Higgs Physics at FCC 100 TeV Collider

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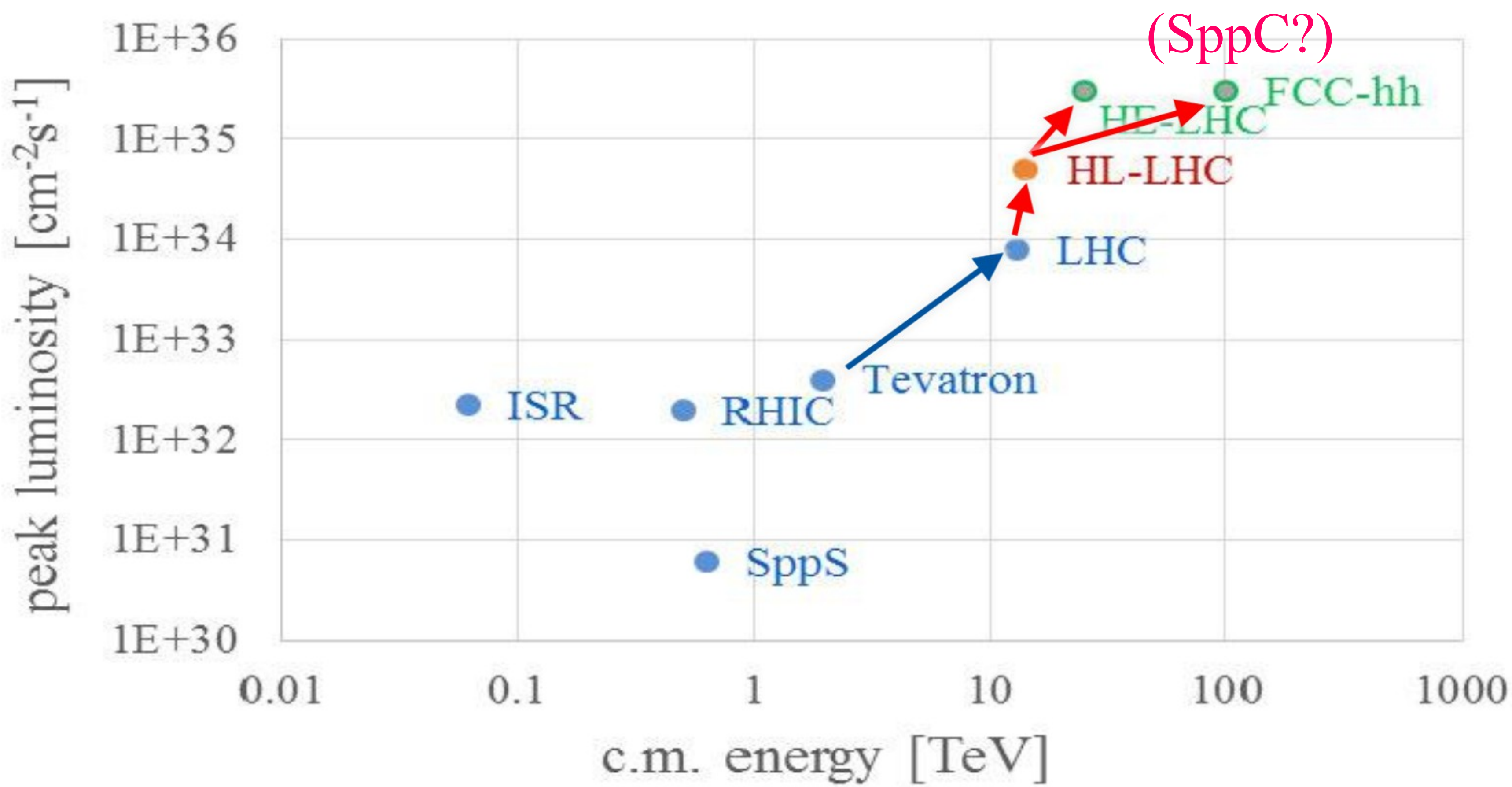
Future projects

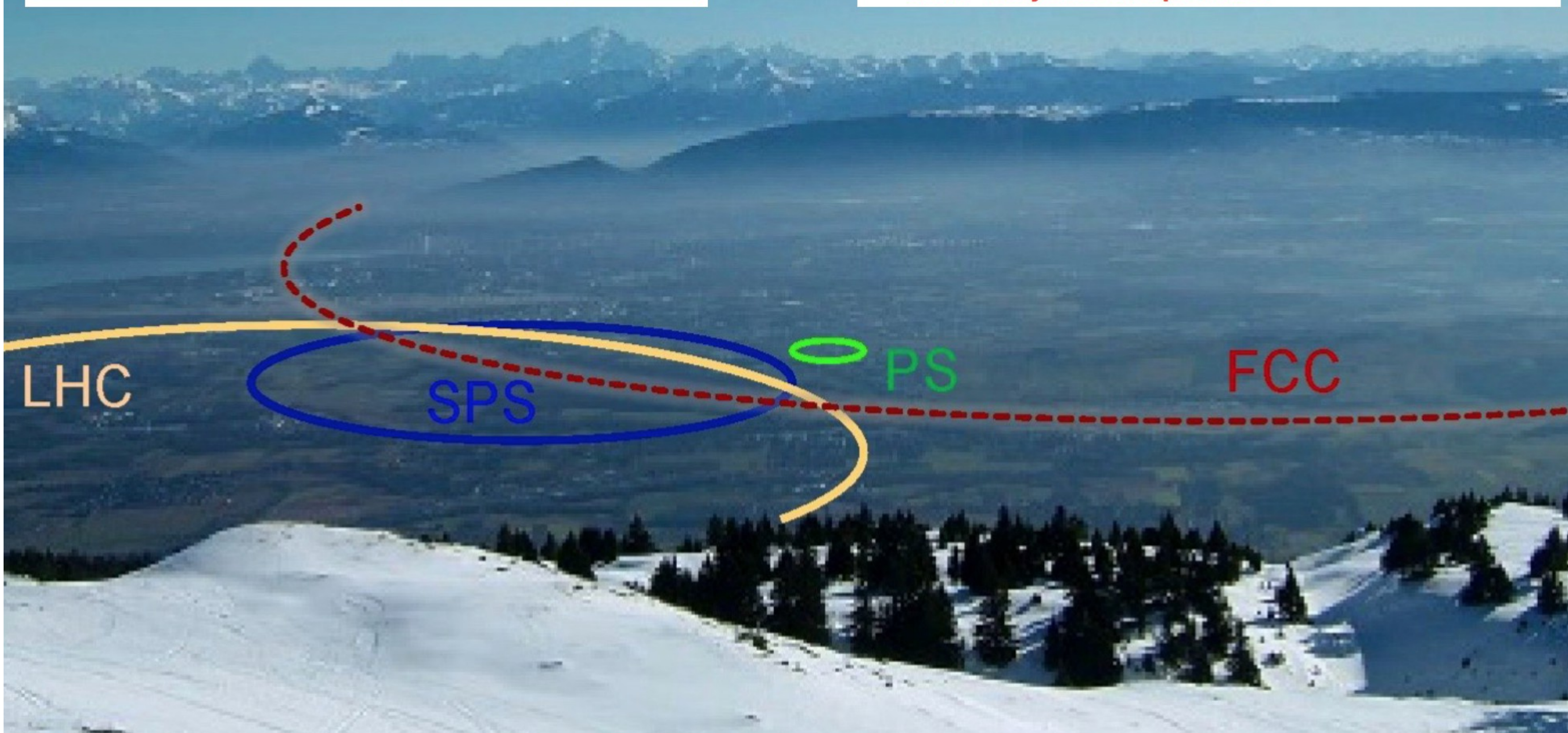


$E_{LHC} \sim \sqrt{(E_{Tevatron} * E_{FCC})}$

The FCC-hh Collider at 100 TeV

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**



Outline

- Physics case for a 100 TeV collider
- Precision Higgs physics including exotic & rare decays
- Discovery of extended Higgs Sectors
- Double-Higgs production
- Conclusion

Disclaim:

- Talk is based on FCC document on "Higgs and EWSB studies"
- Studies contributed by many people
- Some of slides are borrowed from Mangano's ICHEP 2016 talk

Higgs and EWSB Studies at 100TeV

- Not conclusive result, rather starting point for study of FCC physics.
- Providing some initial guide for the detector design.
- Total 187 pages! (1606.0940v1)

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

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Abstract
This report summarises the physics opportunities for the study of Higgs bosons and the dynamics of electroweak symmetry breaking at the 100 TeV *pp* collider.

The Contents

- Study of single-Higgs production modes, cross section predictions
- Prospects for precision measurements of Higgs couplings
- Multi-Higgs production and measurement of the trilinear Higgs self-coupling
- Extended Higgs sectors in BSM theories

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Higgs physics at 100 TeV

- Providing an energy frontier as well as intensity frontier experiment.
- Discovery of extended Higgs sectors >1Tev(EWPT, DM, Naturalness)
- Huge number of Higgs bosons produced (10Billions), two order of magnitude increase with respect to HL-LHC.
- VBF, ttH and other rare processes become more important.

	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

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

$N_{14}=\sigma_{14TeV}*3ab^{-1}$

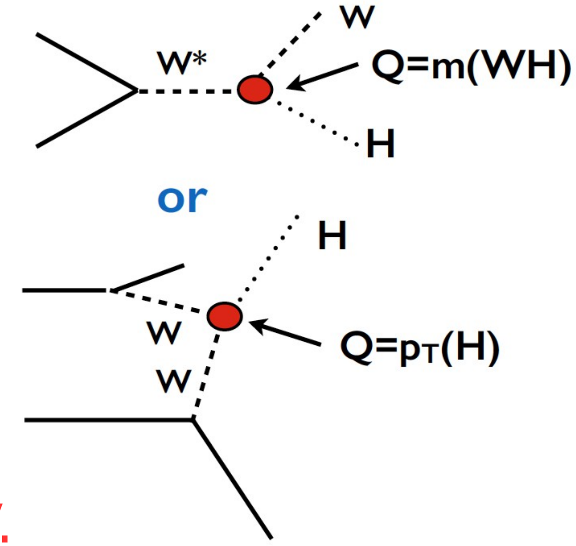
$N_8=\sigma_{8TeV}*20\ fb^{-1}$

Table 20: Indicative total event rates at 100 TeV (N_{100}), and statistical increase with respect to the statistics of the LHC run 1 (N_8) and the HL-LHC (N_{14}), for various prodution channels. We define here $N_{100} = \sigma_{100\ TeV} \times 20\ \text{ab}^{-1}$, $N_8 = \sigma_{8\ TeV} \times 20\ \text{fb}^{-1}$, $N_{14} = \sigma_{14\ TeV} \times 3\ \text{ab}^{-1}$.

Higgs as a Probe for High Mass Scale (λ)

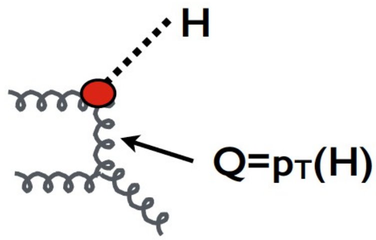
- For BSM EFT, $\mathcal{L} = \mathcal{L}_{SM} + 1/\lambda^2 * \sum O_k + \ldots$ where λ is the cut off scale
- Any observable: $O=|\langle f|\mathcal{L}|i\rangle|^2=O_{SM}(1+O(\mu^2/\lambda^2)+\ldots)$, $\mu=m_H,\nu,Q$
- $\delta O \sim (\nu/\lambda)^2 \sim 6\%(\text{TeV}/\lambda)^2 \sim 1\% \Rightarrow \lambda > 2.5$ TeV.

$\delta BR(H \rightarrow WW^*)$



- $\delta O \sim (Q/\lambda)^2 \sim 15\%$ up to Q=1TeV $\Rightarrow \lambda > 2.5$ TeV.

$\delta BR(H \rightarrow gg)$



H at large Pt

- Sensitive to different Higgs production process directly.
- Hierarchy of production channels changes at large Pt(H)
  - Pt>800 GeV: σ(tth) > σ(gg→H); Pt>1.8TeV: σ(VBF) > σ(gg→H)

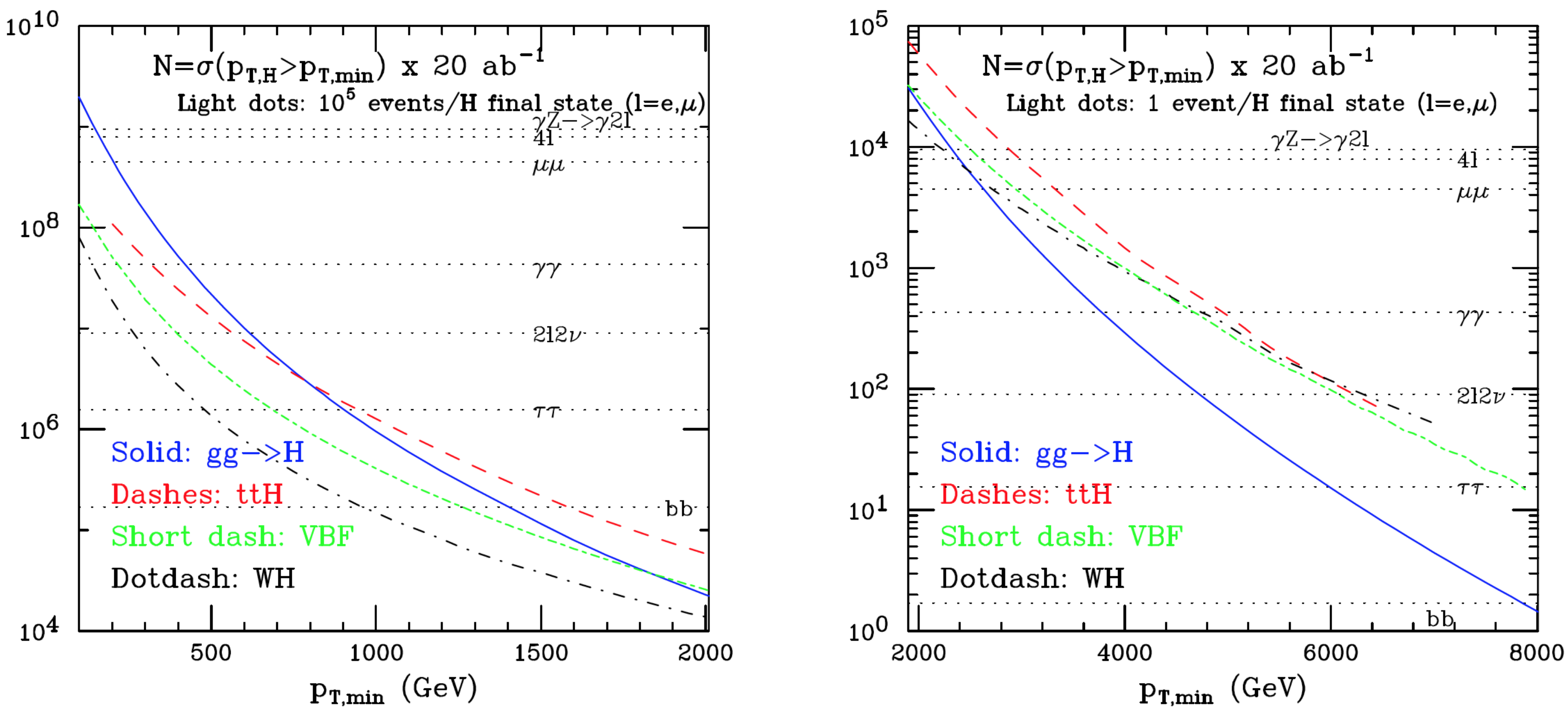


Fig. 40: Integrated Higgs transverse momentum rates, for various production channels, with 20 ab^{-1}. The light-dotted horizontal lines in the left (right) panel correspond to the production of 10^5 (10) events with a Higgs decay to the indicated final states.

gg→H→γγ at large Pt

- With more statistics, we can focus in the semi-boosted region where the backgrounds are smaller, which could improve sensitivities.
- Pt(H)>300 GeV, S/B~1, very clean probe of Higgs up to large Pt.

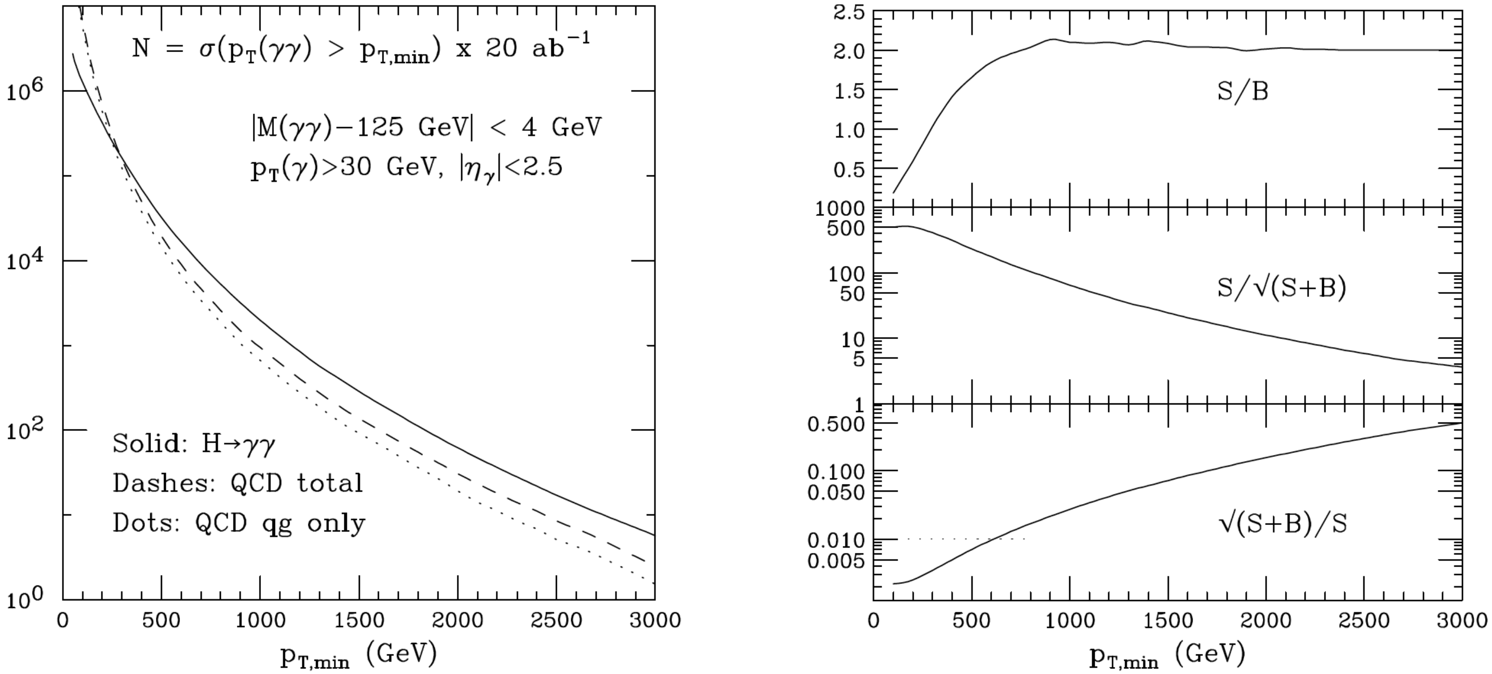


Fig. 45: Left: Integrated transverse momentum rates (20 ab^{-1}) for a photon pair with mass close to the Higgs mass: signal and QCD background. Right: S/B, significance of the signal, and potential statistical accuracy of the sample.

gg→H→μμ at large Pt

- Start reach ~ 1% for Pt(H→μμ)>100 GeV
- Reduce systematics on Br(H→μμ)/Br(H→γγ) by using same fiducial cuts.

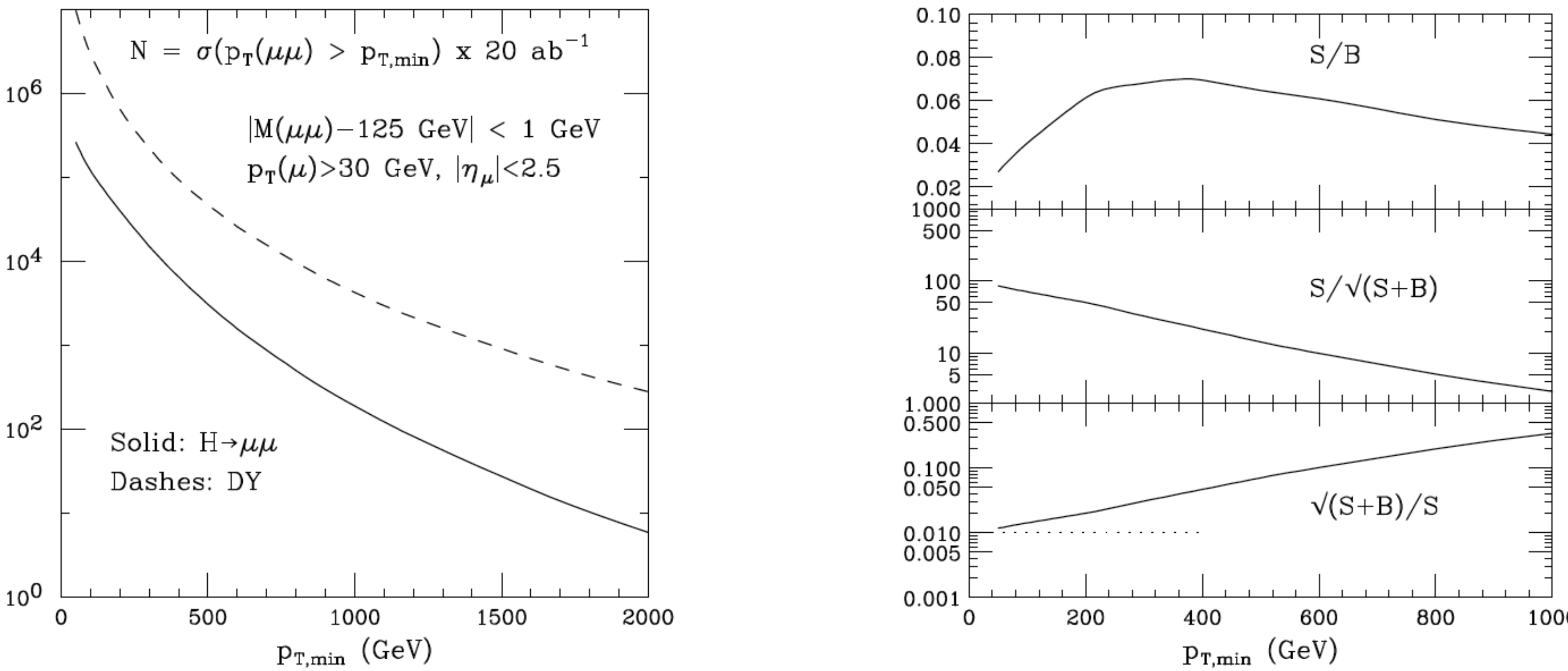
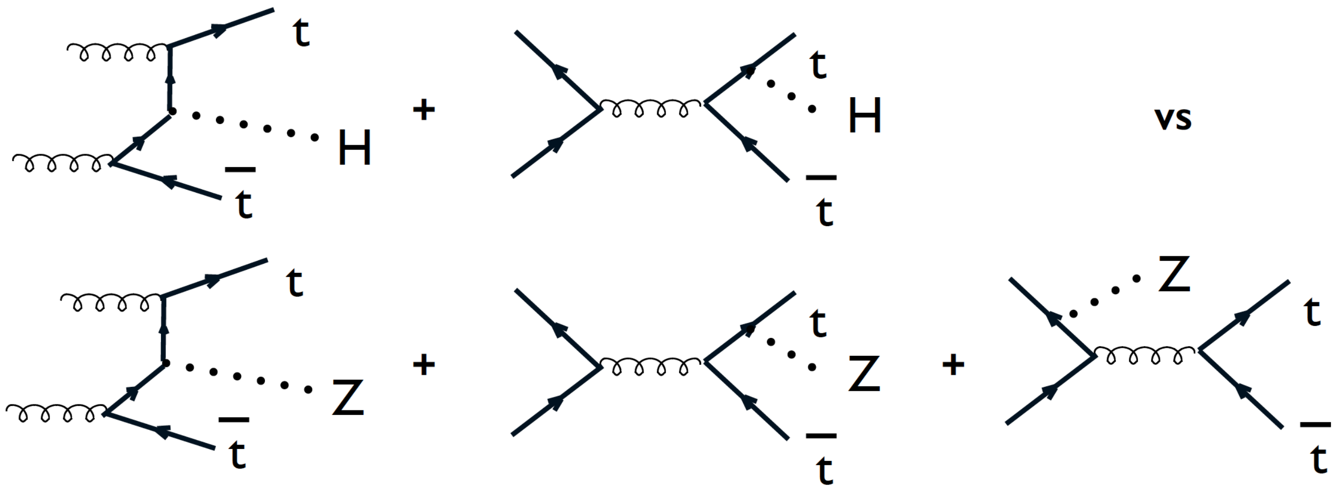


Fig. 46: Left: Integrated transverse momentum rates (20 ab^{-1}) for a muon pair with mass close to the Higgs mass: signal and DY background. Right: S/B, significance of the signal, and potential statistical accuracy of the sample.

Top Yukawa y_{top} from $\sigma(ttH)/\sigma(ttZ)$



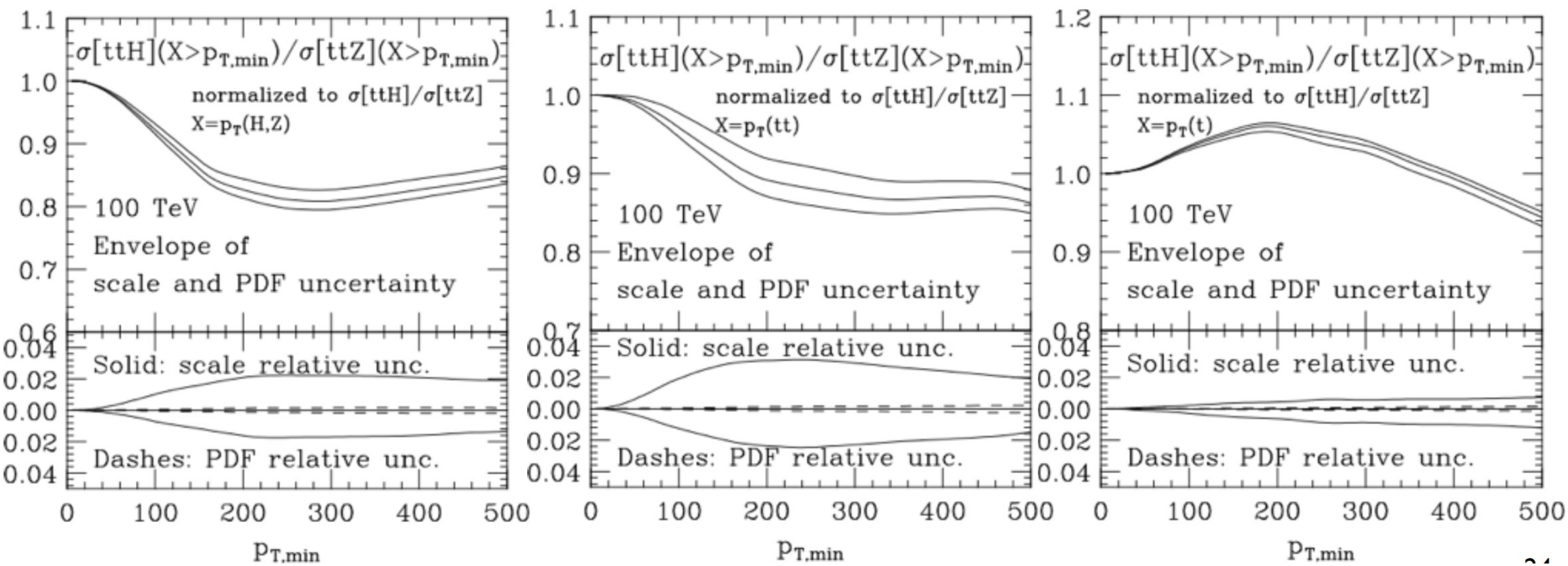
- Identical production dynamics
  - Correlated QCD corrections, correlated scale dependence
  - Correlated αs systematics
- mZ~mH: expect almost identical kinematic boundaries
  - Correlated PDF systematics
  - Correlated Mtop systematics
- For a given y_{top}, the ratio $\sigma(ttH)/\sigma(ttZ)$ is well predicted.

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	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

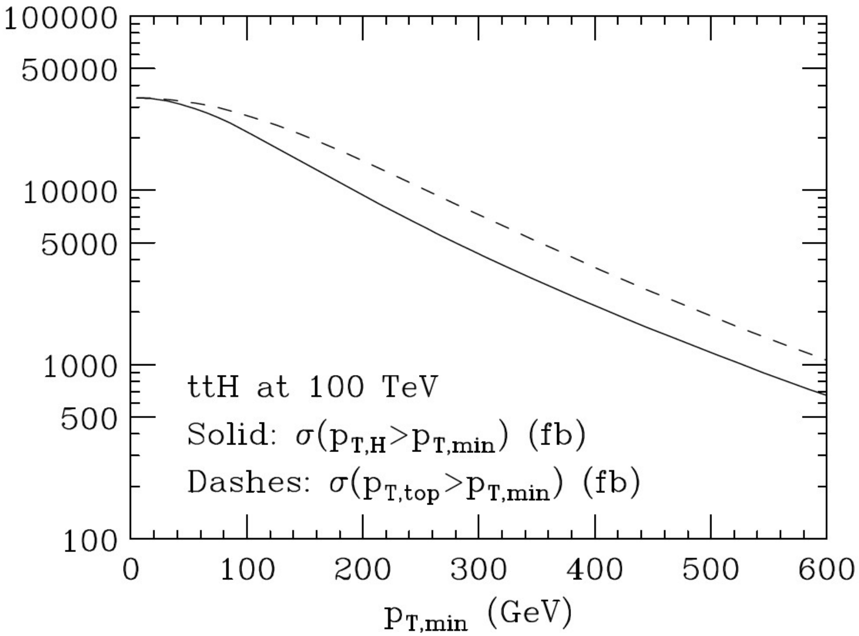
scale PDF

Production kinematics ratio stability



Top Yukawa y_{top} Sensitivity

MLM, Plehn, Reimitz, Schell, Shao 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

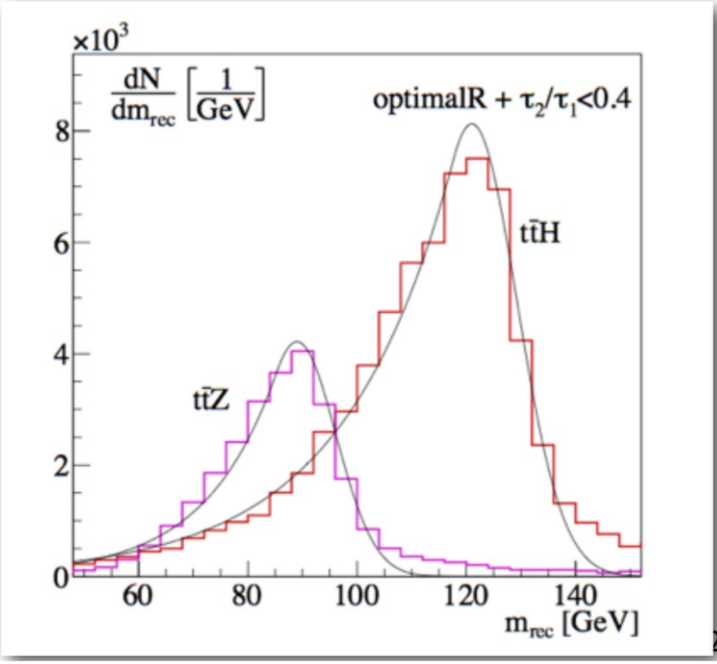
⇒ huge rates, exploit

boosted topologies

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

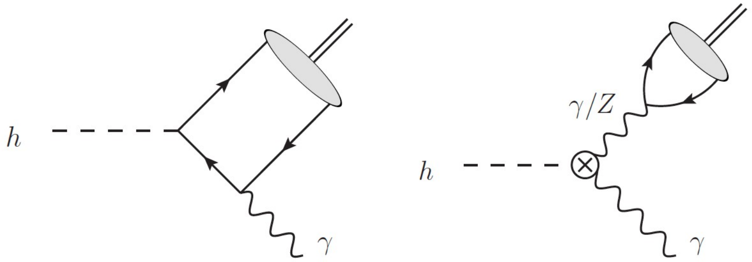
- δy_t (stat + syst $_{TH}$) ~ 1%

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



Rare Higgs decays

- Exclusive modes: BR(H→Vγ)~10^{-6} (V = vector meson) , allow extraction of Yukawa couplings to first 2 quark generations.
  (Bodwin et al PRD 88(2013) 053003, Kagan et al PRL 114(2015) 101802)
  - H → J/Ψ γ (y_c)
  - H → Φ γ (y_s)
  - H → ρ γ ($y_{u,d}$)



- Limits on H→ J/Ψ γ from LHC:
  - Current @ LHC 8 TeV 20 fb^{-1} <$1.5x10^{-3}$
  - LHC @14 TeV 300 fb^{-1} < 150 $x10^{-6}$
  - HL-LHC @14 TeV 3 ab^{-1} <$45x10^{-6}$

- FCC 100 TeV seems able to reach ~10^{-6}, close to SM value with 100 times increases in number of events with respect to the HL-LHC.

Search for Extended Higgs Sectors

- FCC 100 TeV offers unique opportunity to search for extended Higgs sector, which is a prediction of many BSM scenarios.
- They may play a role in the following open questions
  - (EW) Baryogenesis: Modified scalar potential can lead to a first order EW phase transition (EWPT).
  - Identity of Dark Matter
    - Scalar DM with TeV mass
    - Scalar mediators in hidden sector
    - DM coupled to Higgs portal
  - Smallness of the neutrino masses
    - Type-II see-saw through extra scalars
  - Naturalness of the EW scale
    - Extended scalar sectors follows in natural theories
    - SUSY
    - Neutral Naturalness

New analysis of HH production for the FCC report

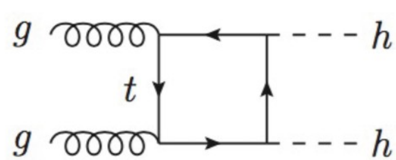
R.C., C. Englert, G. Panico, A. Papaefstathiou, J. Ren, M. Selvaggi, M. Son, M. Spannowsky, W. Yao

- Goals:
  1. improve on previous studies and get a commonly-agreed estimate
  2. study dependence on efficiencies and systematics

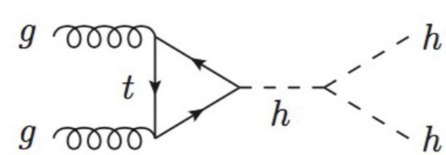
Previous analyses:

W. Yao arXiv:1308.6302 (Snowmass Summer Study 2013)
Barr, Dolan, Englert, de Lima, Spannowsky JHEP 1502 (2015) 016
Azatov, R.C., Panico, Son PRD 92 (2015) 035001
H-J. He, J. Ren, W. Yao PRD 93 (2016) 015003

Signal: double Higgs production via gluon fusion ($gg \to hh$)



$\sim const.$



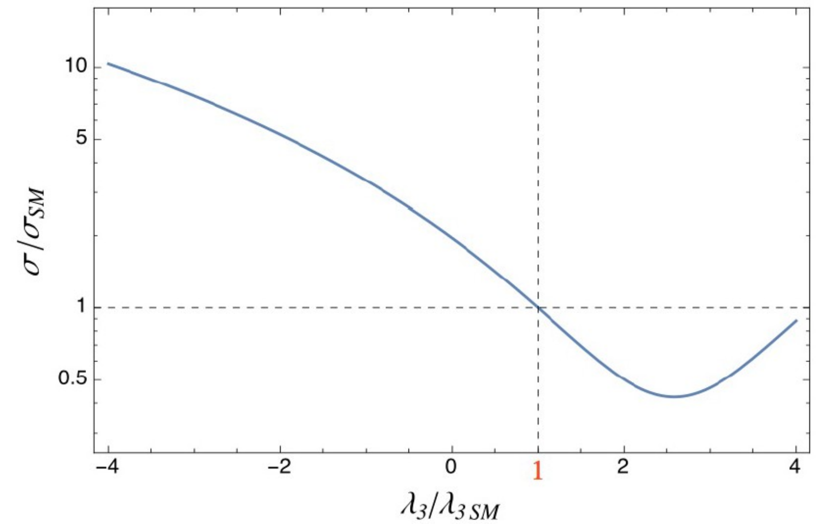
$$\sim \lambda_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$$

→ Most sensitivity on trilinear coupling comes from threshold events

	Signal cross section [fb] at NNLO+NNLL *
14 TeV	$45.05^{+4.4\%}_{-6.0\%} \pm 3.0\% \pm 10\%$
100 TeV	$1749^{+5.1\%}_{-6.6\%} \pm 2.7\% \pm 10\%$

$\sim 40\times$ increase

Theoretical uncertainties: scale, PDFs $+\alpha_s$, infinite m_t approx.



	# Higgs pairs to bbγγ
LHC: 14TeV 300fb^{-1}	36
HL-LHC: 14TeV 3ab^{-1}	360
FCC: 100TeV 20ab^{-1}	92 x 10^3

percent precision physics

Backgrounds:

$b\bar{b}\gamma\gamma$

$t\bar{t}h(\gamma\gamma)$

$b\bar{b}h(\gamma\gamma)$

$jj\gamma\gamma$ (two fake b-jets)

$b\bar{b}j\gamma$ (one fake photon)

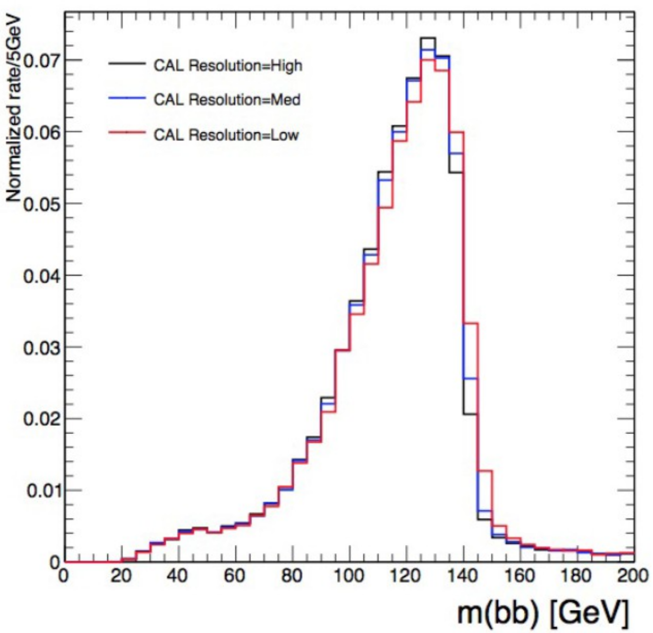
* Results of the recent full-m_{top} NLO calculation (Borowka et al, arXiv: 1604.06447) not included here (as yet….)

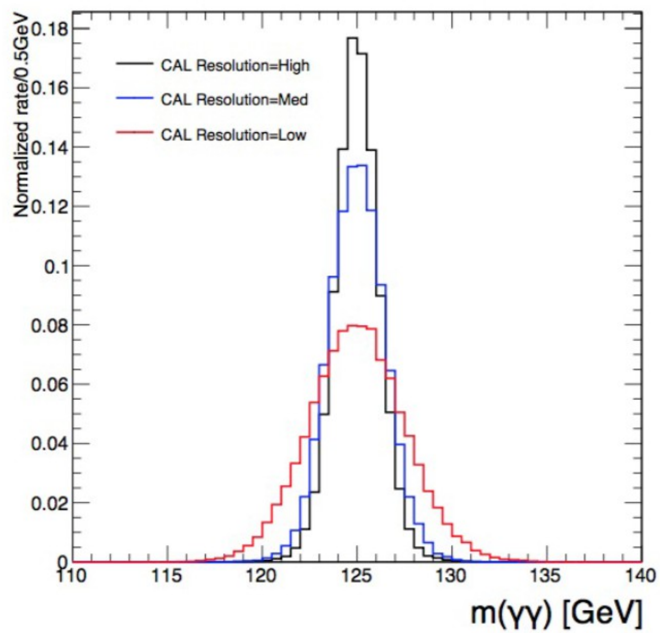
Montecarlo Simulation: MadGraph5_aMC@NLO ⟶ Pythia 6 ⟶ Delphes (FCC card)

Three benchmark scenarios for ECAL and HCAL resolution:

$$\Delta E = \sqrt{a^2 E^2 + b^2 E}$$

	ECAL				HCAL			
	$\lvert\eta\rvert \leq 4$		$4 < \lvert\eta\rvert \leq 6$		$\lvert\eta\rvert \leq 4$		$4 < \lvert\eta\rvert \leq 6$	
	a	b	a	b	a	b	a	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





High
$\Delta m(\gamma\gamma) = 1.5\,\mathrm{GeV}$

Med
$\Delta m(\gamma\gamma) = 2.0\,\mathrm{GeV}$

Low
$\Delta m(\gamma\gamma) = 3.0\,\mathrm{GeV}$

Analysis Strategy of HH → bbγγ

- Interested in events at threshold, no boosted techniques needed.
- Optimize cuts to maximize sensitivity on trilinear coupling not xsec.
- Event selections:
  - Two isolated photons, |eta|<4.5, Pt(1)>60 GeV, Pt(g2)>35 GeV
  - Jets anti-kt with cone 0.4, |eta|<4.5, pt(b1)>60, pt(b2)>35 GeV
  - |mgg -mh|<2.0, 3.0, 4.5 for high/med/low scenarios
  - Pt(bb), Pt(gg)>100 GeV, DeltaR*bb), DeltaR(gg)<3.5

Process	Acceptance cuts [fb]	Final selection [fb]	Events ($L = 30$ ab^{-1})
$h(b\bar{b})h(\gamma\gamma)$ (SM)	0.73	0.40	12061
$bbj\gamma$	132	0.467	13996
$jj\gamma\gamma$	30.1	0.164	4909
$t\bar{t}h(\gamma\gamma)$	1.85	0.163	4883
$b\bar{b}\gamma\gamma$	47.6	0.098	2947
$b\bar{b}h(\gamma\gamma)$	0.098	7.6×10^{-3}	227
$bj\gamma\gamma$	3.14	5.2×10^{-3}	155
Total background	212	1.30	27118

S/B=0.45
S/sqrt(S+B)=61.

- overall rescaling of background rate $n_B \to r_B \times n_B$
- uncertainty on signal rate $\Delta_S = \dfrac{\Delta\sigma(pp \to hh)}{\sigma(pp \to hh)}$

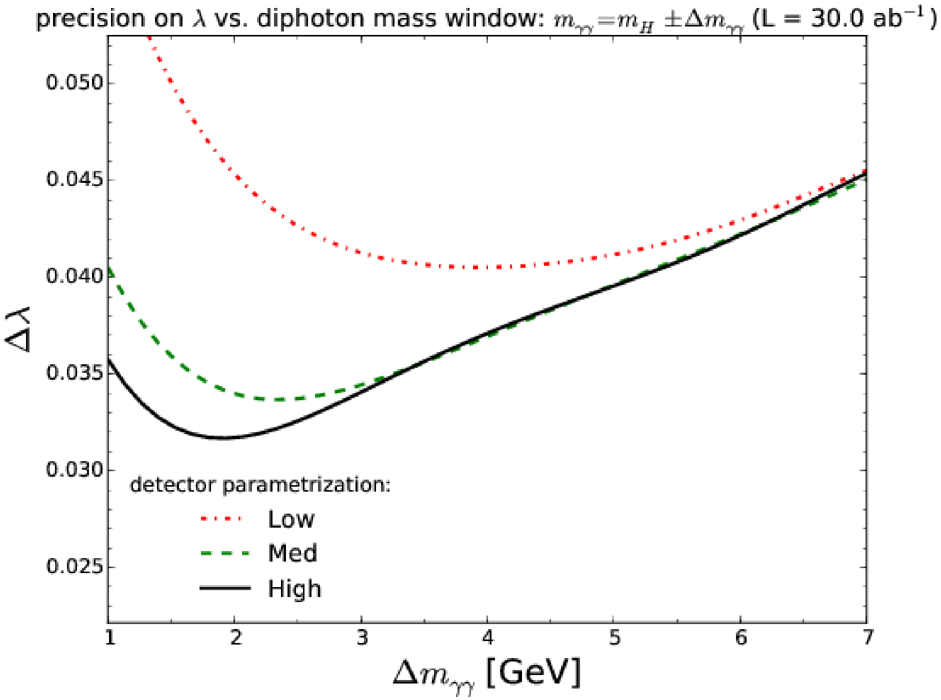
using "medium" calorimeter resolution

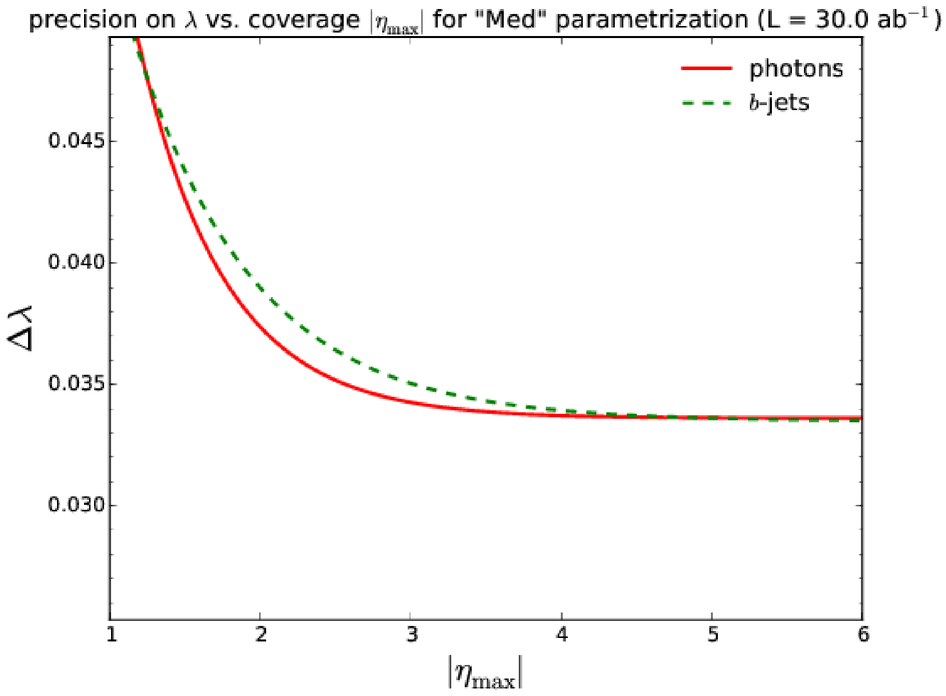
$\Delta\lambda_3$	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$	$\Delta_S = 0.025$
$r_B = 0.5$	2.7%	3.4%	4.1%	4.9%	5.8%
$r_B = 1.0$	3.4%	3.9%	4.6%	5.3%	6.1%
$r_B = 1.5$	3.9%	4.4%	5.0%	5.7%	6.4%
$r_B = 2.0$	4.4%	4.8%	5.4%	6.0%	6.8%
$r_B = 3.0$	5.2%	5.6%	6.0%	6.6%	7.3%

For $\Delta_S \gtrsim 2.5\%$ the precision on λ_3 is dominated by the theory error on the signal: $\Delta\lambda_3 \simeq 2\Delta_S$

Higgs-self Coupling Sensitivity

- Study Higgs-self coupling vs di-photon mass: significant gain from low to Med, small change from Med to High
- Most signal are central, no significant gain beyond |eta|>3.5 GeV.

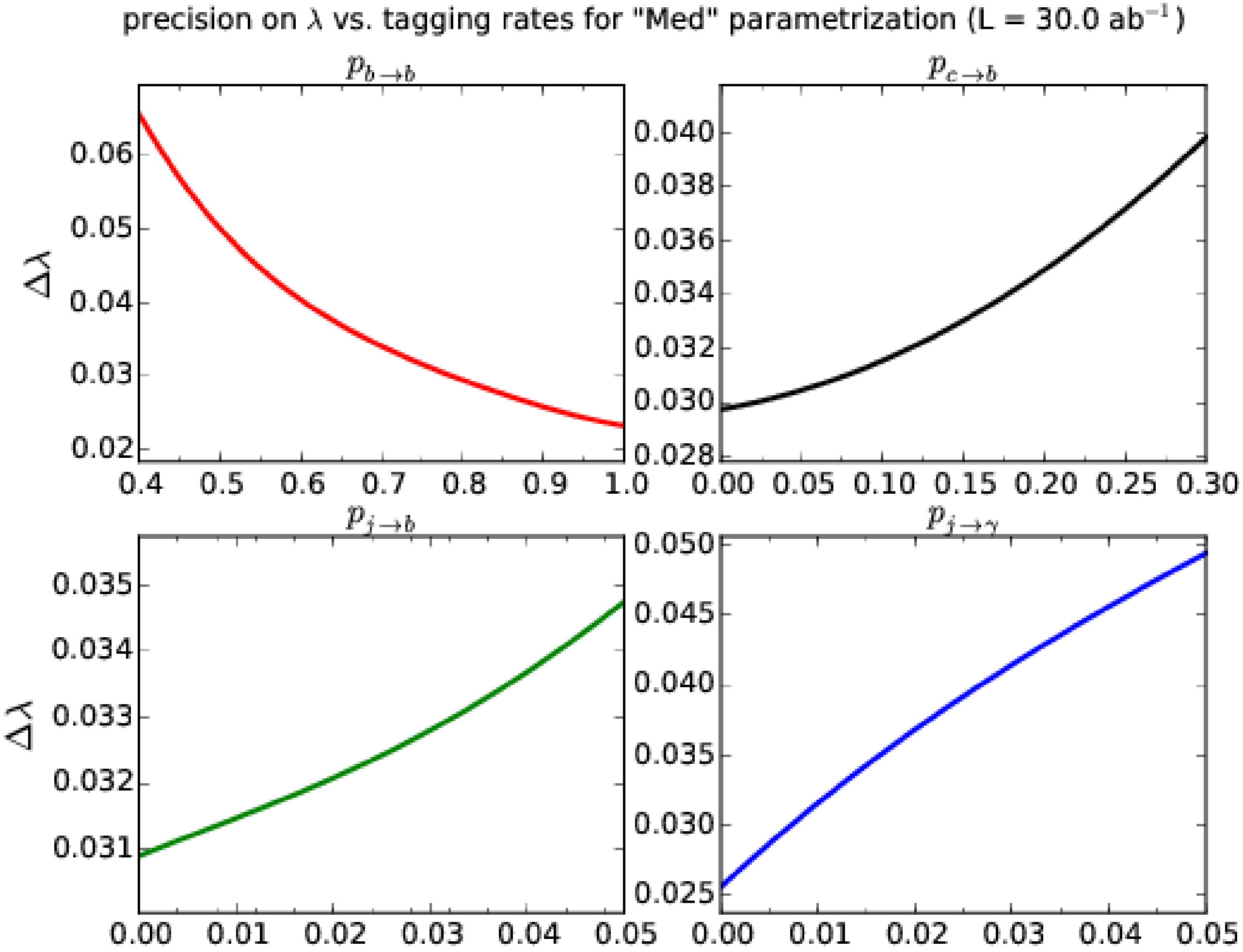




Higgs-self Coupling Precision

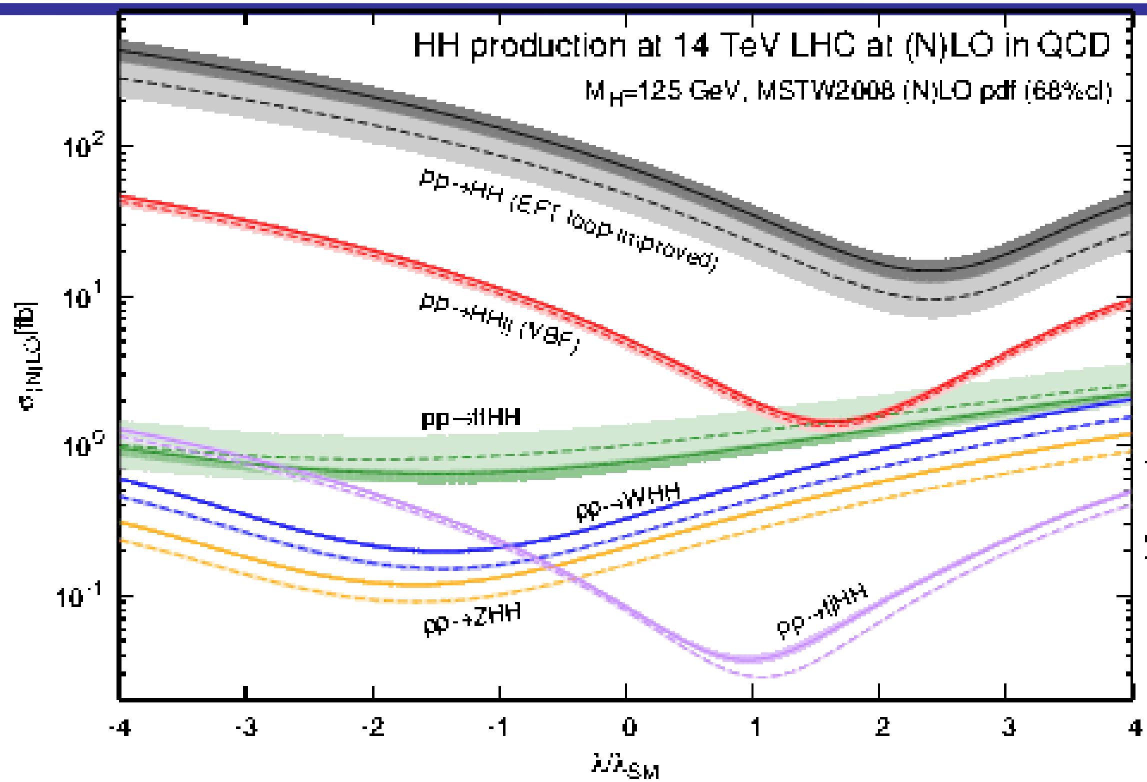
•Checked the Higgs-self coupling vs tagging rates (Med+30ab-1)

•Precision is below ~3.5% with reasonable of tagging/mis-tagging rates.



Triple Higgs coupling sensitivity

- Higgs self-coupling dependence at 14 TeV and 100 TeV are similar.



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

Conclusion

- FCC Volume on “Higgs and EWSB studies” first important step towards a careful assessment of the physics potential of a FCC-hh.
- FCC-hh both an energy and an intensity frontier machine.
- Unique opportunities for Higgs and EWSB physics at 100 TeV:
  - Measuring the Higgs trilinear coupling at <5% level
  - Ultra-rare Higgs decays including h → V gamma
  - Discovering extended Higgs sectors (new EW-charged or singlet scalars)
  - Testing EW Baryogenesis
  - Discovering DM sectors
  - Many more ...