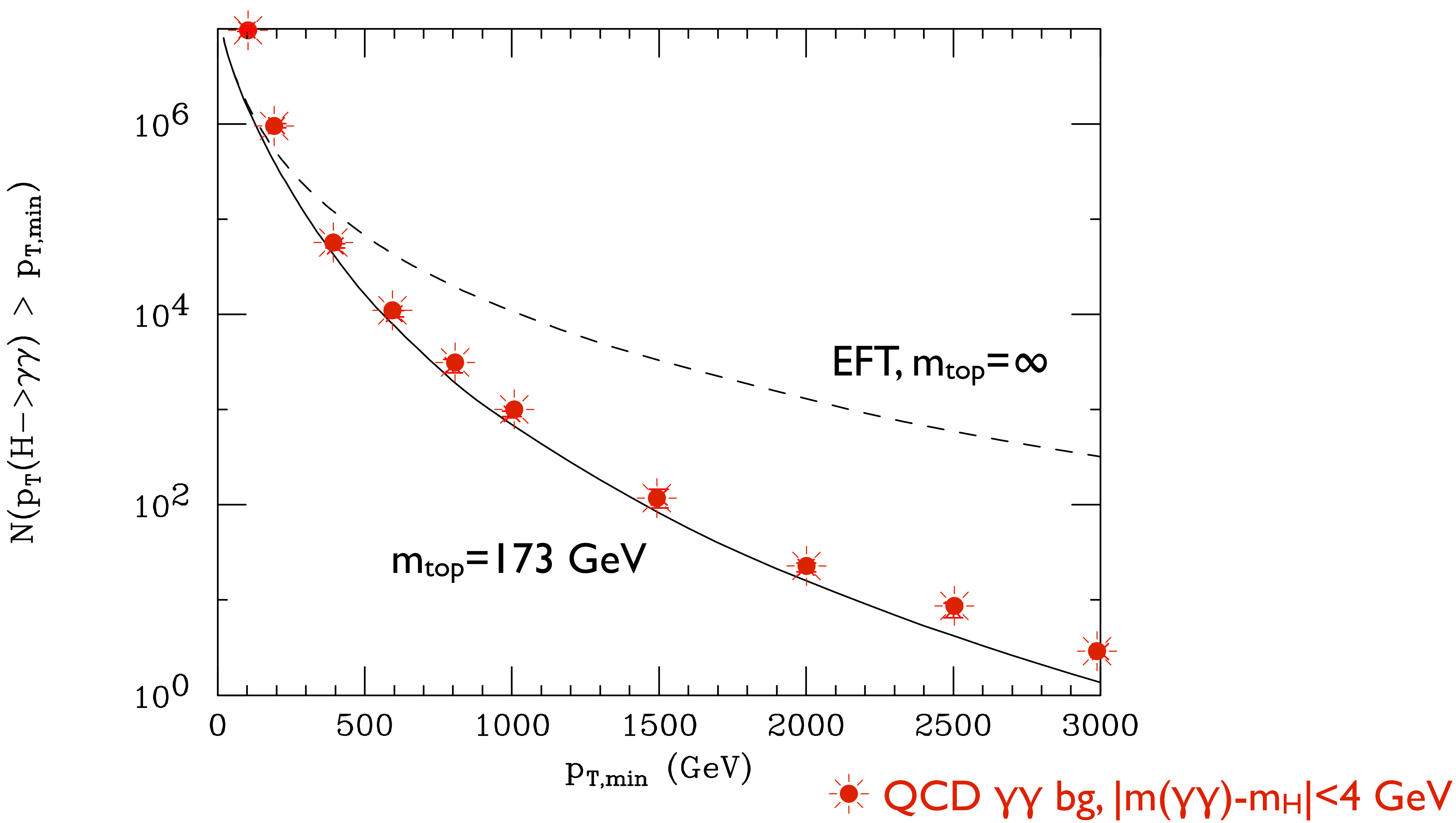
No need to use MC's to model H pt spectrum, N_{jet} rates, etc.etc.

Reach at high p_T

Using as in the 8 TeV analysis $\mathbf{N_{obs}(pp \to H \to \gamma\gamma) \sim 1/2\ \sigma(pp \to H) * BR(H \to \gamma\gamma) * Lum}$

$\sim \varepsilon_{fid} \times \varepsilon_{eff}$

and assuming it holds even at high p_T (where we'd expect acceptance to be larger, but ?? ID efficiency ??)



Example, $H \to ZZ^* \to 4\ell$ (fiducial, all channels)

8 TeV reference results from ATLAS, arXiv:1504.05833

Fiducial cross section for $m_{4\ell}$ in 118-129 GeV, $|\eta_\mu| < 2.7$, $|\eta_e| < 2.47$

with $p_{T\,\ell}$ > 20, 15, 10 GeV and 6 (7) GeV for softest lepton if μ (e)

Signal dominated by $gg \to H$, bg mostly $q\bar{q} \to ZZ^*$ => S/B improves at 100 TeV

Fiducial volume acceptance: $\varepsilon_{fid} \sim 1/2$

Detection efficiency within fiducial volume: $\varepsilon_{eff} \sim 1/2$

$\Rightarrow$ $\mathbf{N_{signal}} \sim 1/2 * 1/2 * \sigma(pp \to H) * BR(H \to 4\ell) * Lum \sim \mathbf{3 \cdot 10^{-5}\, \sigma(pp \to H) * Lum}$

Observe 24 ± 6 signal events, over a bg of ~ 9 events

Extract $\boldsymbol{\sigma_{FIDUCIAL}(pp \to H \to 4\ell) = 2.1 \pm 0.5\ (stat.) + 0.08\ (syst.)\ fb}$

(SM expectation = 1.30 ± 0.13 fb)

$\delta(\sigma \cdot B) / (\sigma \cdot B) \sim 25\%$ (stat.) + 4% (syst.)

Example, $H \to ZZ^* \to 4\ \ell$ (fiducial, all channels)

8 TeV 20 fb^{-1} *$\delta (\sigma \cdot B) / (\sigma \cdot B) \sim 25\%$ (stat.) + 4% (syst.)*

Extrapolations

(assume bg XS scales like signal, an overestimate since $gg \to ZZ^*$ is not the dominant process at 8 TeV ....)

14 TeV 300 fb^{-1} ($N_{14}/N_8 \sim 40$)

$\delta (\sigma \cdot B) / (\sigma \cdot B) \sim 4\ \%$ (stat.) + X_{14} % (syst.)

14 TeV 3000 fb^{-1} ($N_{14}/N_8 \sim 400$)

$\delta (\sigma \cdot B) / (\sigma \cdot B) \sim 1.3\ \%$ (stat.) + X_{14} % (syst.)

100 TeV 20 ab^{-1} ($N_{100}/N_8 \sim 40000$)

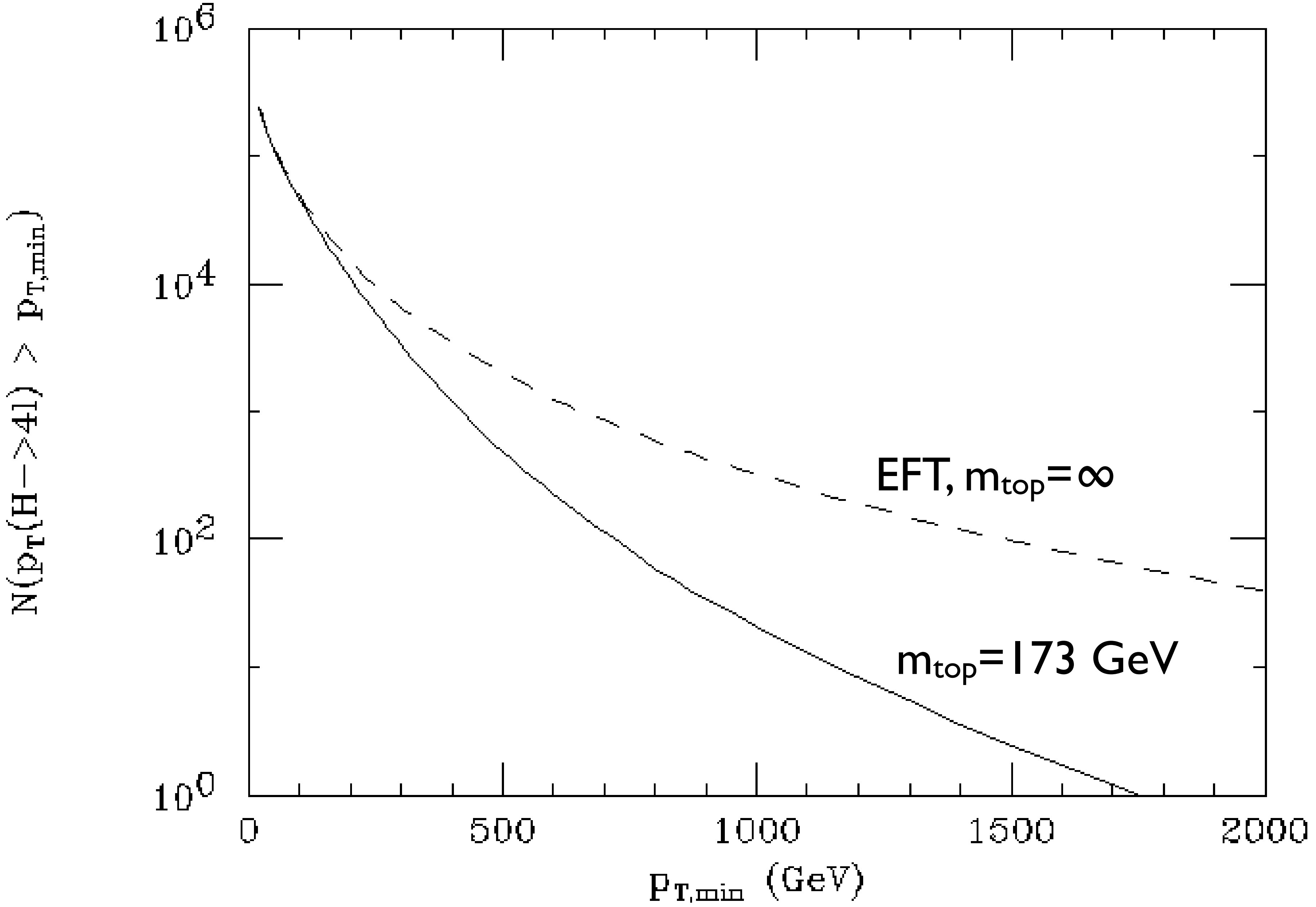
$\delta (\sigma \cdot B) / (\sigma \cdot B) \sim 0.1\ \%$ (stat.) + X_{100} % (syst.)

Cfr: ATLAS ATL-PHYS-PUB-2013-007 for TOTAL rate, not FIDUCIAL ....

$H \to \gamma\gamma$	with TH syst's	without TH syst's
300 fb^{-1}	16%	9.3%
3000 fb^{-1}	13%	4.7%

- Possibility to get a sub-% precision measurement of $B(ZZ^*)/B(\gamma\gamma)$?
    - Could export $B(ZZ^*)$ absolute measurement from e^+e^- to sub-% absolute determination of $B(\gamma\gamma)$

Reach for H→4 leptons at high p_T



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

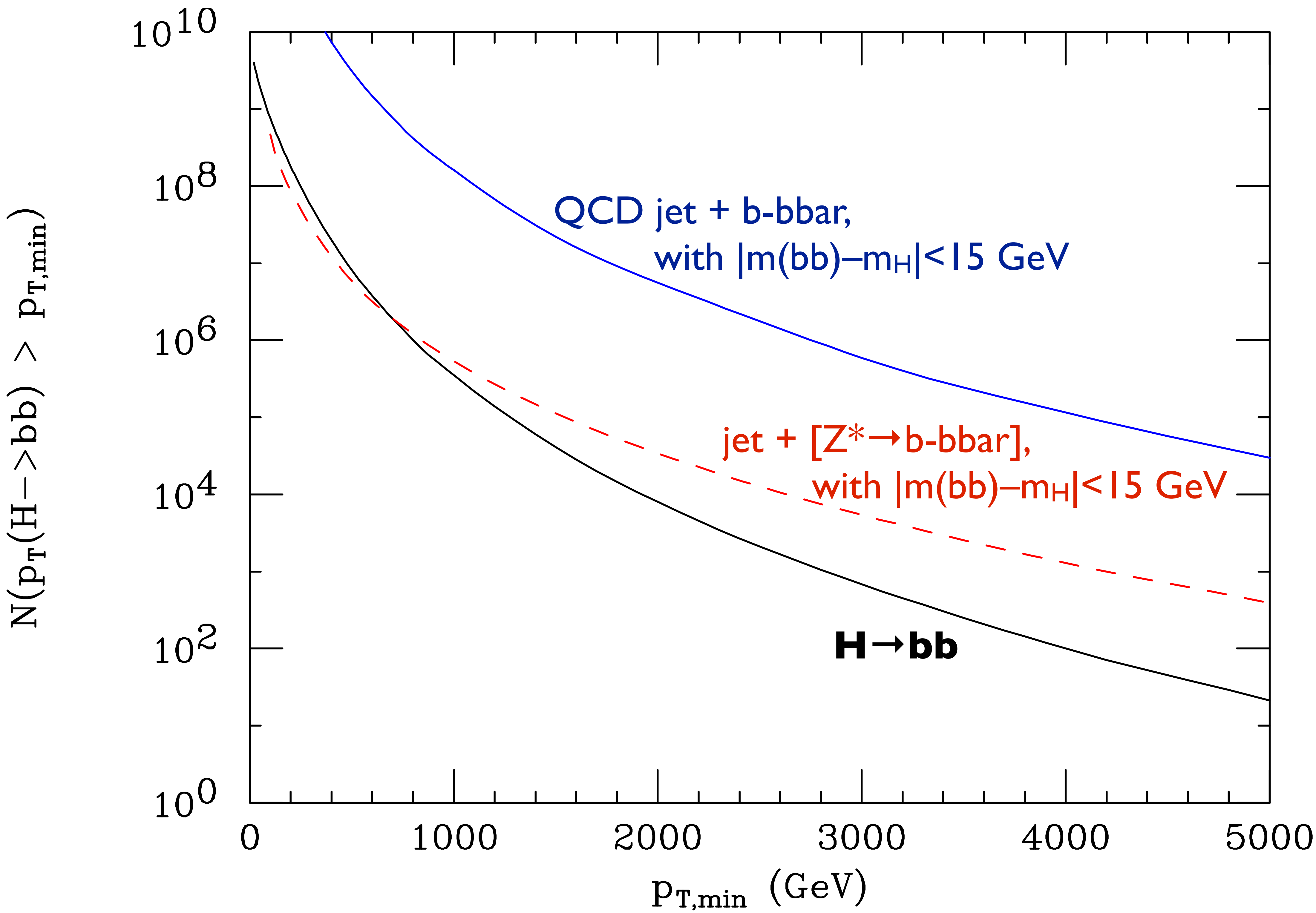
$\sqrt{B}/S$ for $10ab^{-1}$ — $\Delta m_{\mu\mu} = \pm$ 1 GeV

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

1 % level measurement of $B(H \to \mu\mu)/B(H \to \gamma\gamma)$?

Similar numbers for $(H \to Z\gamma)$ ...

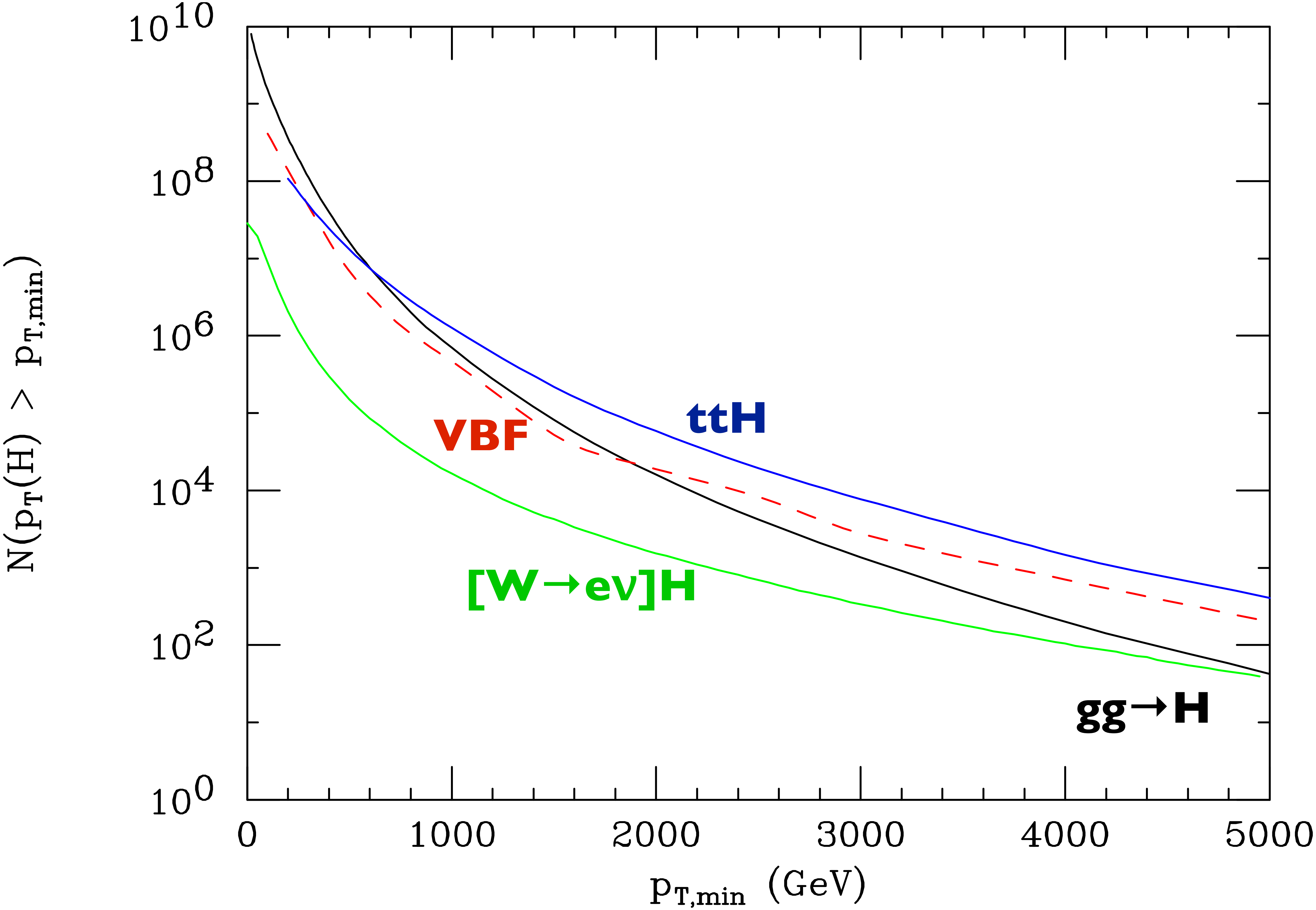
Reach for H→bb at high pT



$S/\sqrt{B}$ ~ 1 at $p_{T\ min}$ ~ 3 TeV, but plenty of room to outsmart the QCD rate ....

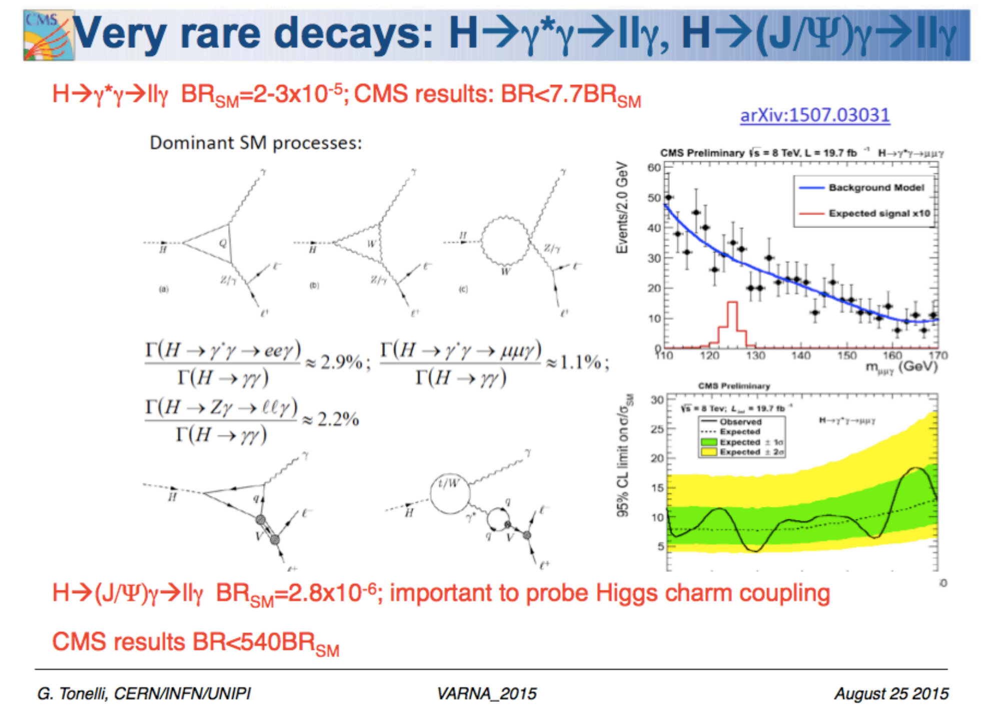
Higgs →bb tagging at multi-TeV ?

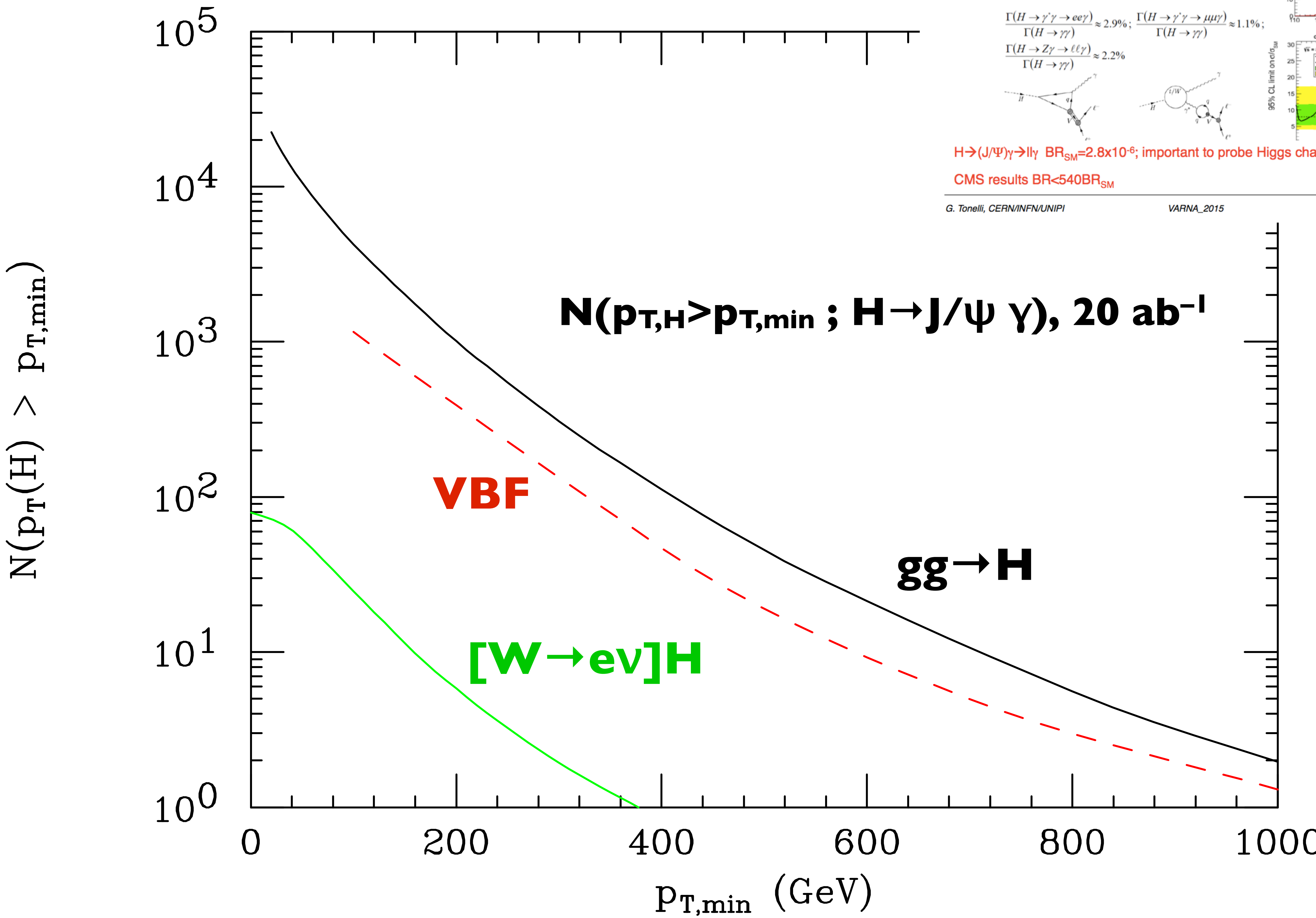
Various production procs at high p_T



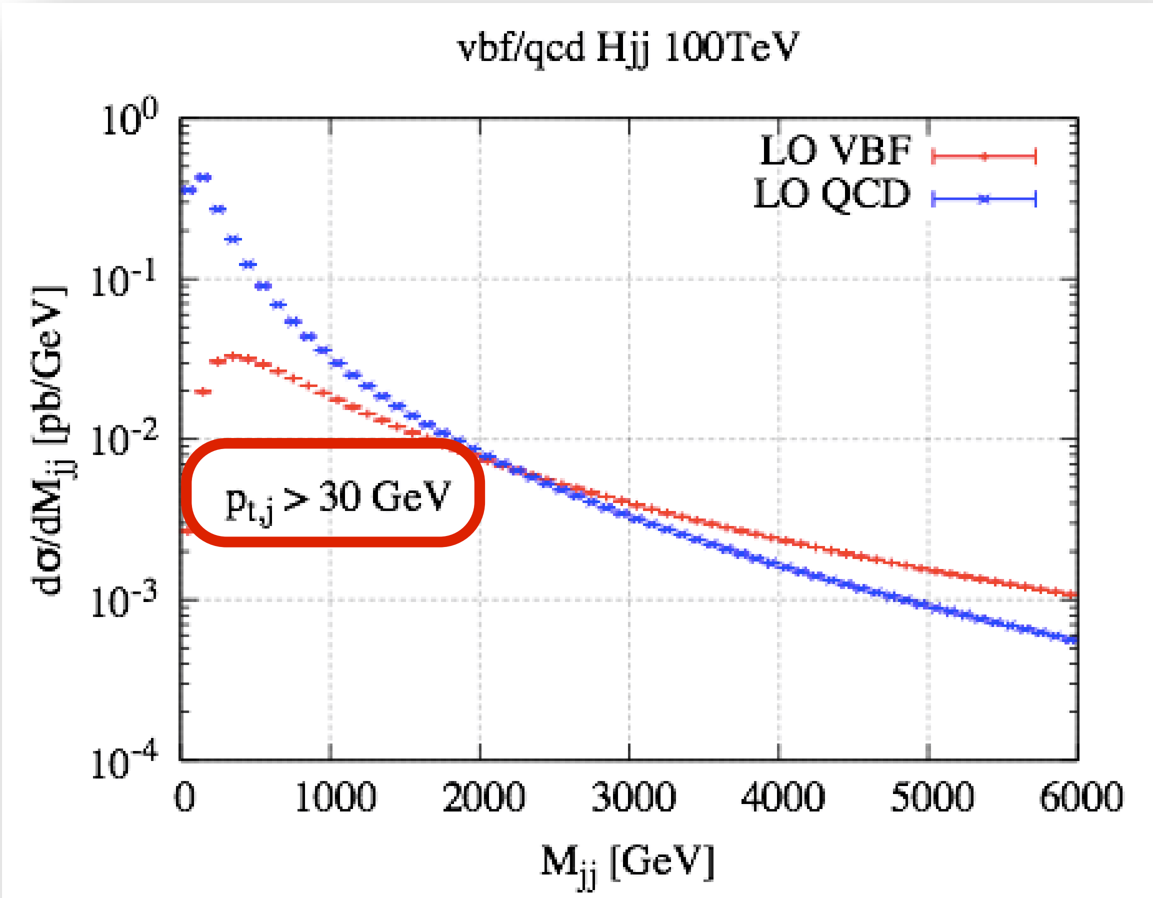
$H \to J/\psi\ \gamma$?

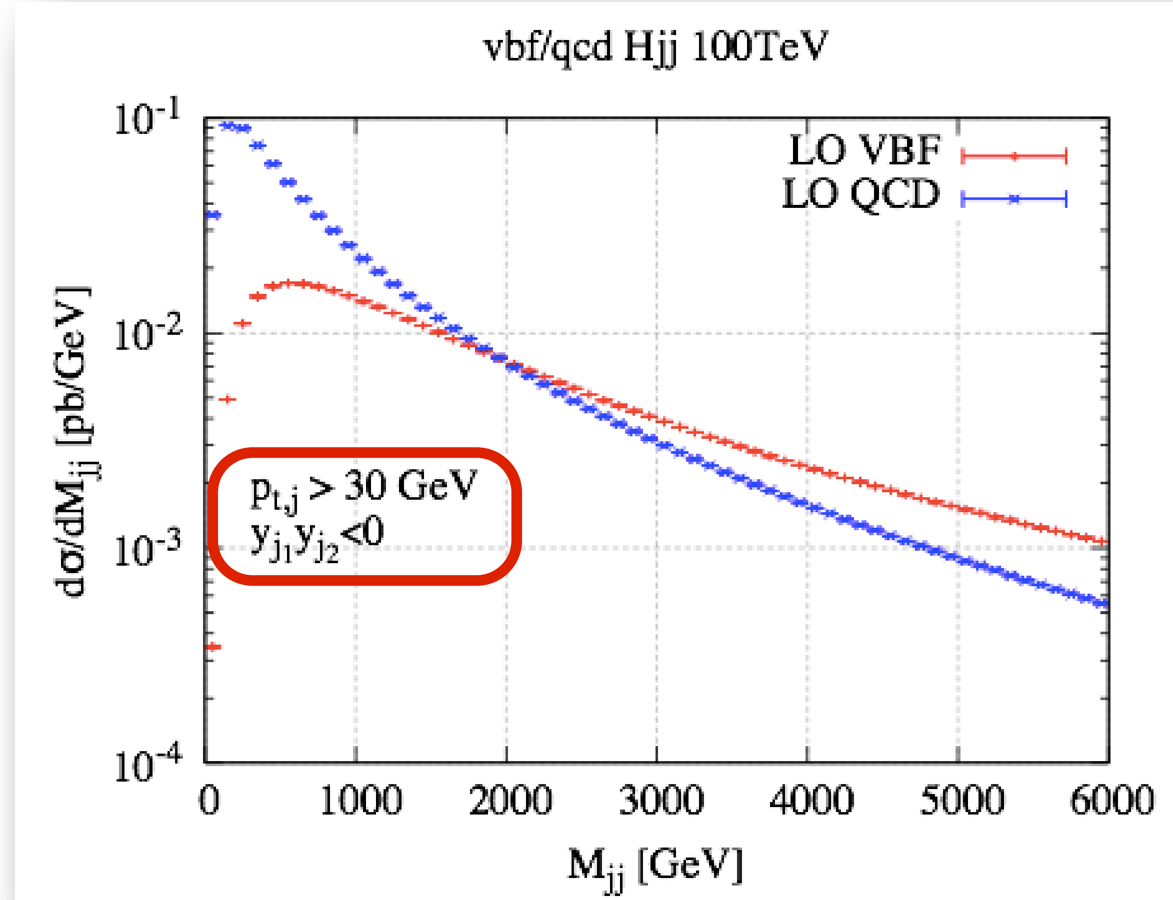
$BR(H \to J/\psi\ \gamma) = 2.8 \times 10^{-6}$

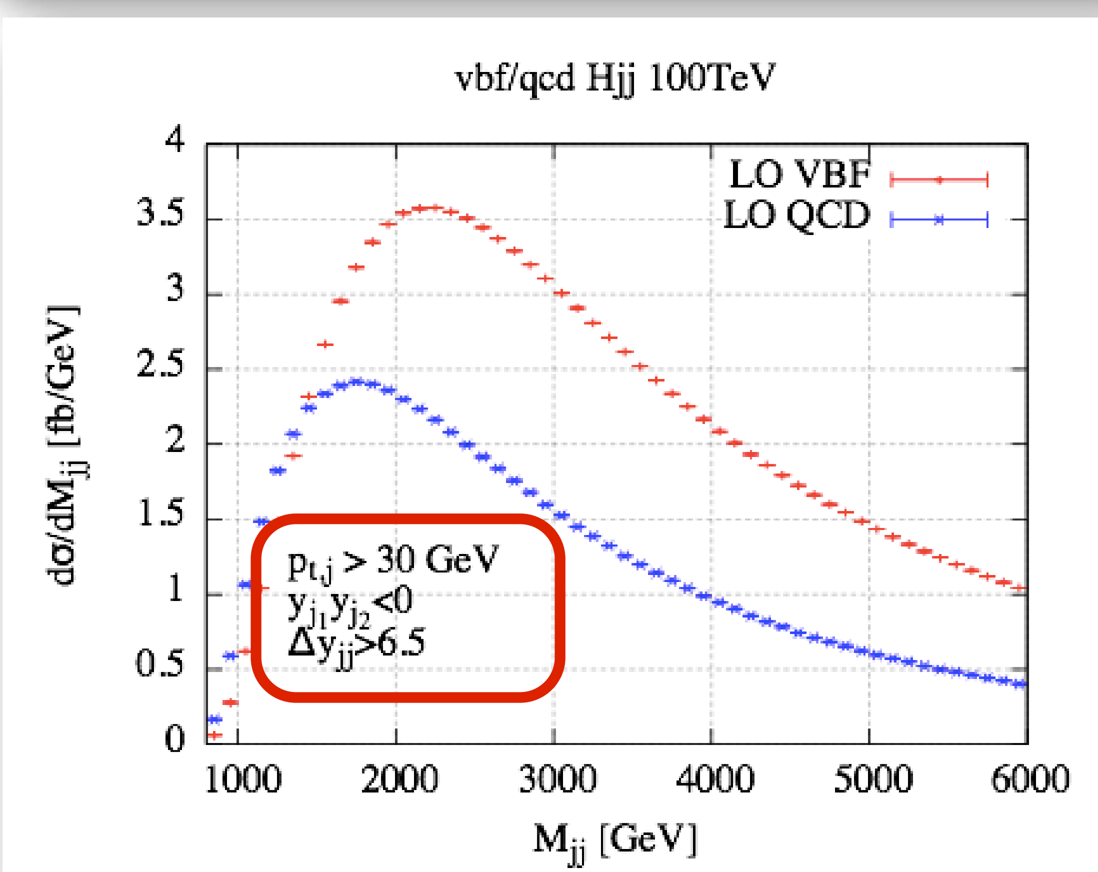


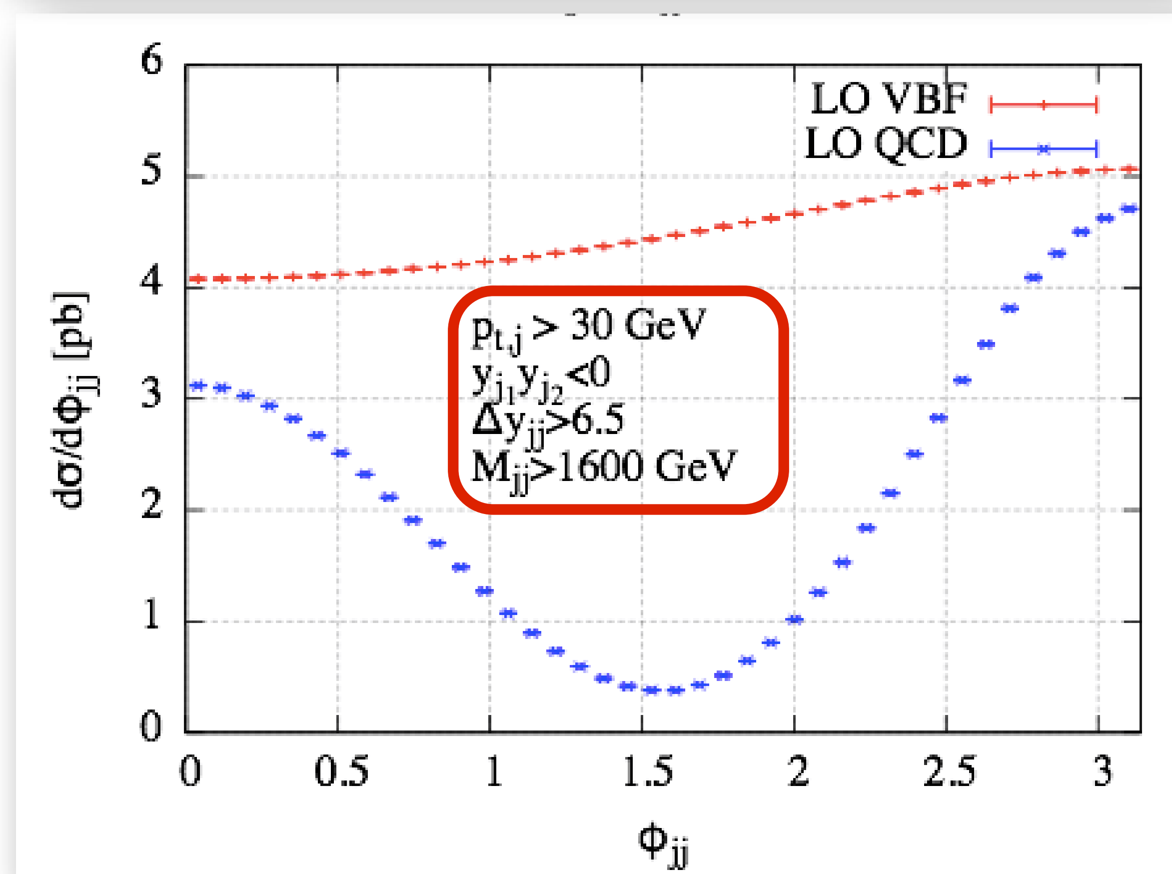


VBF Karlberg SM@100 TeV



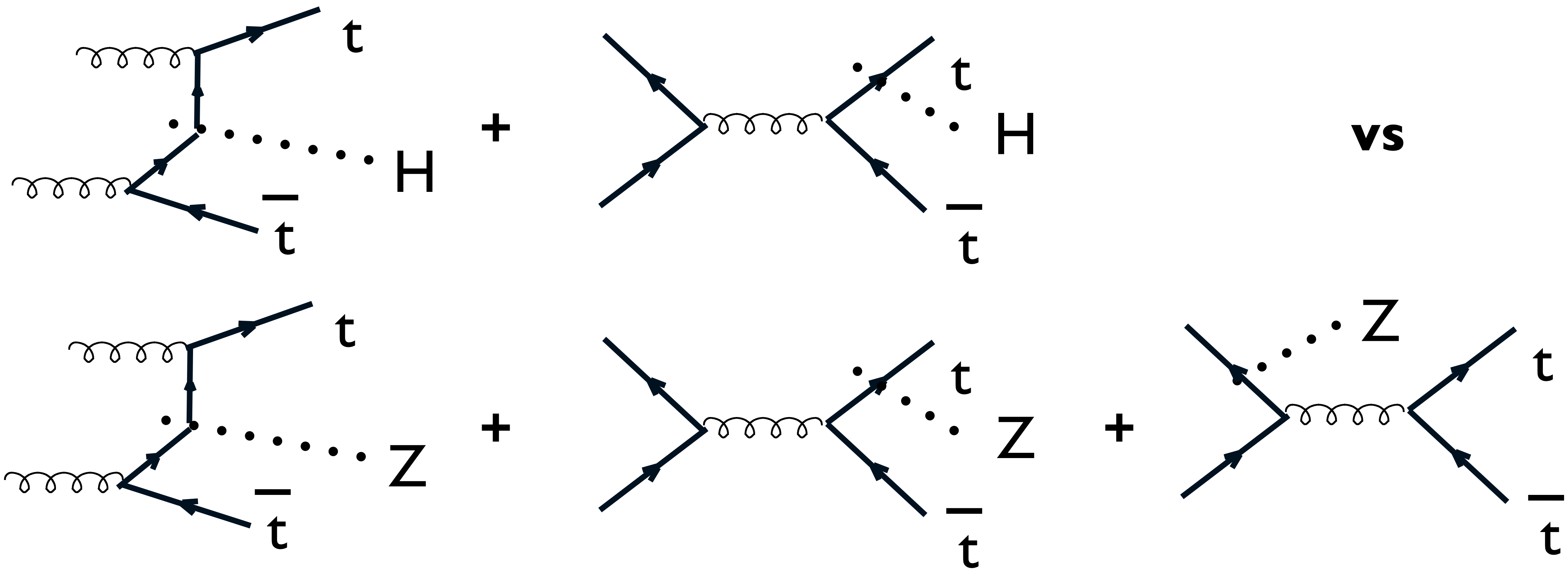






Top Yukawa coupling from σ(ttH)/σ(ttZ)

arXiv:1507.08169



To the extent that the qqbar → tt Z/H contributions are subdominant:

- **Identical production dynamics:**

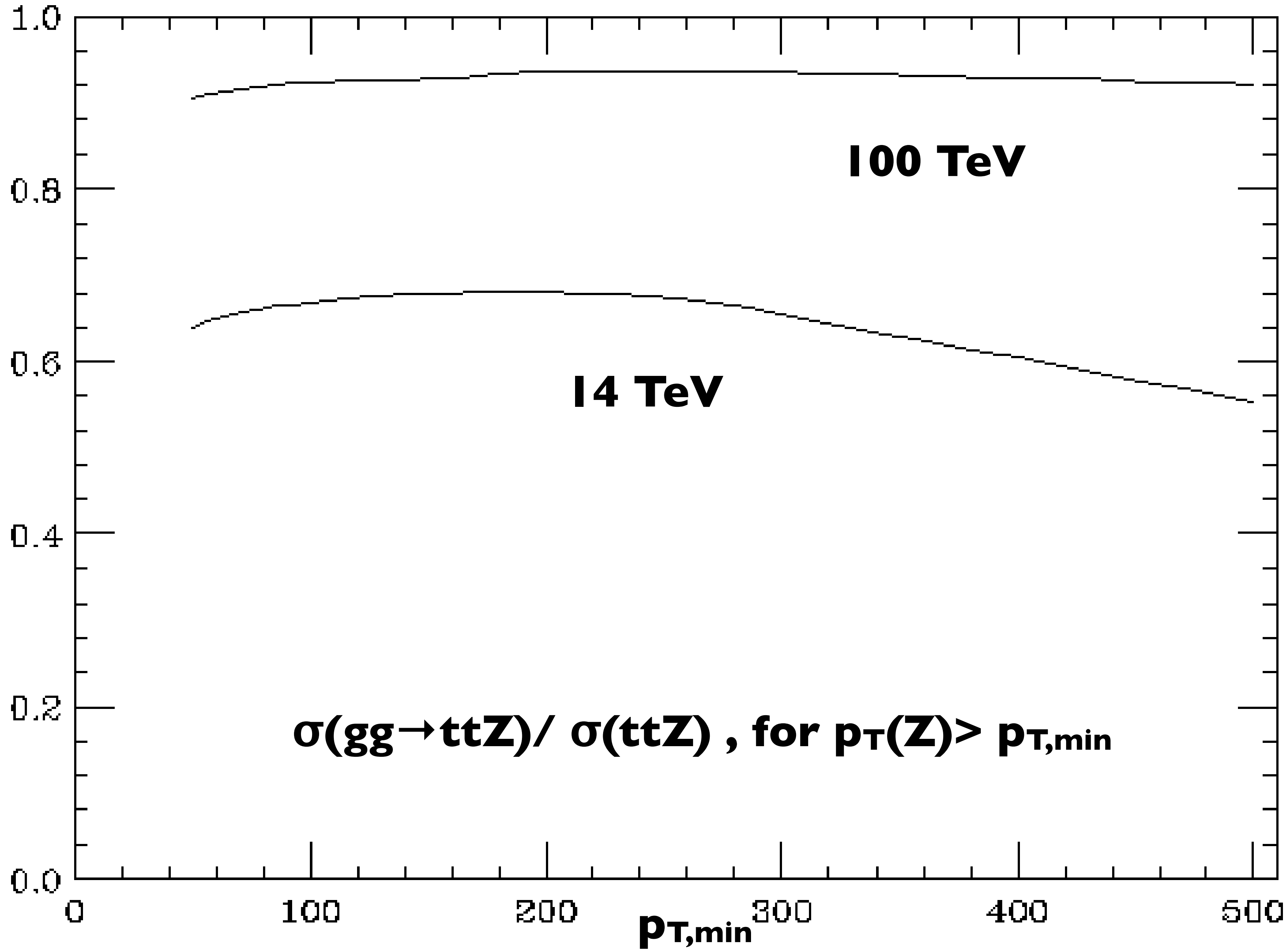
  o correlated QCD corrections, correlated scale dependence
  o correlated α_S systematics

- **$m_Z \sim m_H \Rightarrow$ almost identical kinematic boundaries:**

  o correlated PDF systematics
  o correlated m_{top} systematics

For a given y_{top}, we expect σ(ttH)/σ(ttZ) to be predicted with great precision

At 100 TeV, gg→tt X is indeed dominant ....



NB: At lower p_T values, gg fraction is slightly larger for ttZ than for ttH, since $m_Z < m_H$

Cross section ratio stability

	$\sigma(t\bar{t}H)$[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

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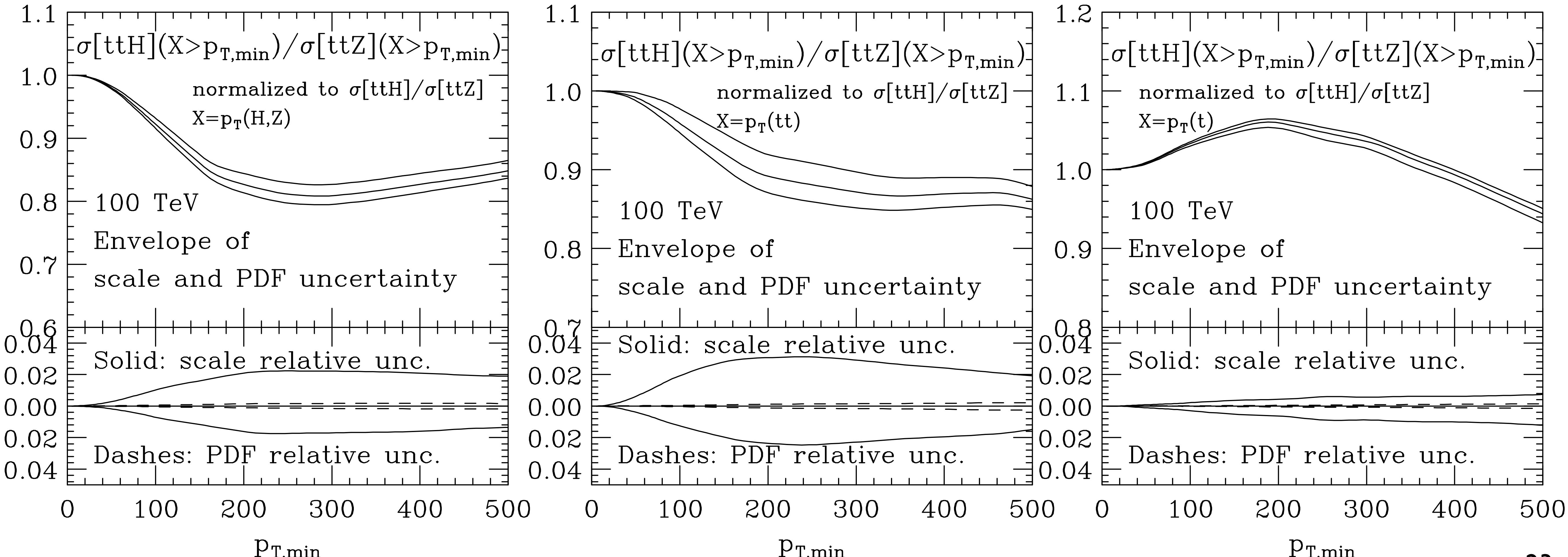
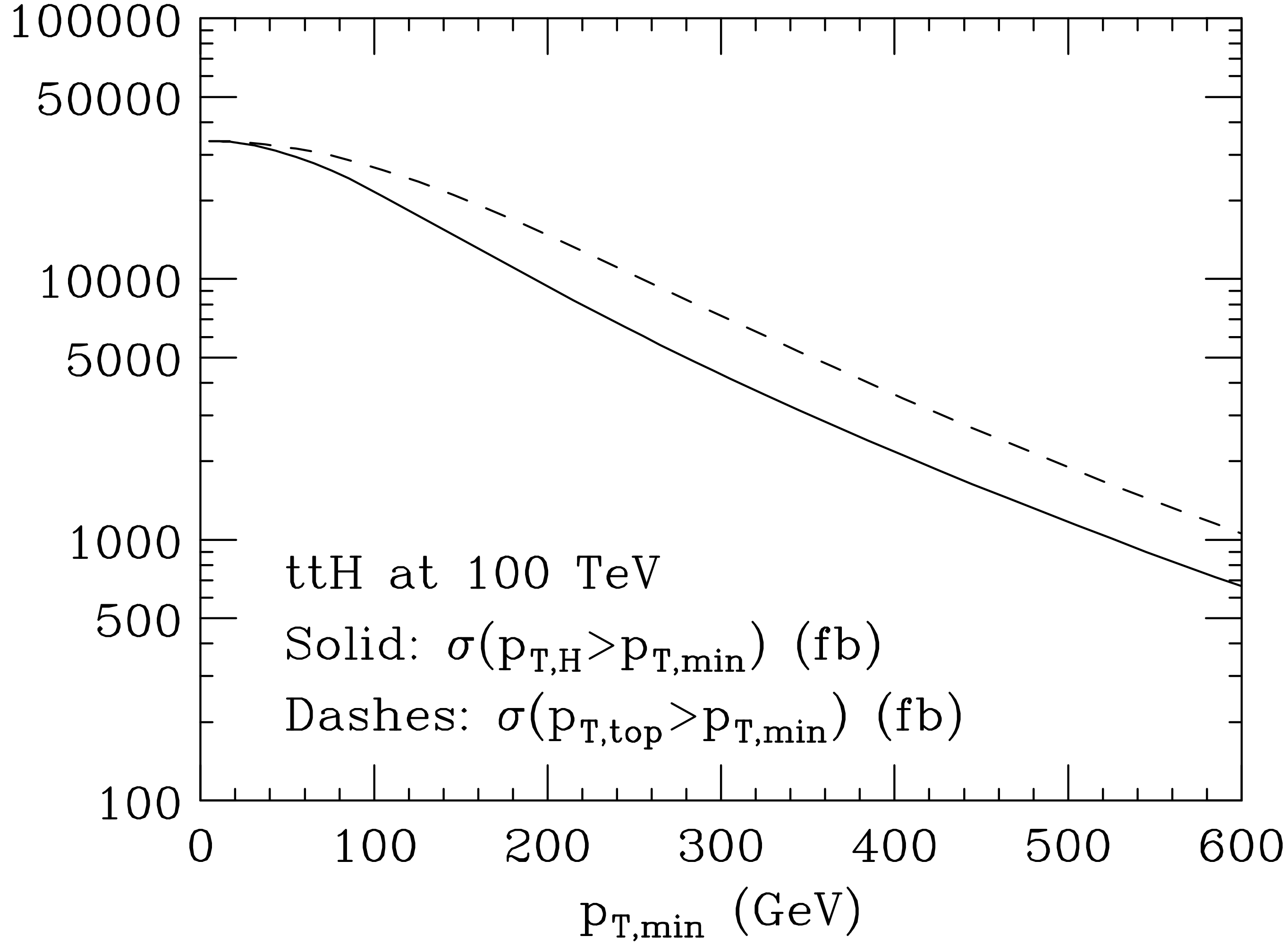
scale PDF

Production kinematics ratio stability



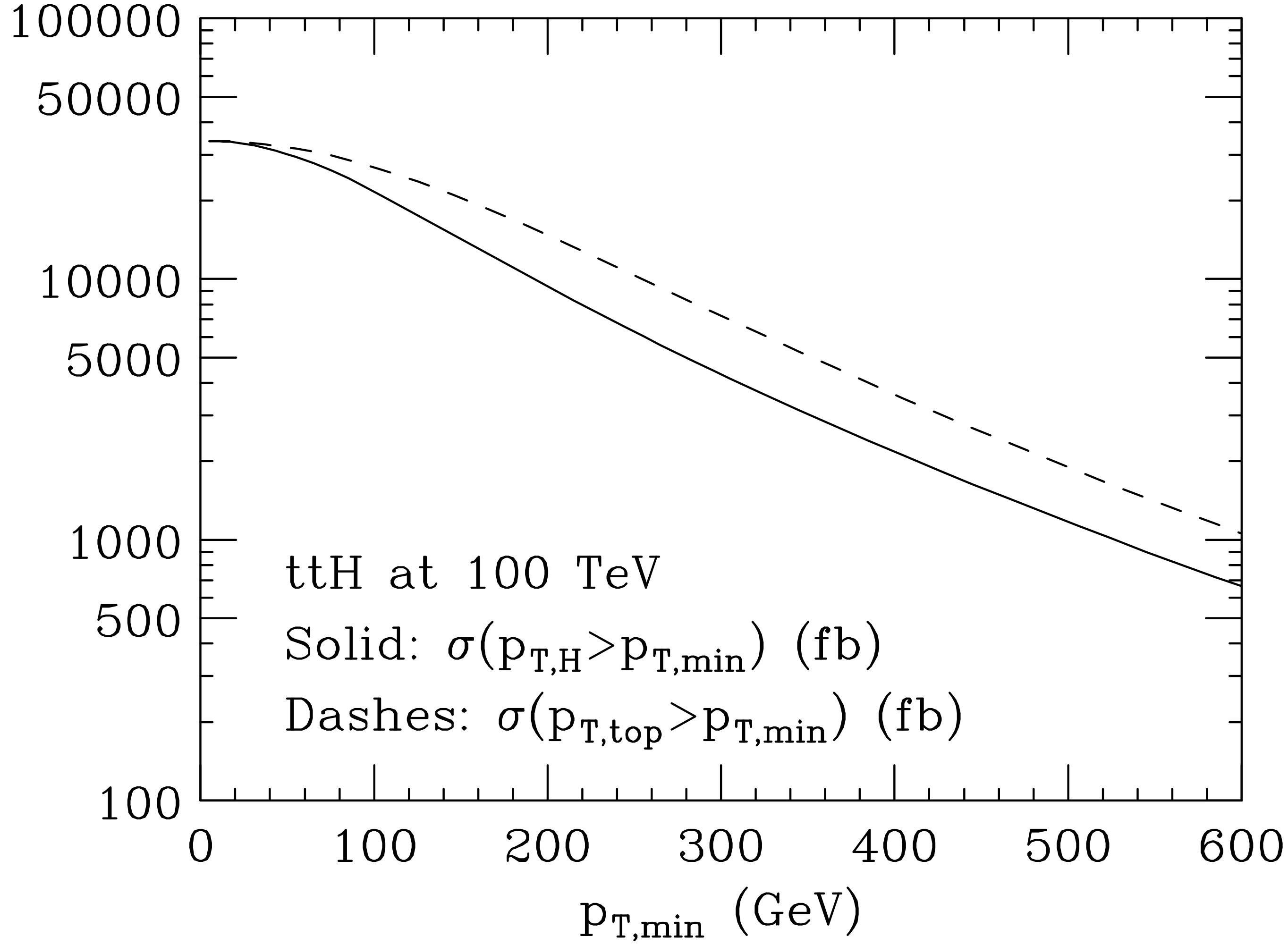
arXiv:1507.08169



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

Events/20ab^{-1} , with tt→$\ell\nu$+jets

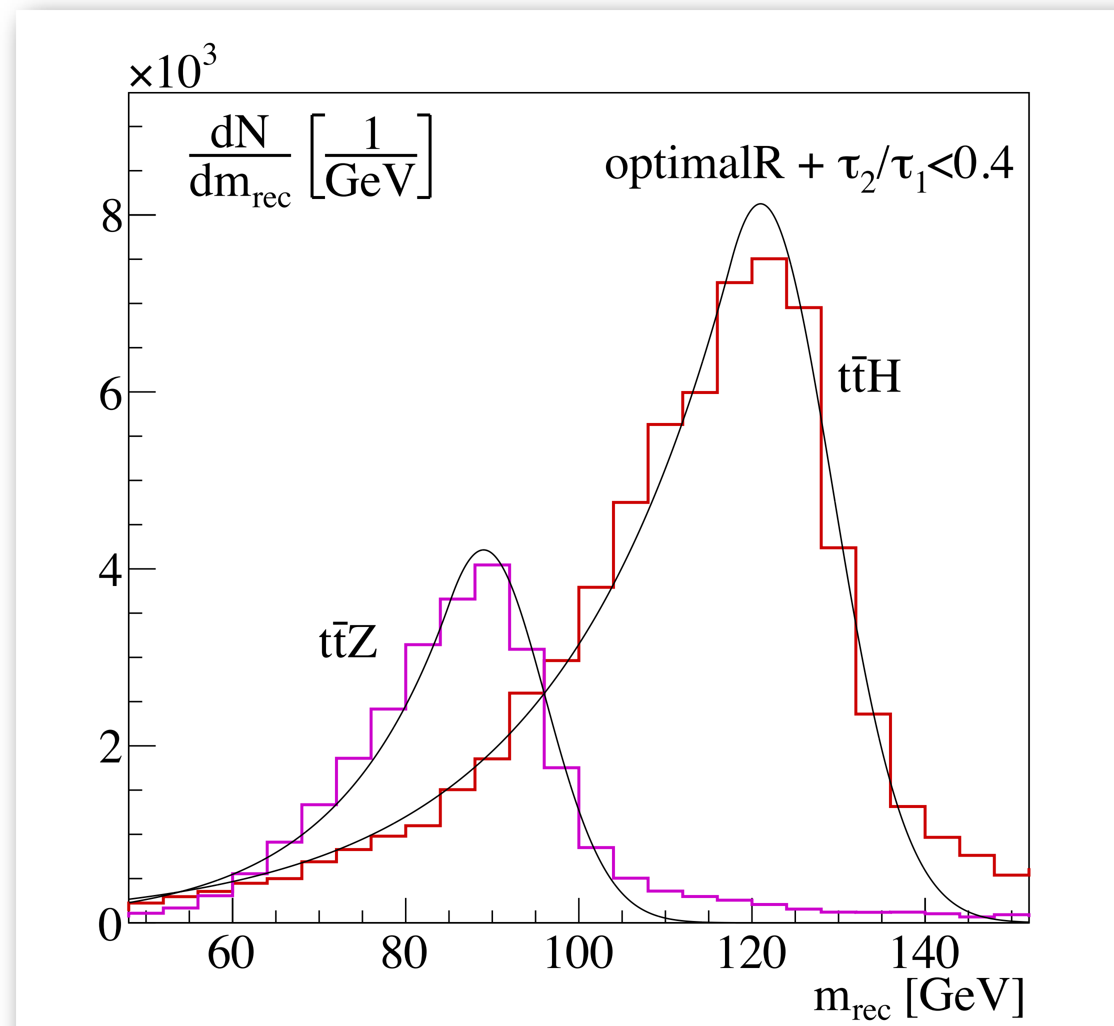
⇒ huge rates, exploit boosted topologies



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

Events/20ab^{-1} , with tt→$\ell\nu$+jets

⇒ huge rates, exploit boosted topologies



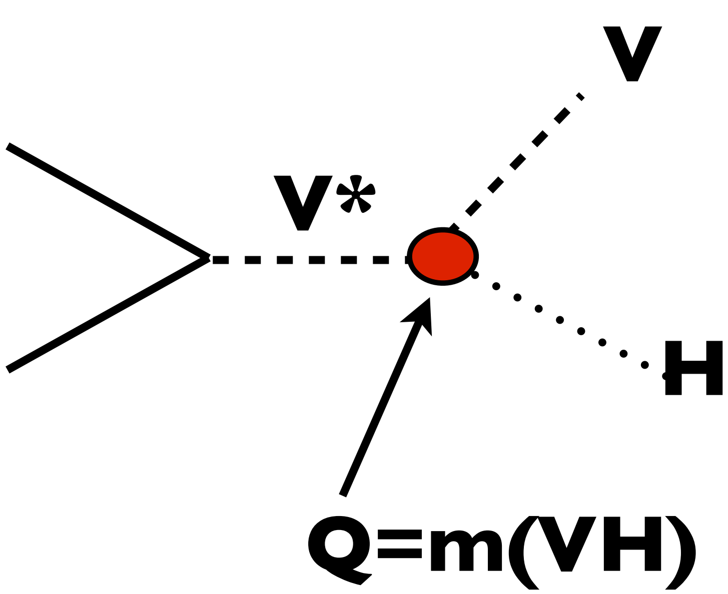
Top fat C/A jet(s) with R = 1.2, |y| < 2.5, and $p_{T,j}$ > 200 GeV

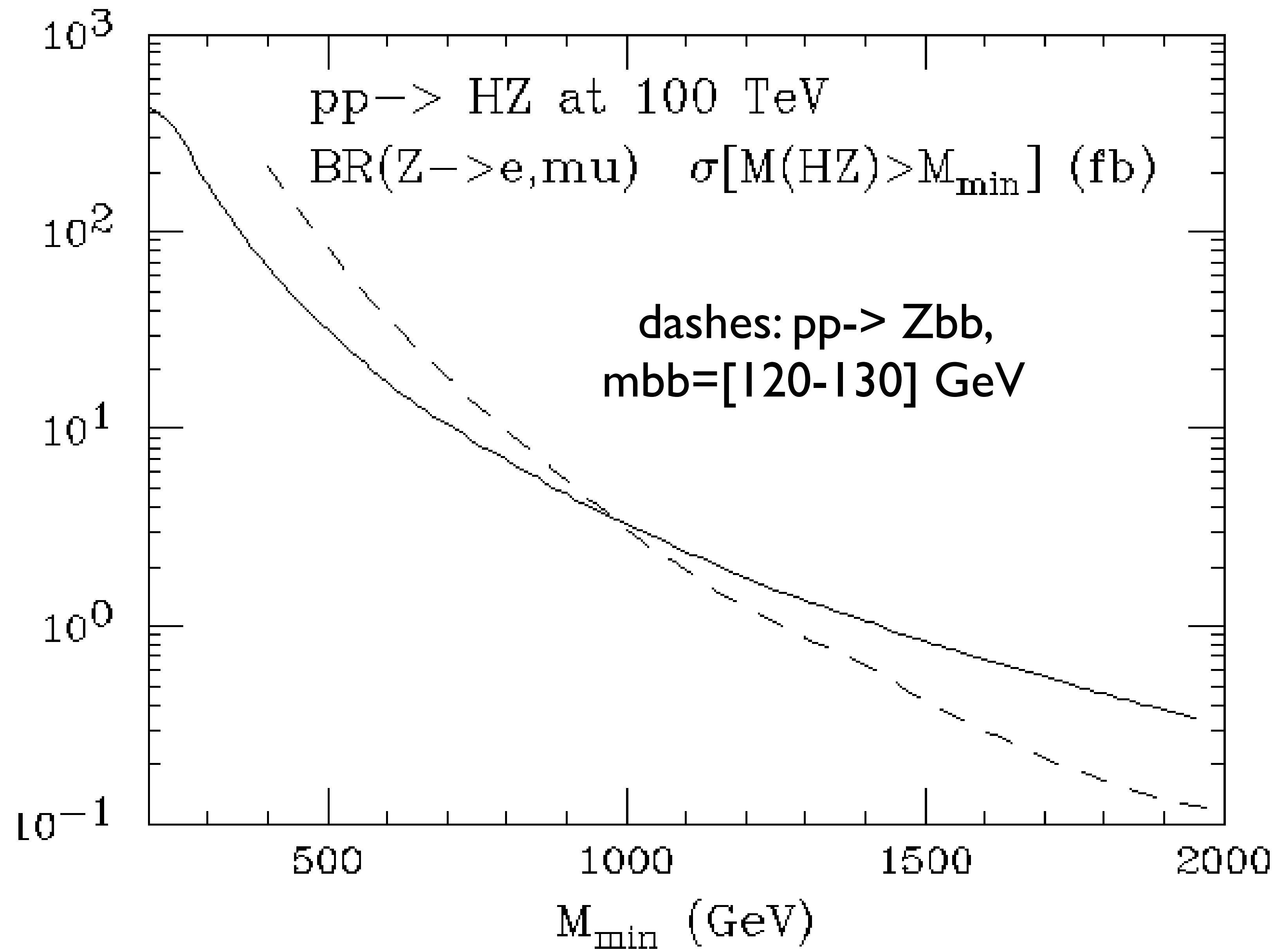
- δy_t (stat + syst $_{TH}$) ~ 1%

- great potential to reduce to similar levels $\delta_{\text{exp syst}}$
- consider other decay modes, e.g. 2l2nu

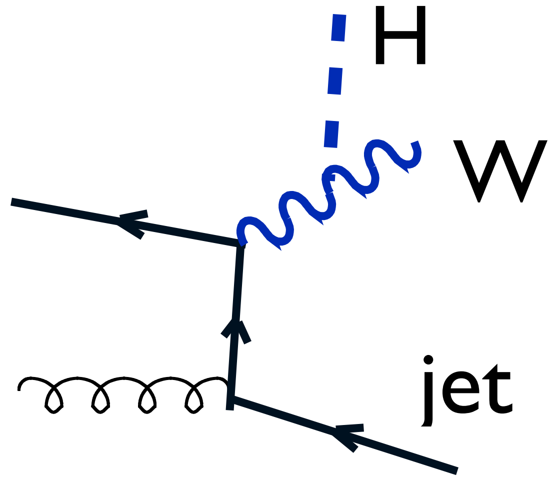
ZH at large mass

- Sensitivity to anomalous VVH couplings complementary to what given by high-precision B(H→VV) measurements ?
- Optimal use of boosted object tagging, to access both hadronic and leptonic W/Z decays, H→bb, etc,



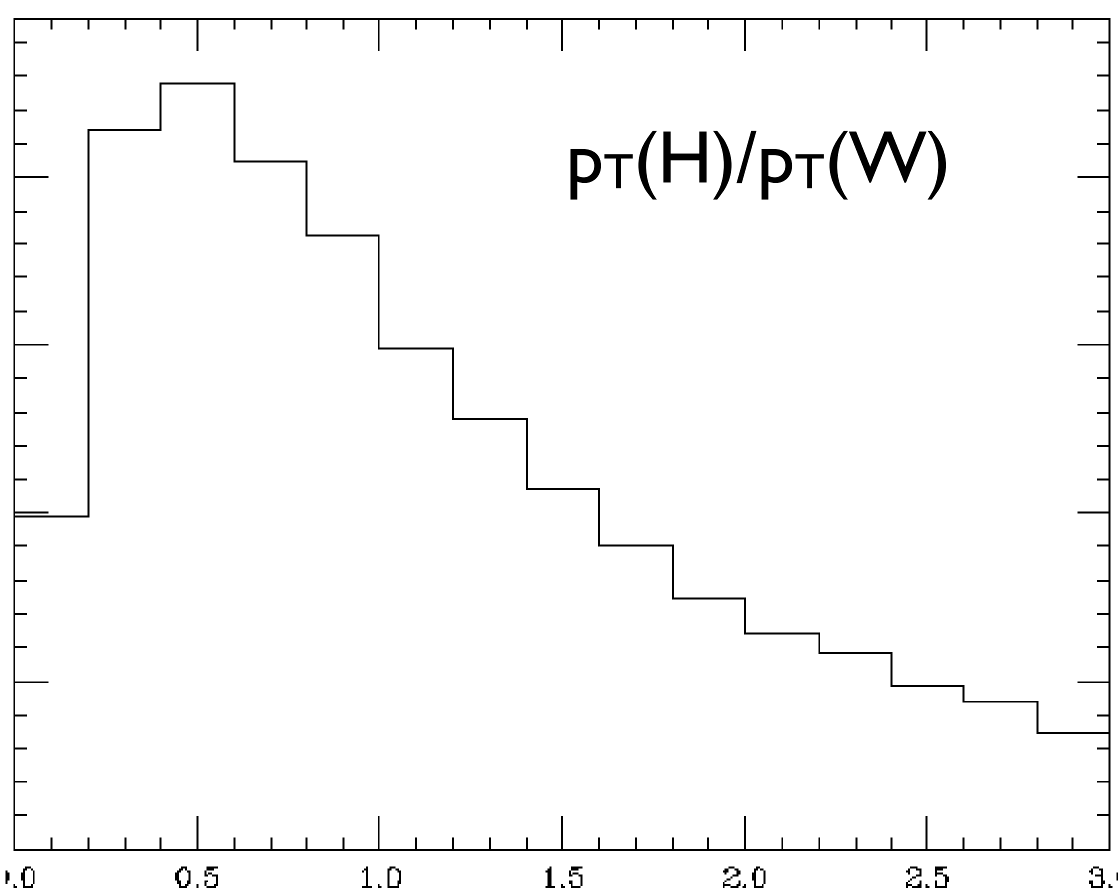


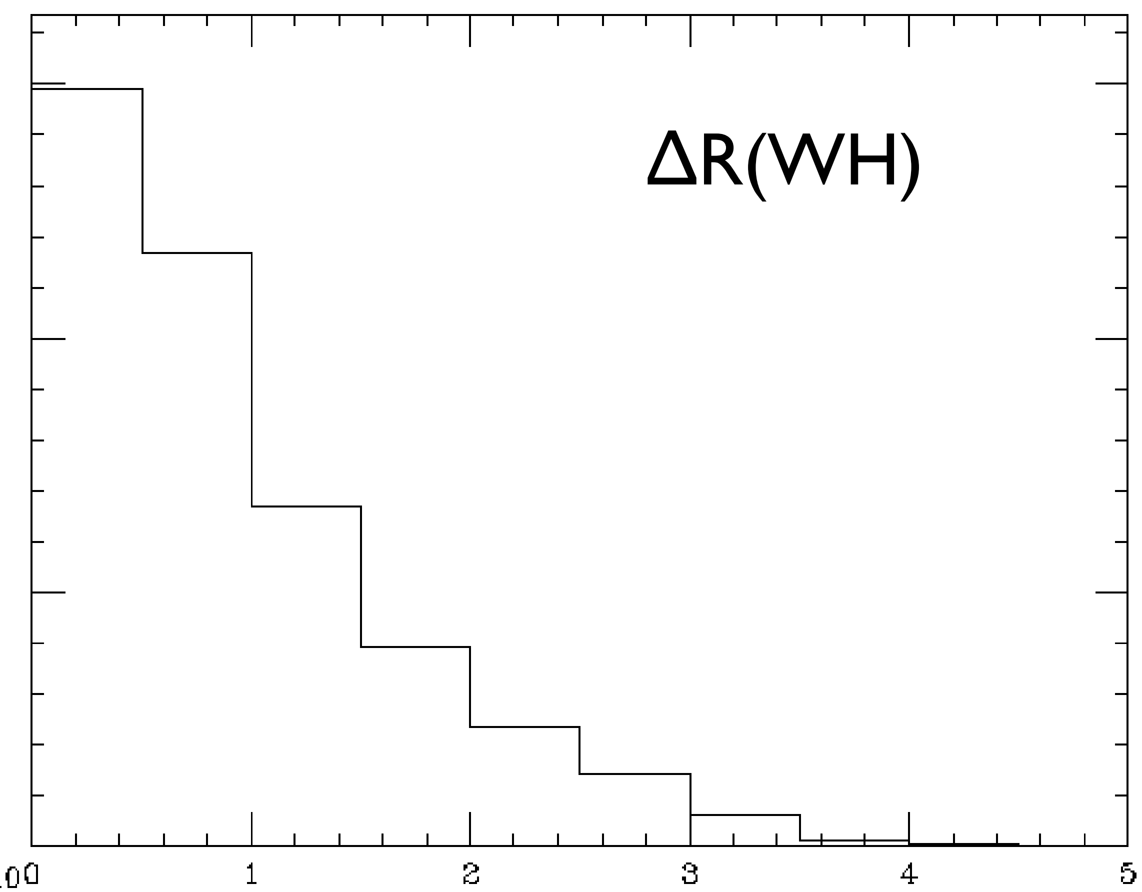
- At large p_T, important contribution from the following diagram:

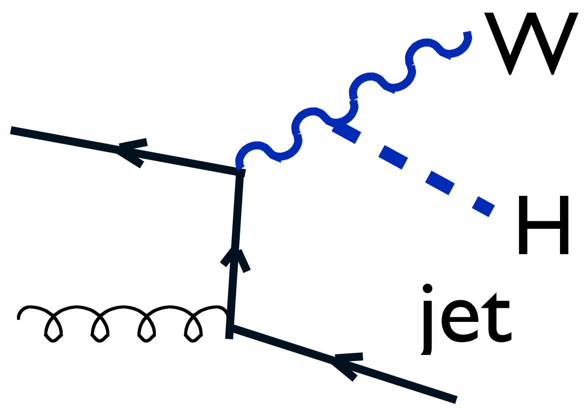


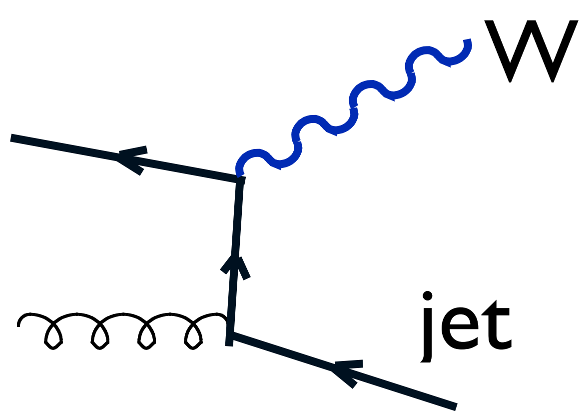
- Production in this kinematics tends to have small m(HW), and the WH system recoiling against the jet

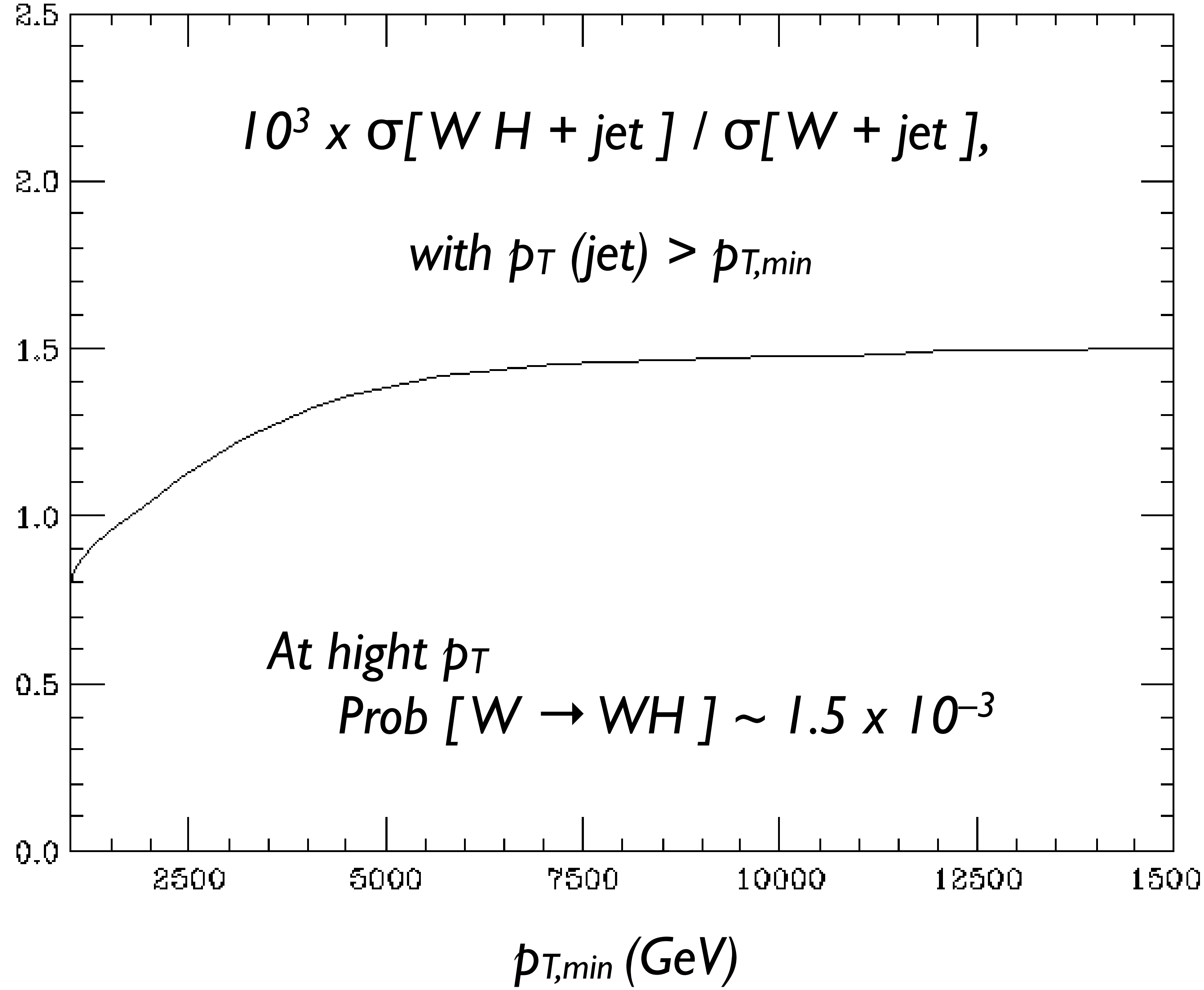
E.g for events with p_T(jet) > 1 TeV





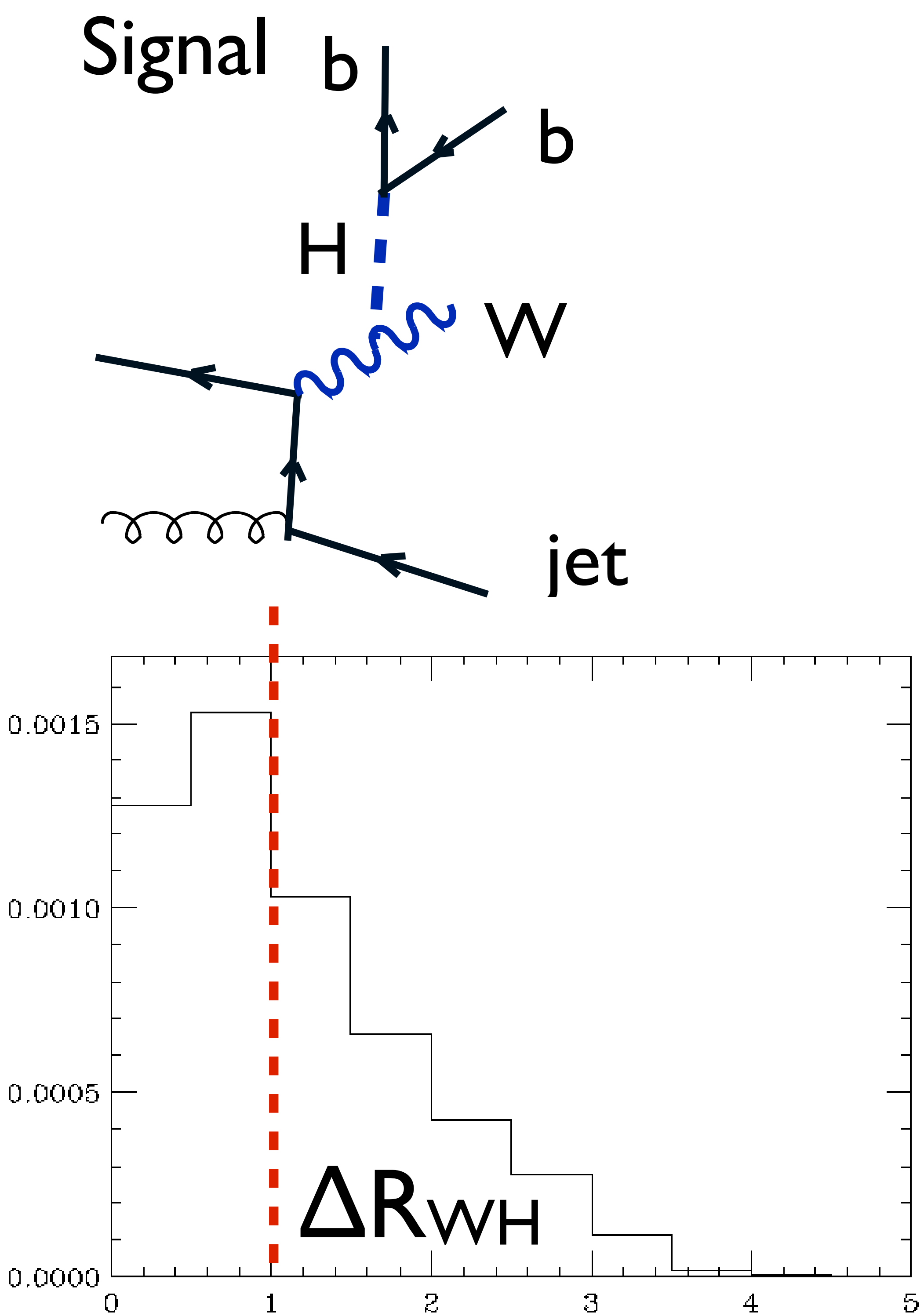

W
H
jet

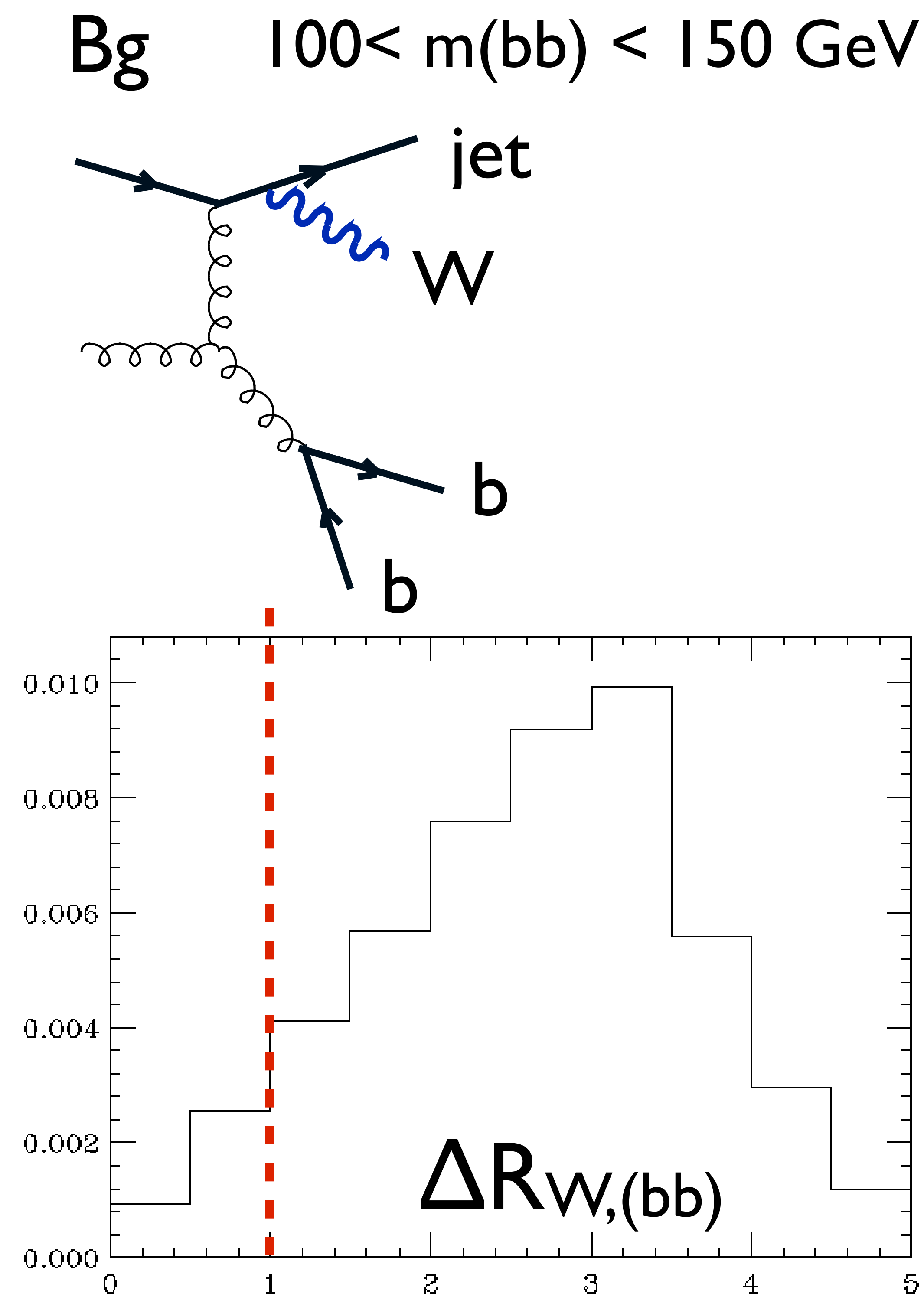

W
jet


10^3 x σ[W H + jet] / σ[W + jet],
with p_T (jet) > $p_{T,min}$
At hight p_T
Prob [W → WH] ~ 1.5 x 10^{-3}
2.5
2.0
1.5
1.0
0.5
0.0
2500
5000
7500
10000
12500
15000
$p_{T,min}$ (GeV)

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 !

Higgs selfcouplings: $pp \to HH$

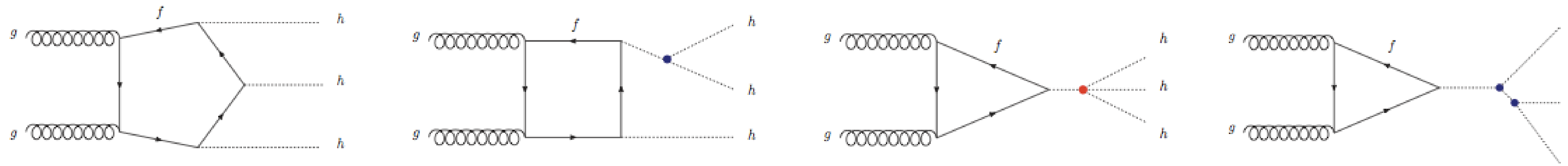
- $gg \to HH$ (most promising?) , $qq \to HHqq$ (via VBF)
- Reference benchmark process: $HH \to bb\ \gamma\gamma$
- Goal: 5% (or better) precision for SM selfcoupling

$HH \to b\bar{b}\gamma\gamma$	Barr,Dolan,Englert,Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren Yao arXiv:1506.03302
$FCC_{@100TeV}$ 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

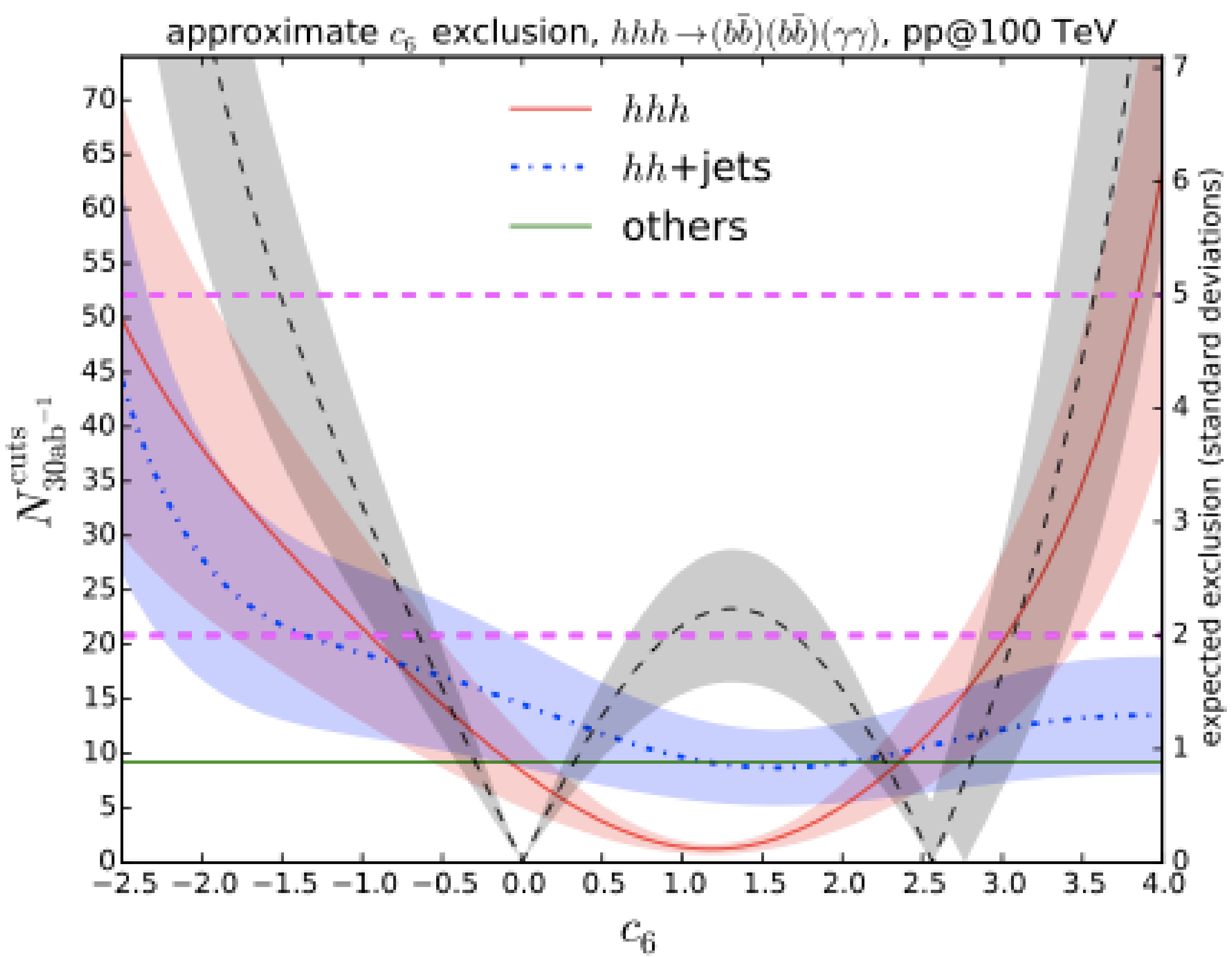
HHH production and quartic coupling constraints

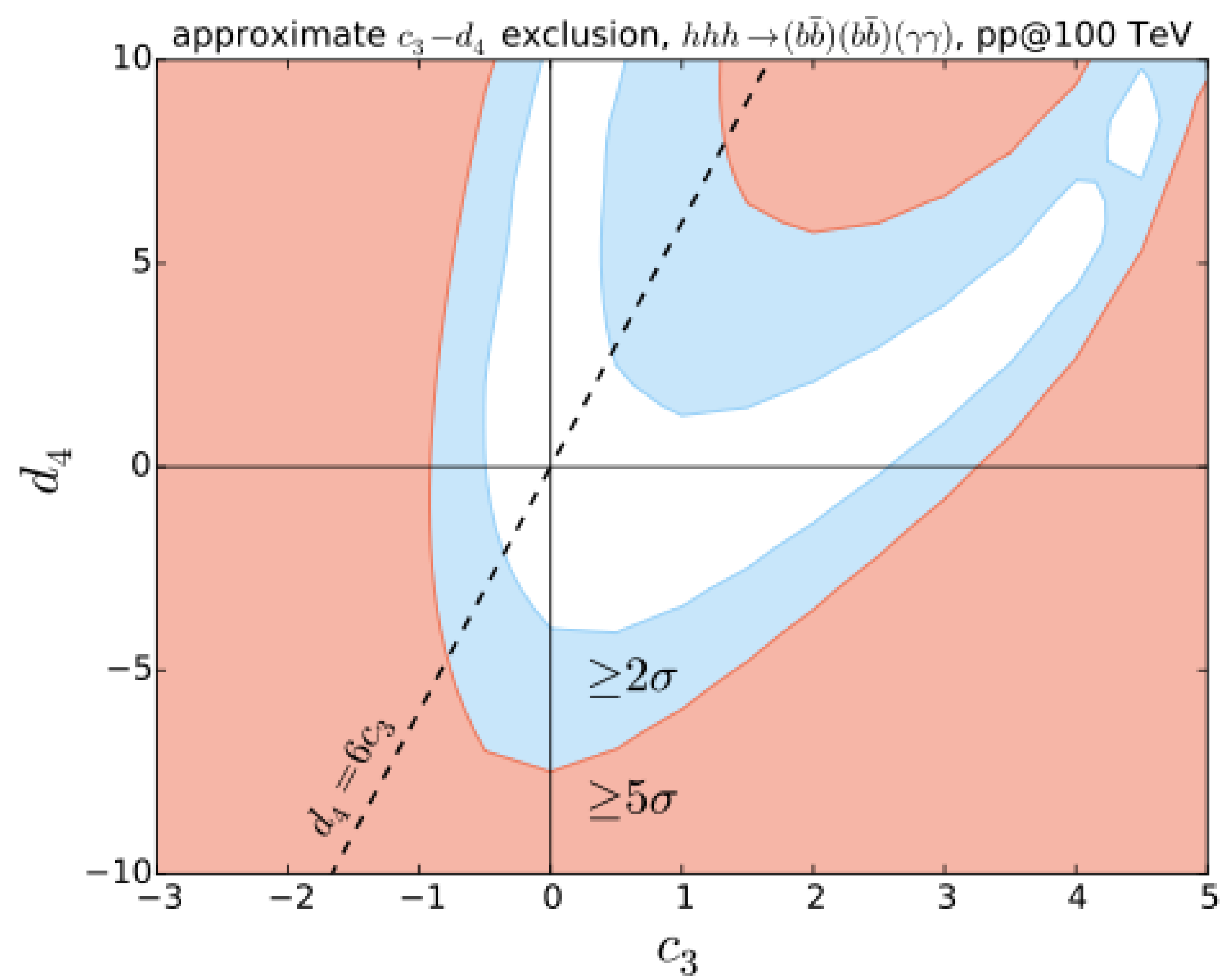
Papaefstathiou, Sakurai, arXiv:1508.06524



$$V_{\rm self} = \mu^2|H|^2 + \lambda|H|^4 + \mathcal{O}_6,\ \mathcal{O}_6 \equiv \frac{c_6}{\Lambda^2}\lambda|H|^6 \qquad \mathcal{V}_{\rm self} = \frac{m_h^2}{2v}(1+c_3)h^3 + \frac{m_h^2}{8v^2}(1+d_4)h^4 \qquad c_3 = c_6,\ d_4 = 6c_6$$

$$hhh \to (b\bar{b})(b\bar{b})(\gamma\gamma)$$





Rare production modes: any good use for them?

$pp \to HW^+W^-$ (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
$pp \to HW^\pm j$	$3.18 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-1\%}$	$1.07 \cdot 10^4\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	34
$pp \to HW^\pm jj$	$6.06 \cdot 10^1\ ^{+6\%}_{-8\%}\ ^{+1\%}_{-1\%}$	$4.90 \cdot 10^3\ ^{+2\%}_{-6\%}\ ^{+1\%}_{-1\%}$	81
$pp \to HZj$	$1.71 \cdot 10^2\ ^{+4\%}_{-4\%}\ ^{+1\%}_{-1\%}$	$6.31 \cdot 10^3\ ^{+2\%}_{-7\%}\ ^{+2\%}_{-1\%}$	37
$pp \to HZjj$	$3.50 \cdot 10^1\ ^{+7\%}_{-10\%}\ ^{+1\%}_{-1\%}$	$2.81 \cdot 10^3\ ^{+2\%}_{-5\%}\ ^{+1\%}_{-1\%}$	80

Table 1: Production of a single Higgs boson at the LHC and at a 100 TeV FCC-hh. The rightmost column reports the ratio ρ of the FCC-hh to the LHC cross sections. Theoretical uncertainties are due to scale and PDF variations, respectively. Monte-Carlo-integration error is always smaller than theoretical uncertainties, and is not shown. For $pp \to HVjj$, on top of the transverse-momentum cut of section 2, I require $m(j_1, j_2) > 100$ GeV, j_1 and j_2 being the hardest and next-to-hardest jets, respectively. Processes $pp \to Htj$ and $pp \to Hjj$ (VBF) do not feature jet cuts.

P.Torrielli, arXiv:1407.1623

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