2022 IUEP Theory Meeting for Future Colliders
2022. 1. 8.

New Physics @ ep collider

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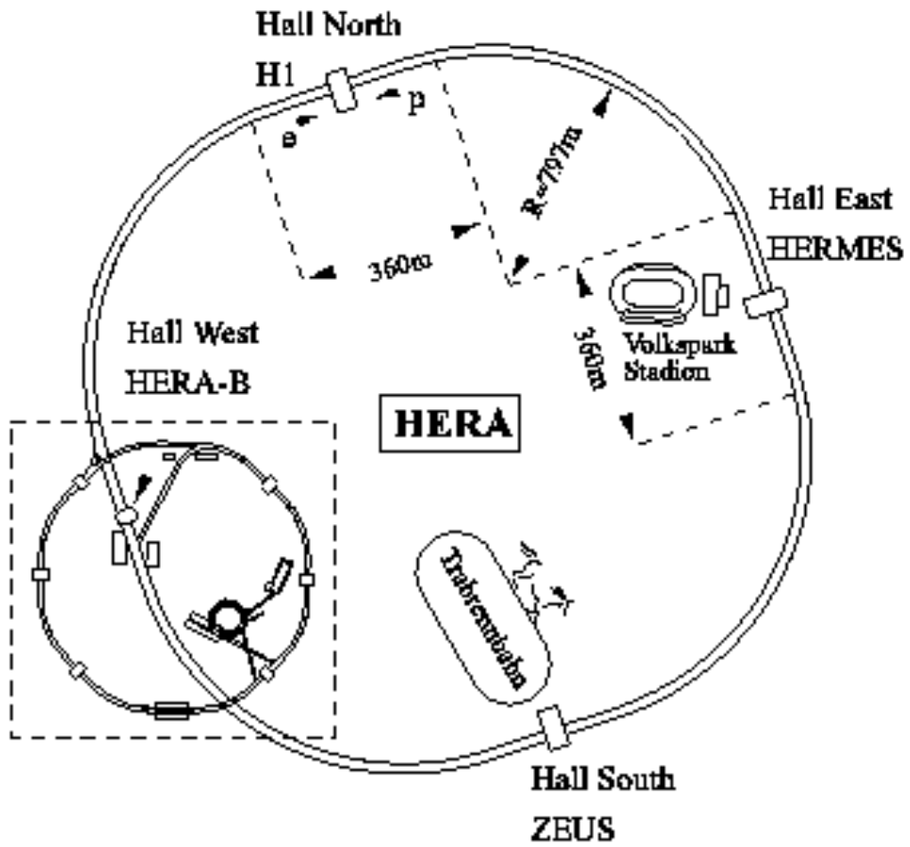
(Konkuk University, Korea)

w/ A. Jueid, J. Kim, S. Lee, PLB 819 (2021) 136417

1. LHeC, very possible in the near future

e-p collider: proton substructure

HERA (construction from 1984 to 1992)



- $\boldsymbol{E_e = 27.5\ \text{GeV}, \quad E_p = 920\ \text{GeV} \Longrightarrow \sqrt{s} \simeq 0.3\ \text{TeV}}$

Next ep collider design?

- the need for higher energy

- the need for much higher luminosity

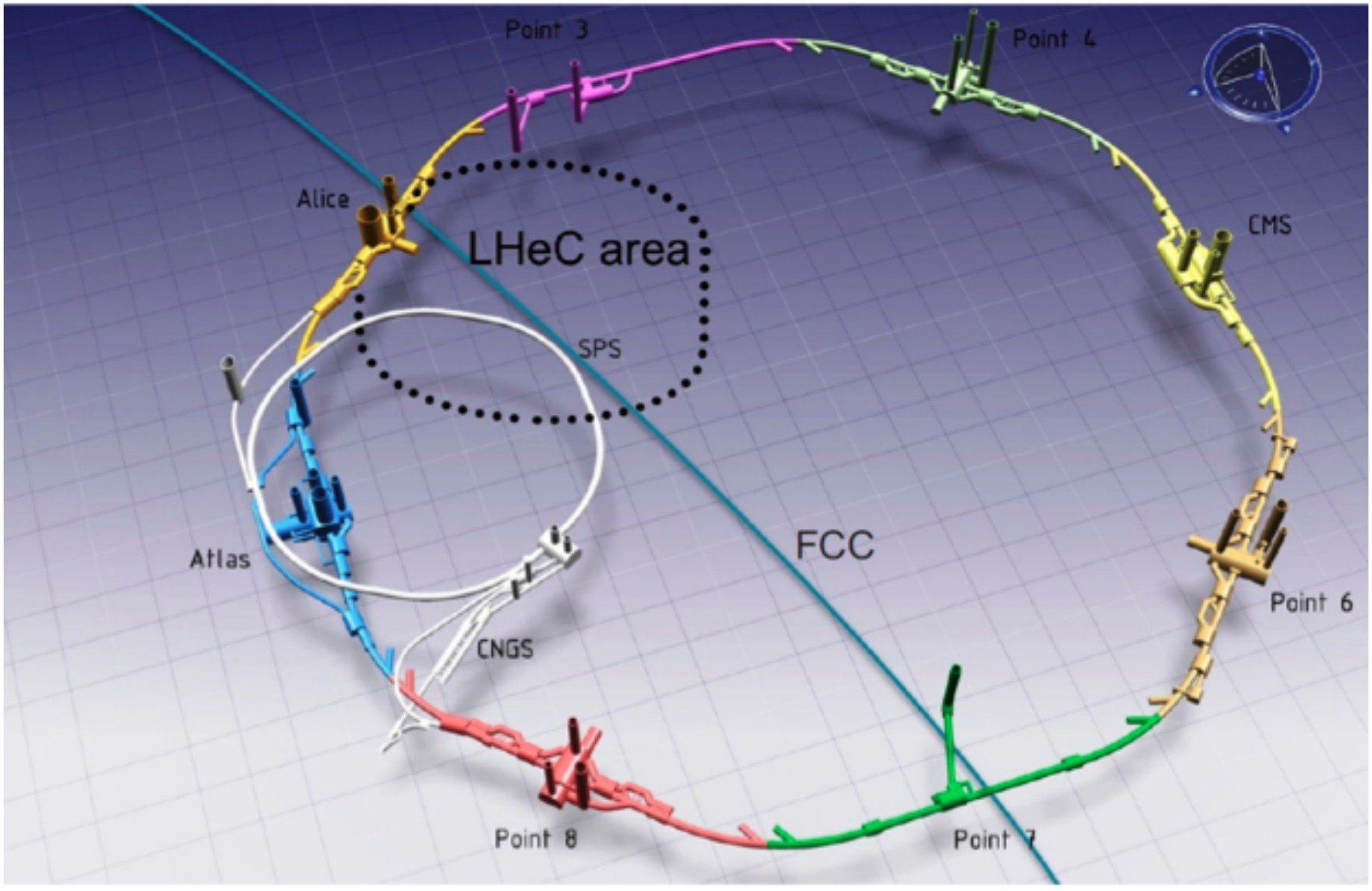
Next ep collider design?

- the need for higher energy

- the need for much higher luminosity

LHeC: the most feasible!

1. LHeC


Point 3
Point 4
Alice
LHeC area
CMS
SPS
Atlas
FCC
CNGS
Point 6
Point 8
Point 7

First CDR in 2012

CERN-OPEN-2012-015
LHeC-Note-2012-002 GEN
Geneva, June 13, 2012

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

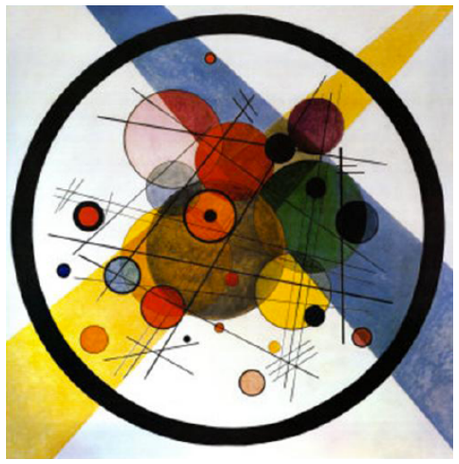
LHeC Study Group

CDR in 2020 : 2007.14491

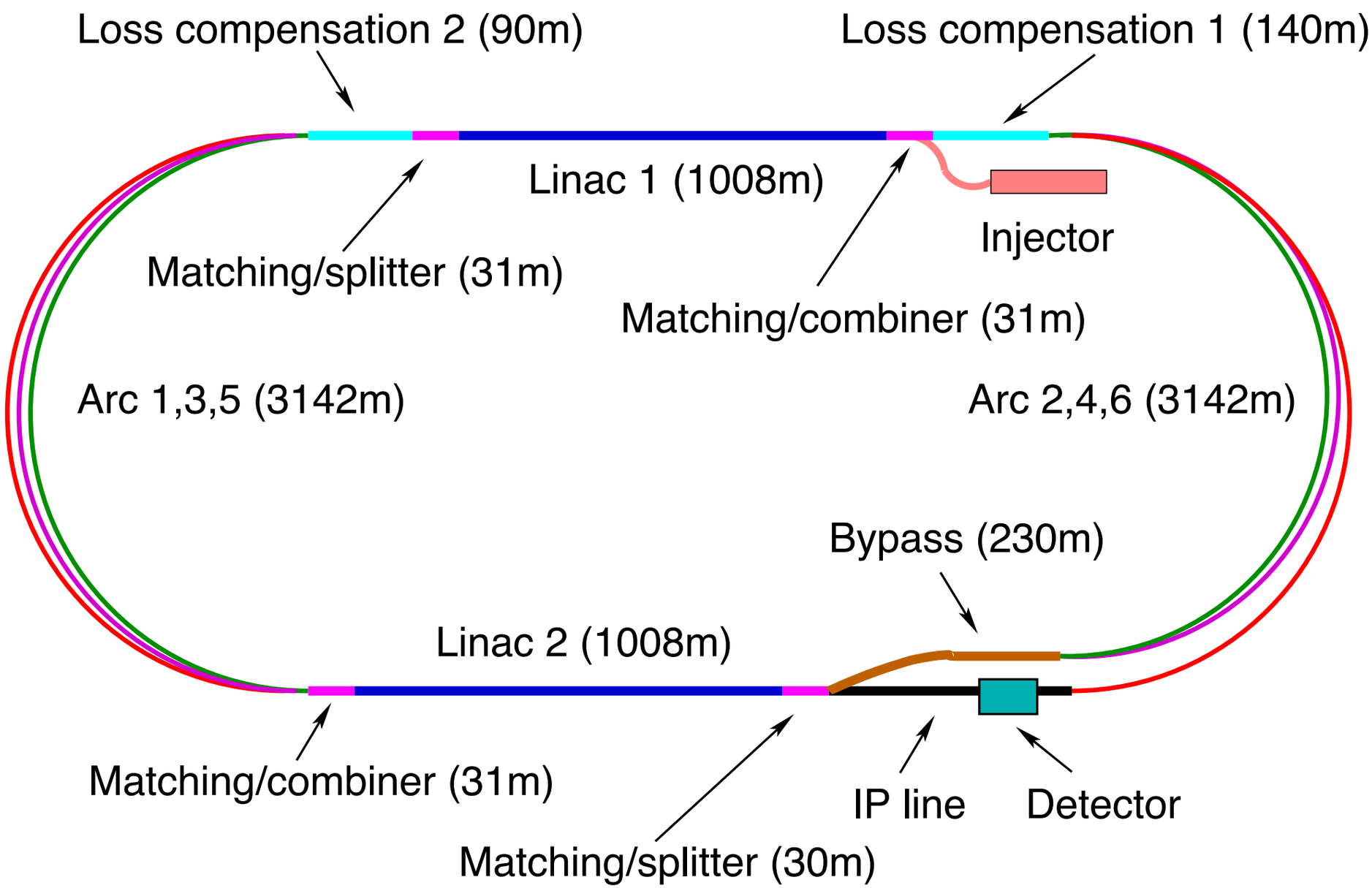
CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

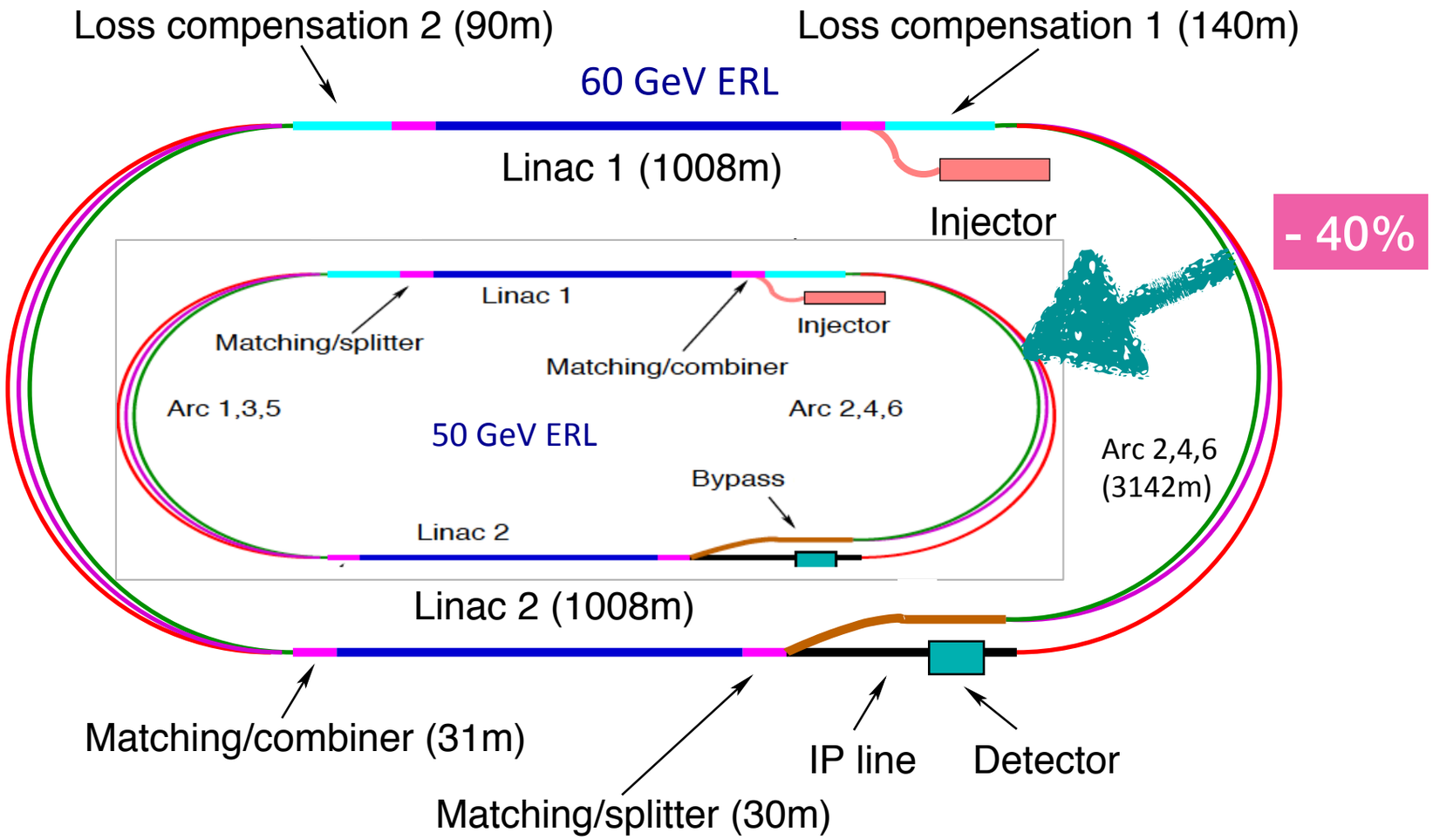


1. LHeC

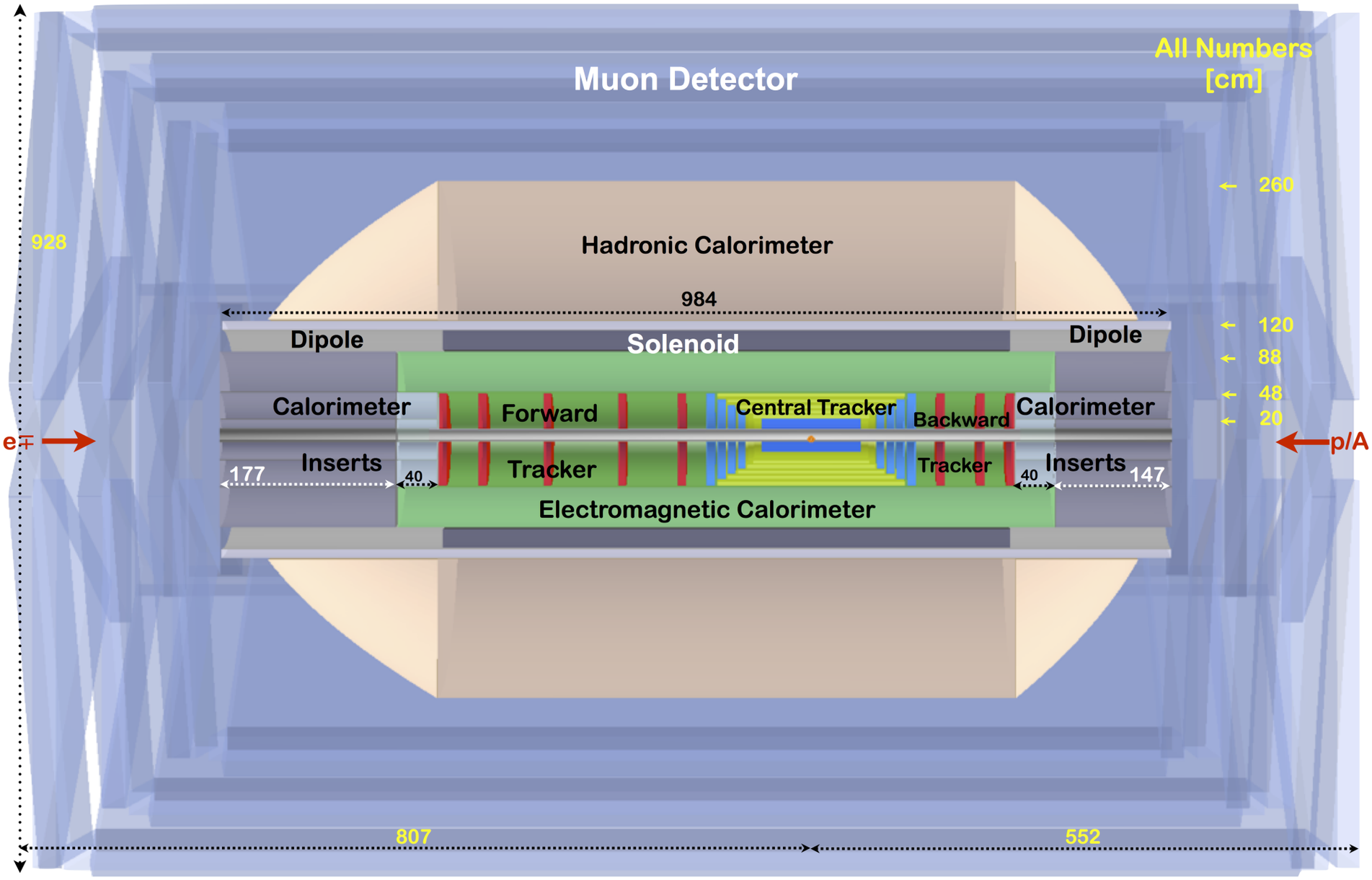


- Default LHeC racetrack configuration.
- After 3 passes, we have the target electron energy.
- Simultaneous run of LHC and LHeC

CDR in 2020: cost reduction



1. LHeC



We can distinguish forward from backward

CDR in 2020: cost reduction

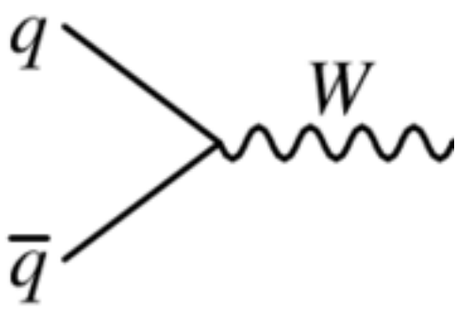
Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	9	23	8	15

with LHC

a final, dedicated, stand-alone ep phase

Merit 1: small backgrounds

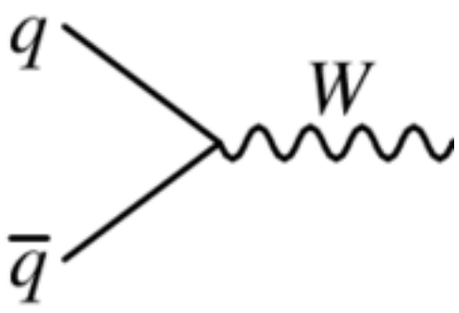
LHC: single W production



$$\sigma(pp \to W^{\pm}) \simeq 10^5 \text{ pb}$$

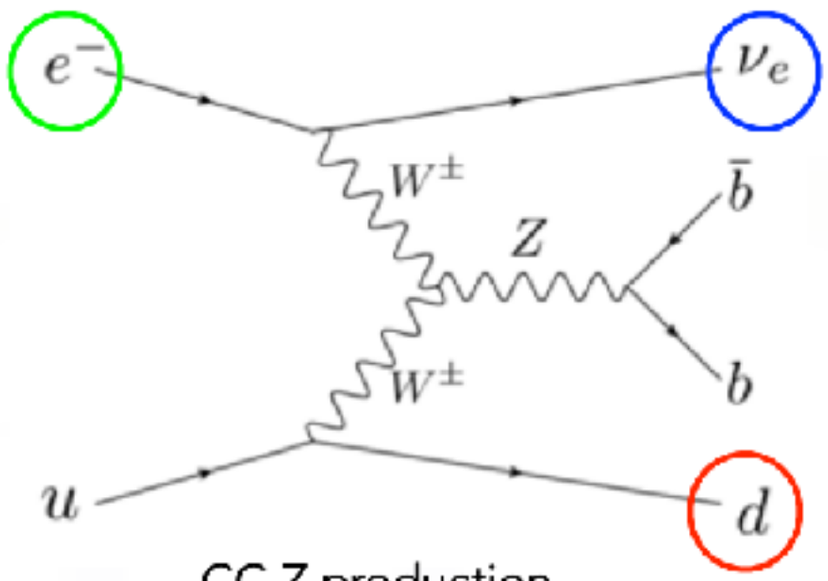
Merit 1: small backgrounds

LHC: single W production



$$\sigma(pp \to W^{\pm}) \simeq 10^5 \text{ pb}$$

LHeC: only through VBF



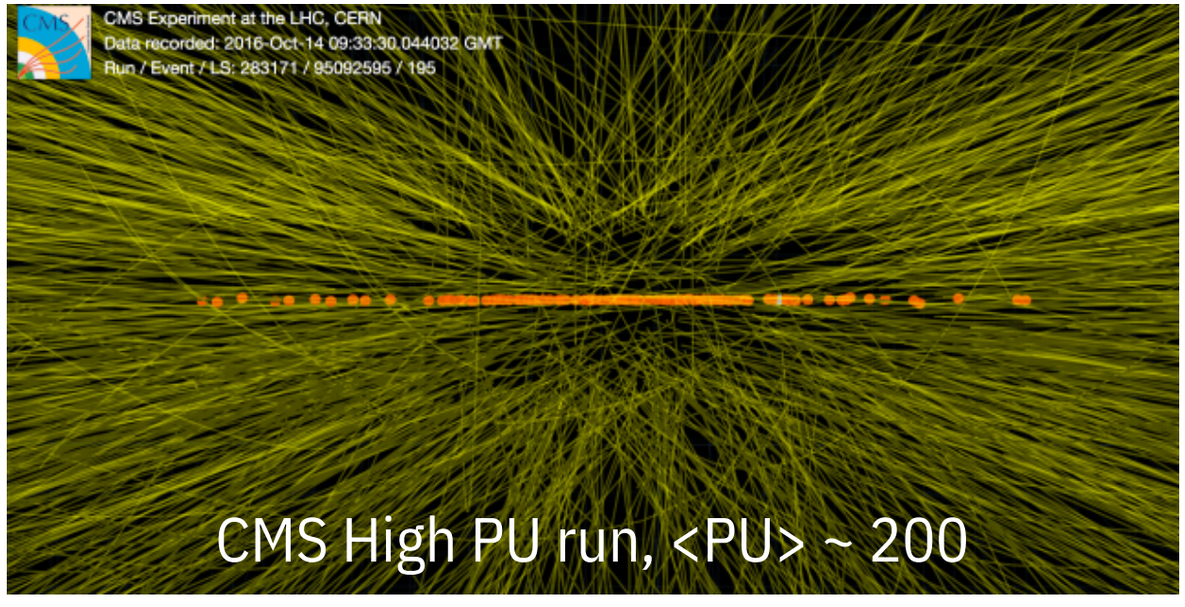
CC Z production

Process	$E_e = 50\,\text{GeV},\ E_p = 7\,\text{TeV}$ $p_T^e > 10\,\text{GeV}$
$e^- W^+ j$	1.00 pb
$e^- W^- j$	0.930 pb
$\nu_e^- W^- j$	0.796 pb
$\nu_e^- Z j$	0.412 pb
$e^- Z j$	0.177 pb

Merit 2: No gluon fusion at LO

Merit 2: No gluon fusion at LO

Merit 3: Practically no Pile-up



At LHeC, PU is only 0.1

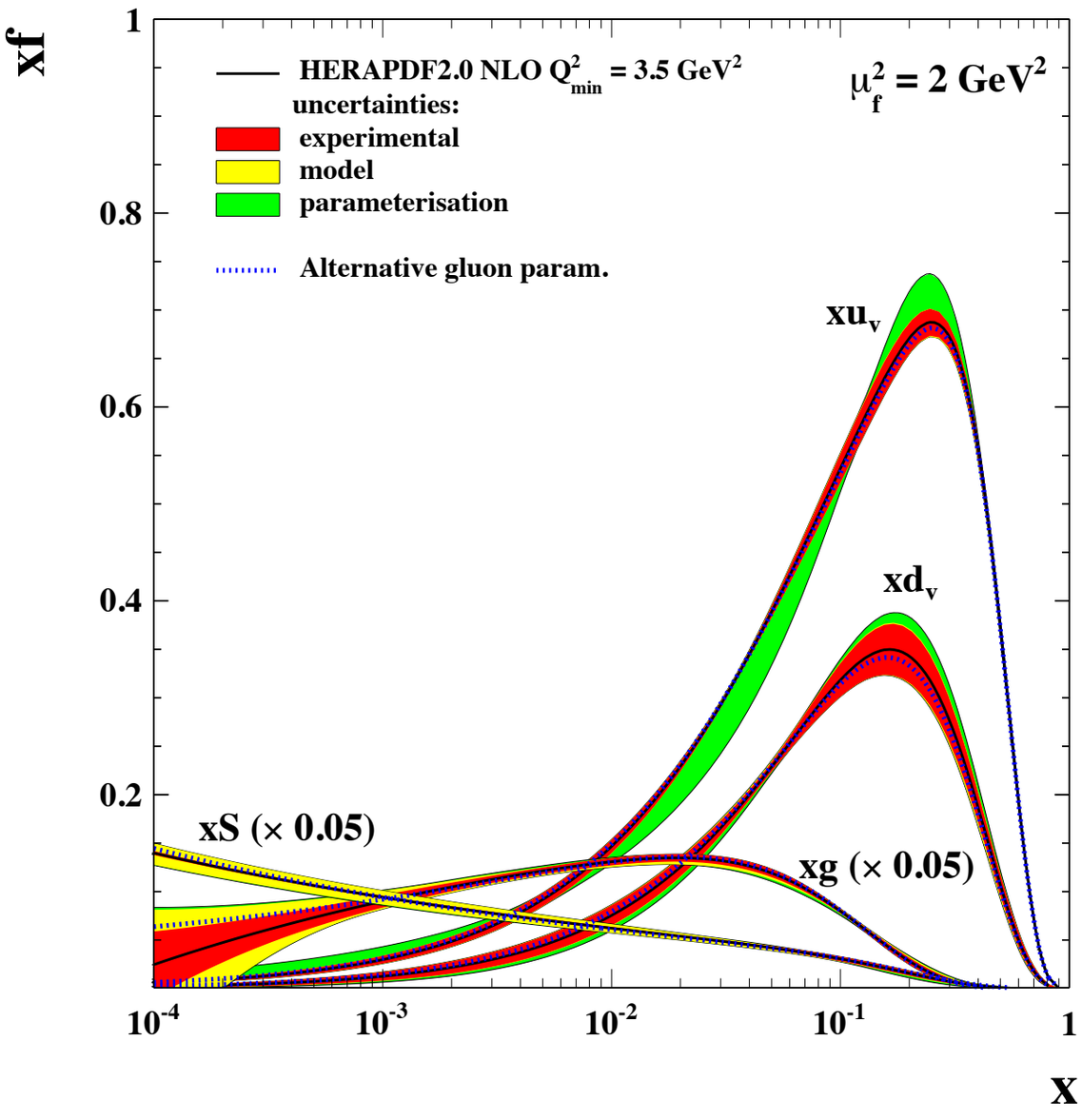
Merit 4: electron beam polarization

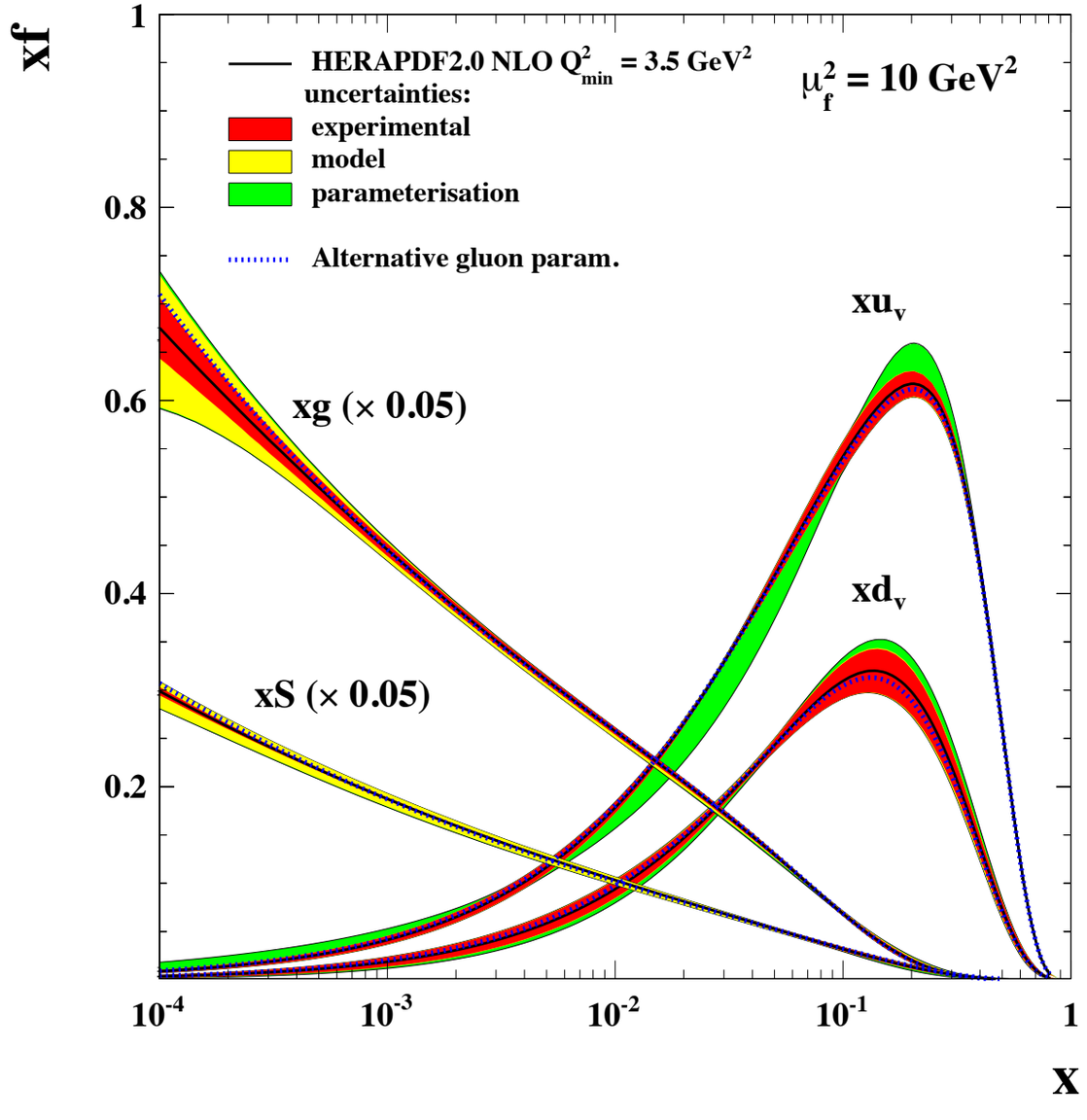
Pe=80% can enhance the CC mode.

Doubling the luminosity!

2. Parton Distribution Functions

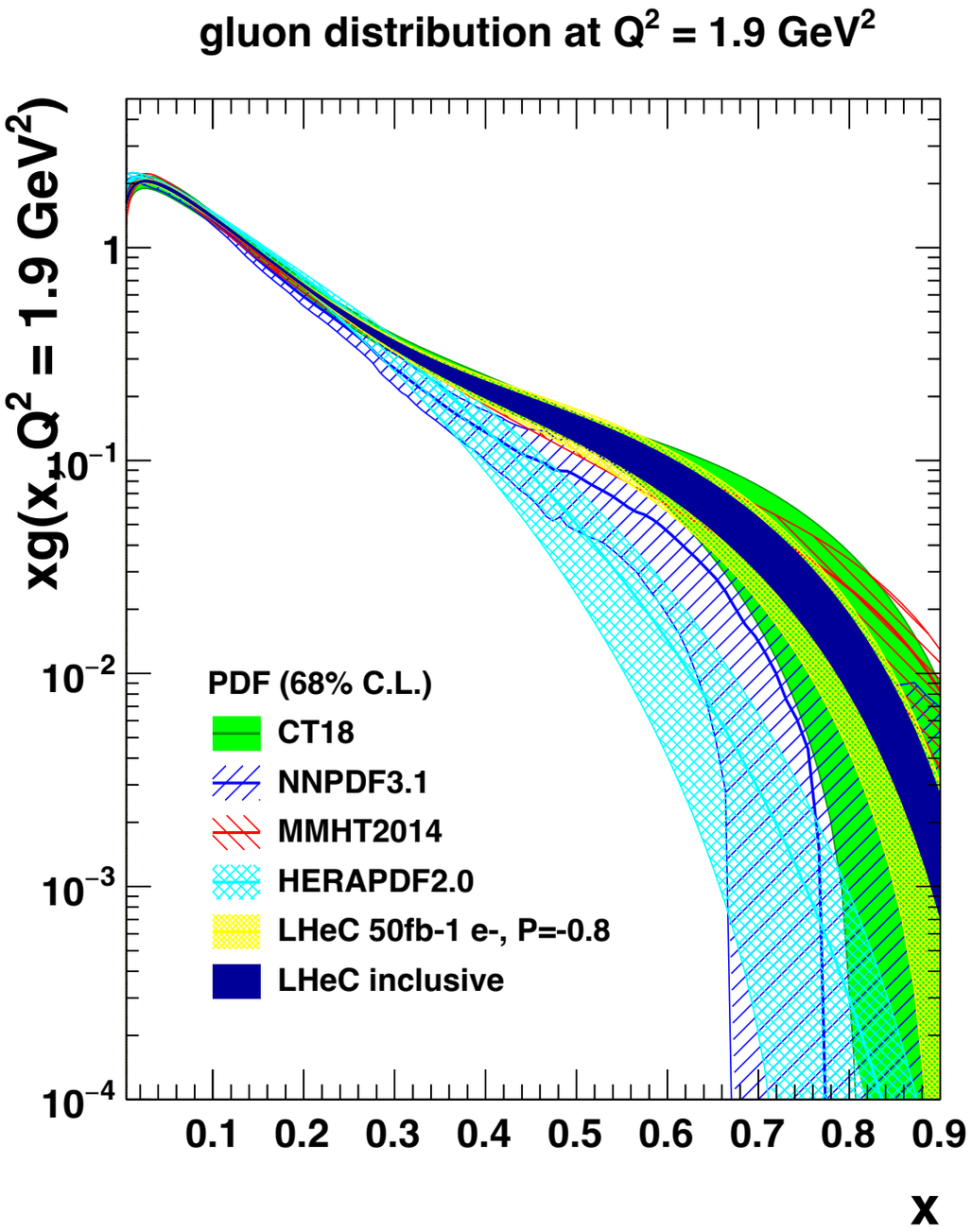
From the QCD fit to the combined H1 and ZEUS data



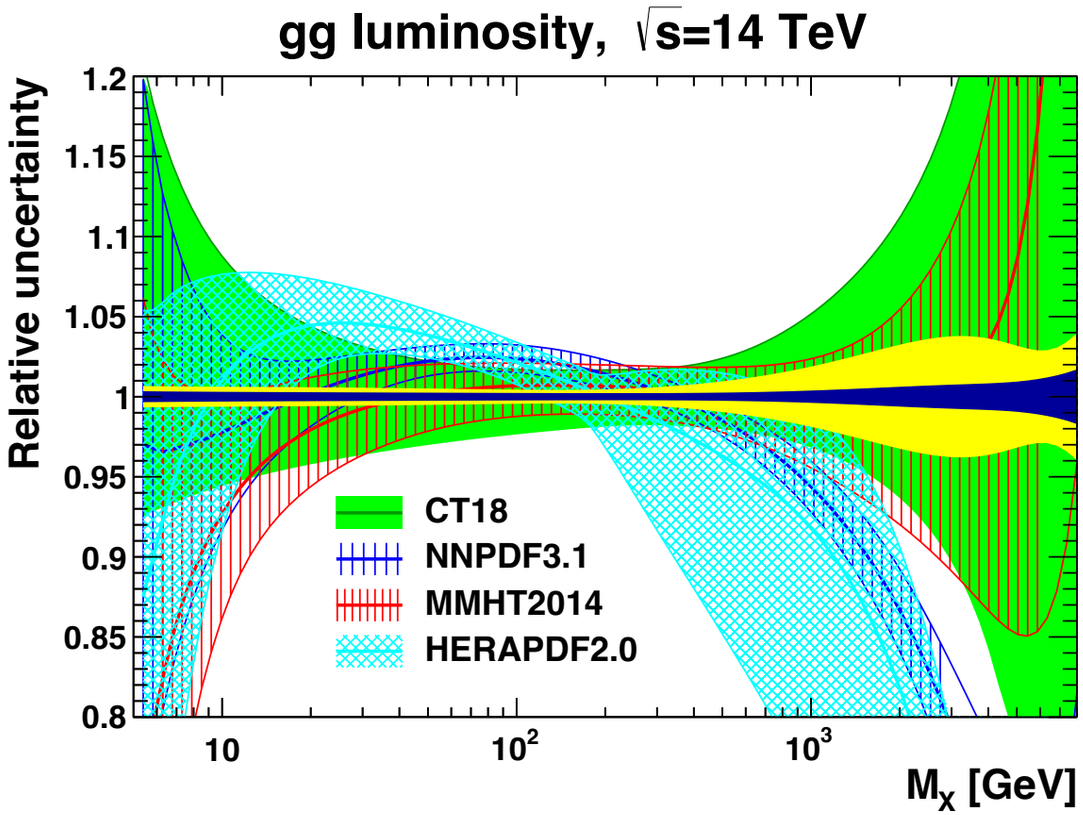


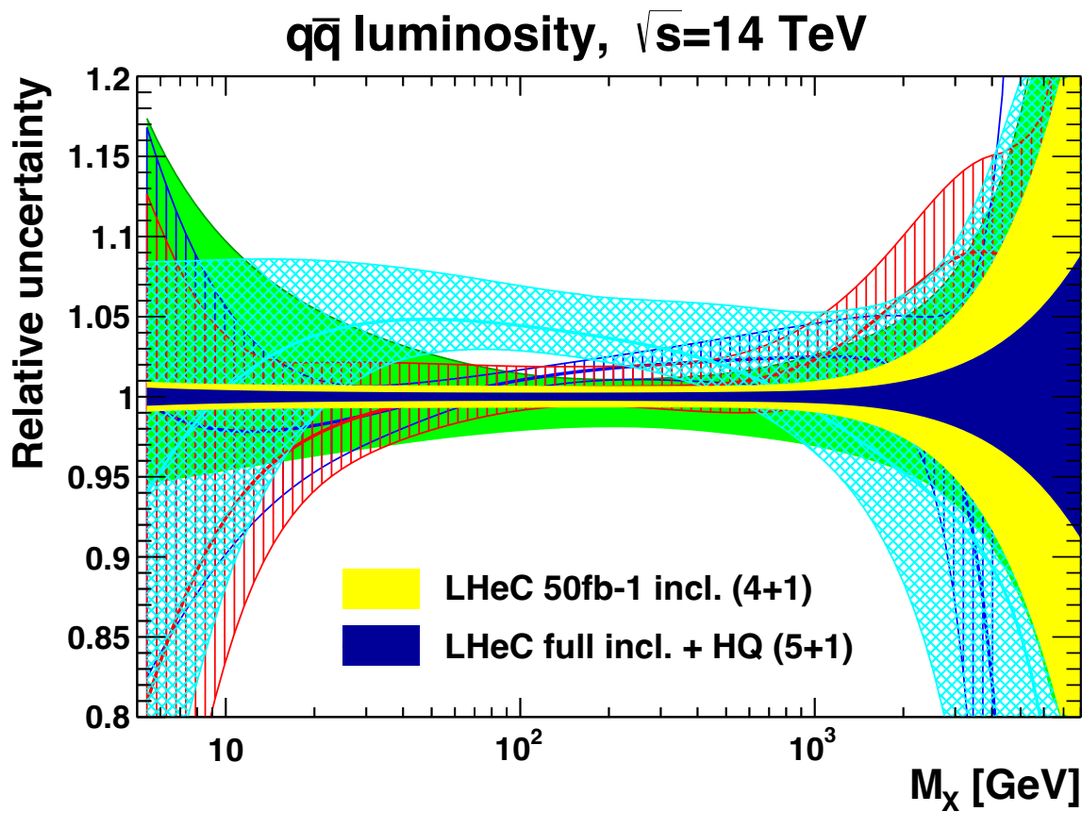
Large uncertainty, especially small x for gluon PDF

Significant improvement

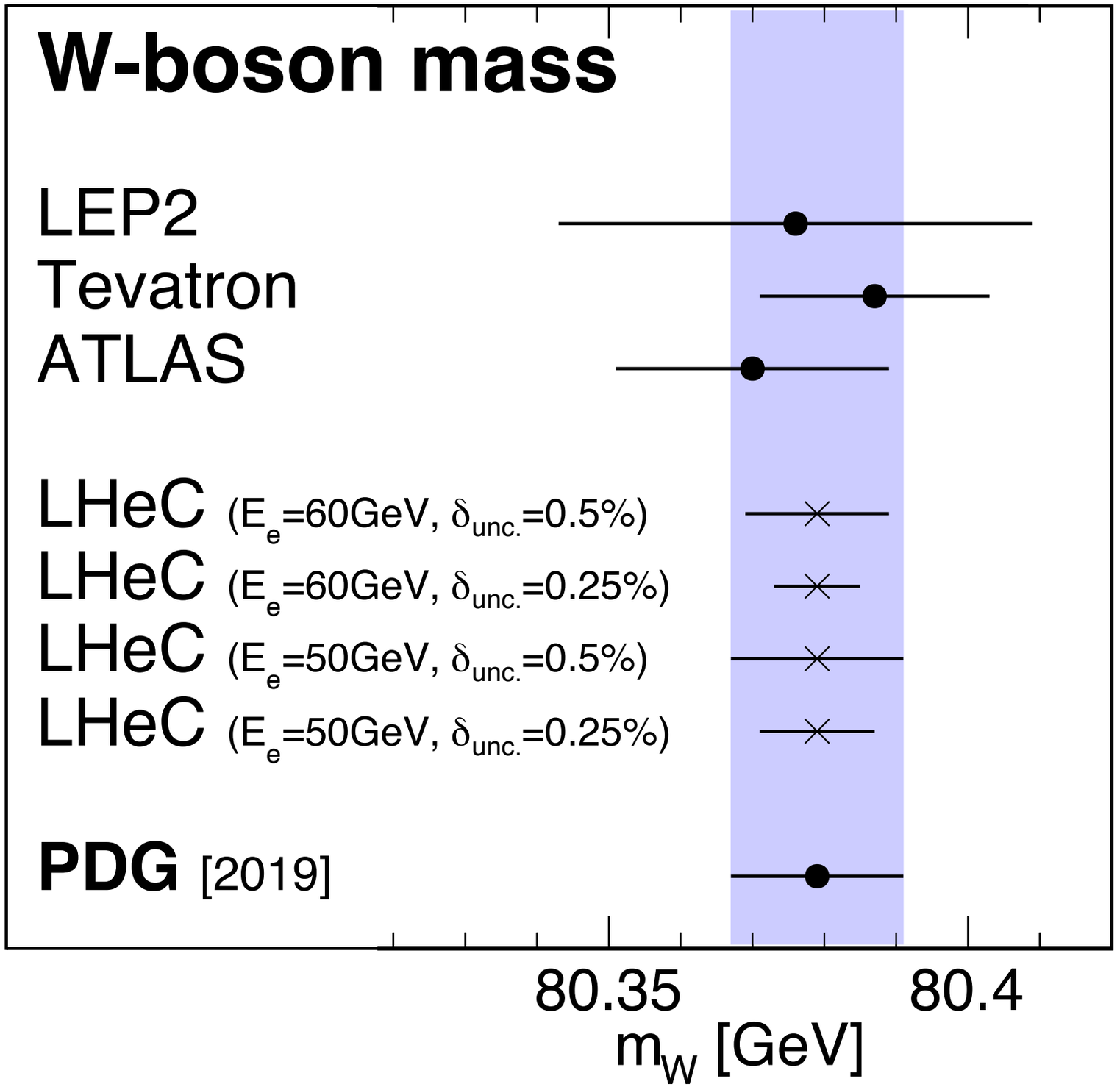


Uncertainty bands for parton luminosities as a function of the mass





3. Electroweak and Top Quark Physics

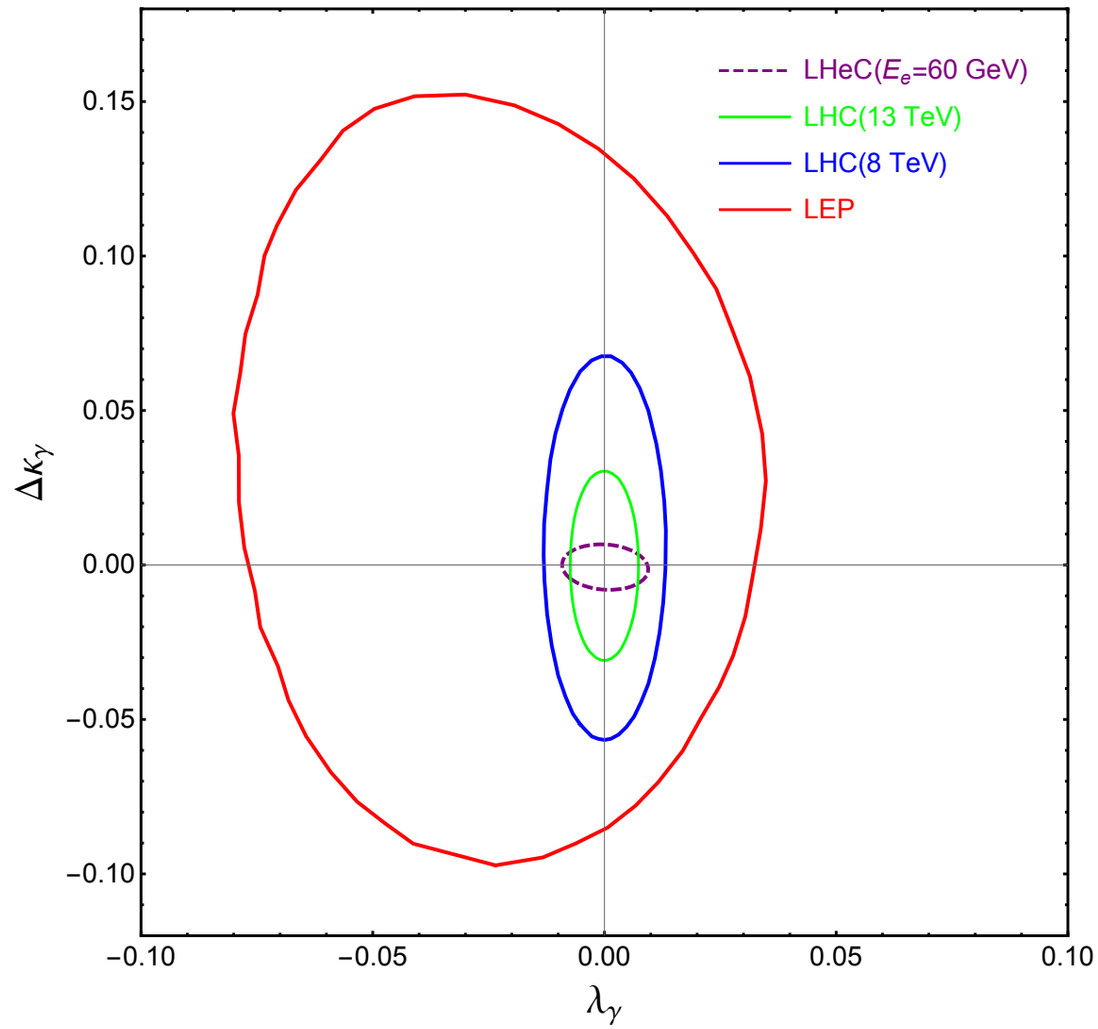

W-boson mass
LEP2
Tevatron
ATLAS
LHeC (E_e=60GeV, δ_unc.=0.5%)
LHeC (E_e=60GeV, δ_unc.=0.25%)
LHeC (E_e=50GeV, δ_unc.=0.5%)
LHeC (E_e=50GeV, δ_unc.=0.25%)
PDG [2019]
80.35
80.4
m_W [GeV]

Weak Neutral Current Couplings

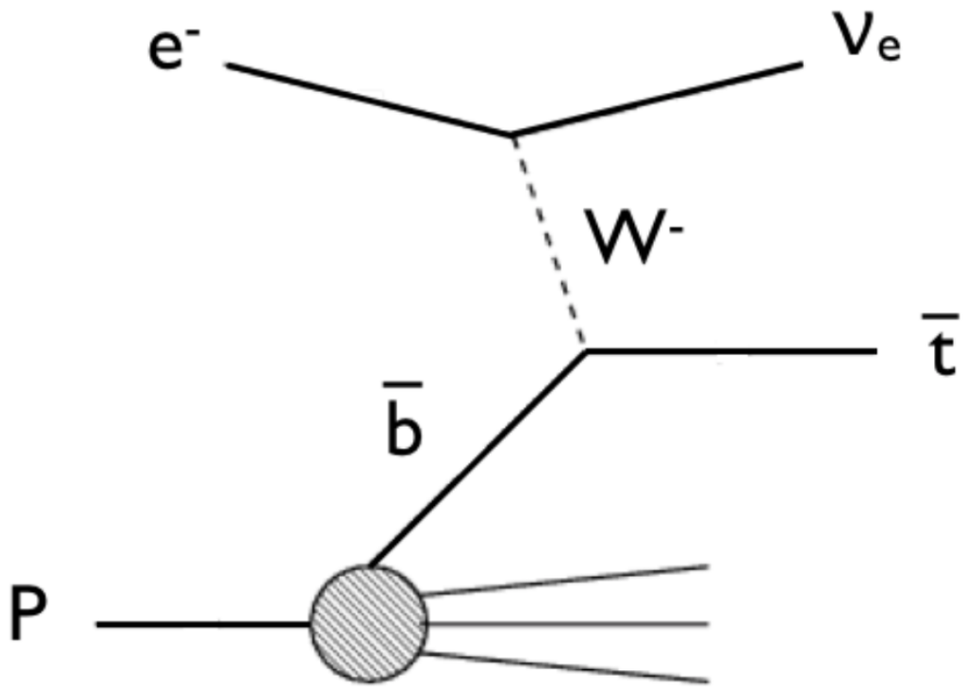
Coupling parameter	PDG value	Expected uncertainties		
		LHeC-60	LHeC-60 ($\delta_{\text{uncor.}}$=0.25 %)	LHeC-50
g_A^u	$0.50\ ^{+0.04}_{-0.05}$	0.0022	0.0015	0.0035
g_A^d	$-0.514\ ^{+0.050}_{-0.029}$	0.0055	0.0034	0.0083
g_V^u	$0.18\ \pm 0.05$	0.0015	0.0010	0.0028
g_V^d	$-0.35\ ^{+0.05}_{-0.06}$	0.0046	0.0027	0.0067

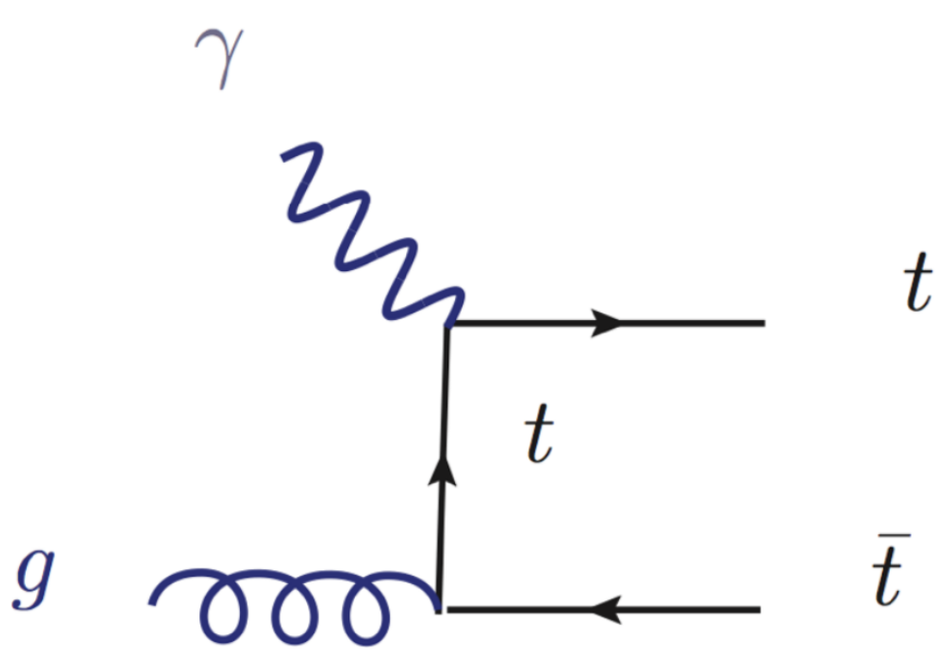
Anomalous Triple Gauge Couplings

$$\begin{aligned}\mathcal{L}_{TGC}/g_{WWV} &= ig_{1,V}(W^+_{\mu\nu}W^-_\mu V_\nu - W^-_{\mu\nu}W^+_\mu V_\nu) + i\kappa_V W^+_\mu W^-_\nu V_{\mu\nu} + \frac{i\lambda_V}{M_W^2}W^+_{\mu\nu}W^-_{\nu\rho}V_{\rho\mu} \\ &+ g_5^V \epsilon_{\mu\nu\rho\sigma}(W^+_\mu \overleftrightarrow{\partial}_\rho W^-_\nu)V_\sigma - g_4^V W^+_\mu W^-_\nu(\partial_\mu V_\nu + \partial_\nu V_\mu) \\ &+ i\tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}_{\mu\nu} + \frac{i\tilde{\lambda}_V}{M_W^2}W^+_{\lambda\mu}W^-_{\mu\nu}\tilde{V}_{\nu\lambda}, \end{aligned} \quad (5.1$$



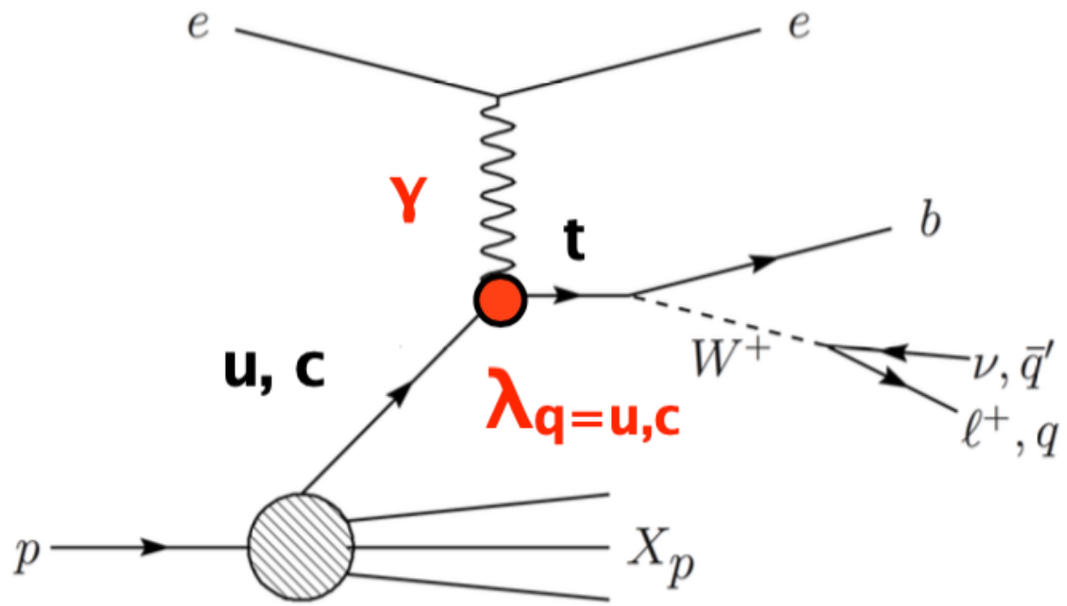
Top quark production @ ep

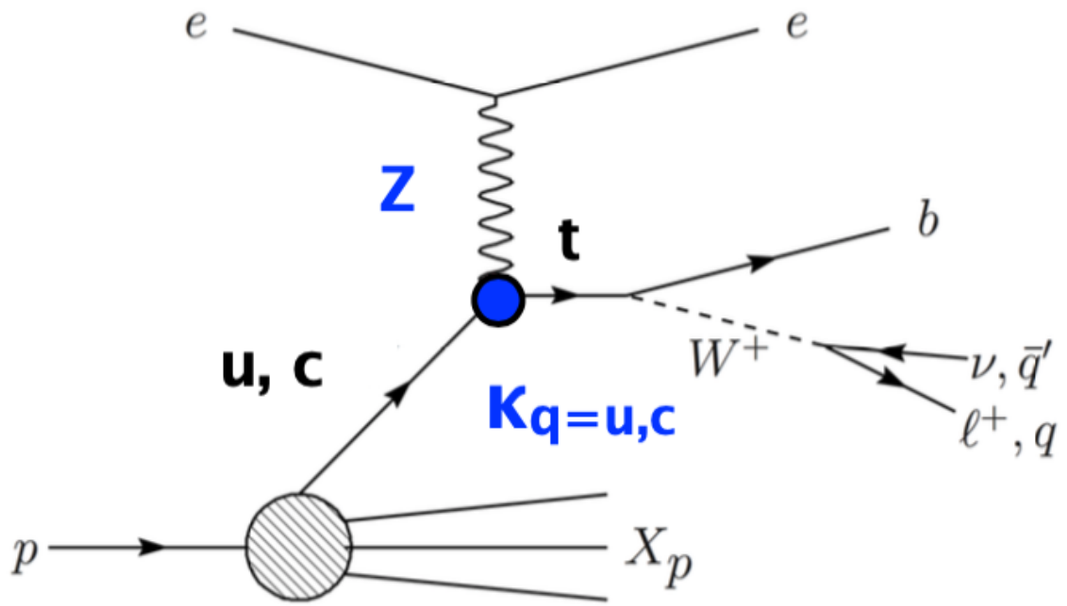




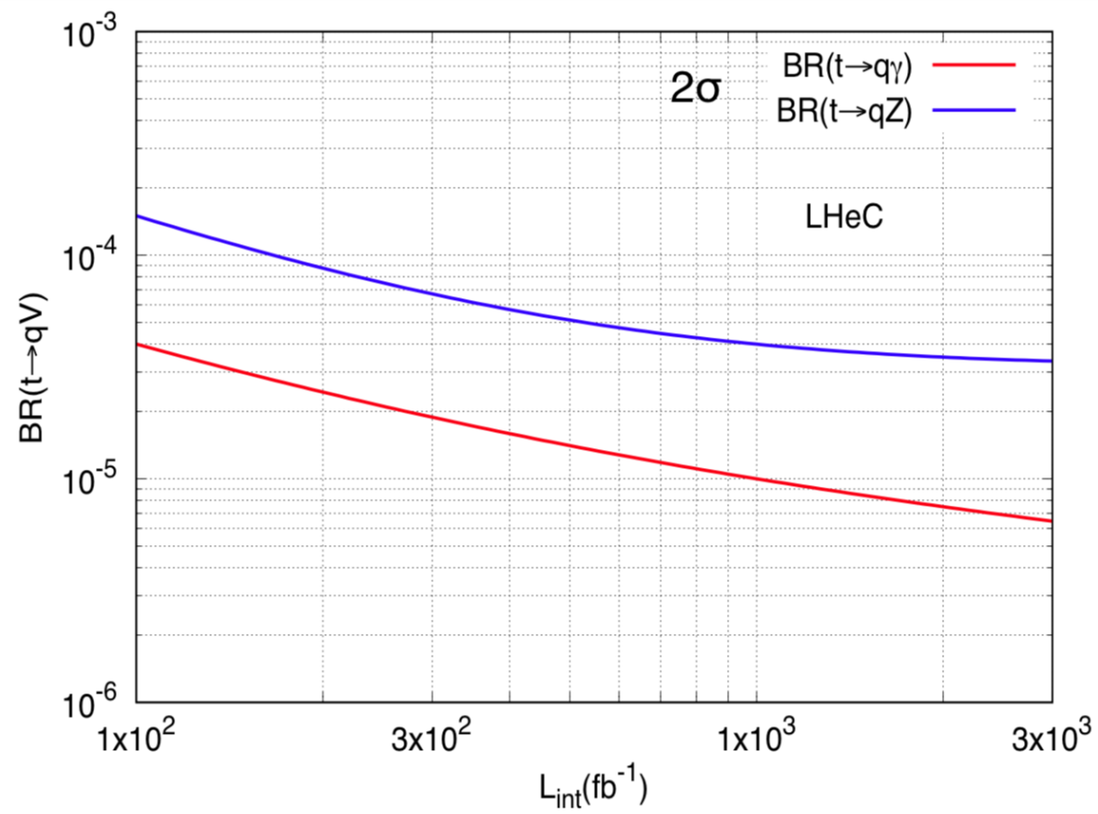
FCNC Top Quark Couplings @ ep

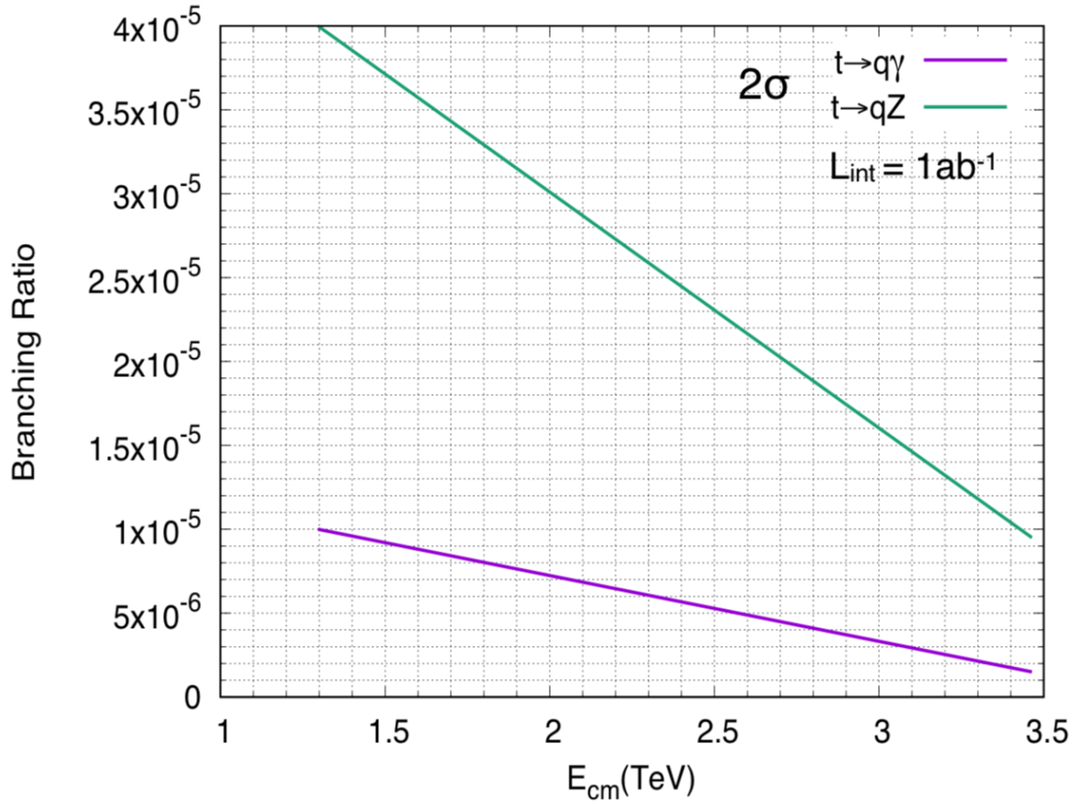
$$tu\gamma, \quad tc\gamma, \quad tuZ, \quad tcZ$$



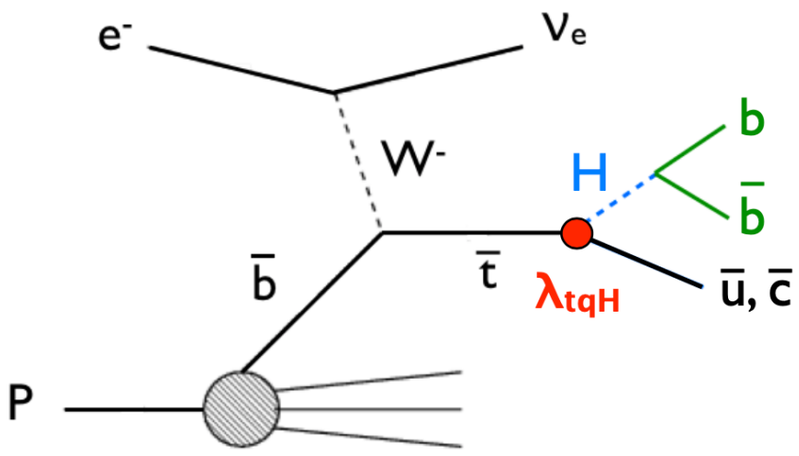


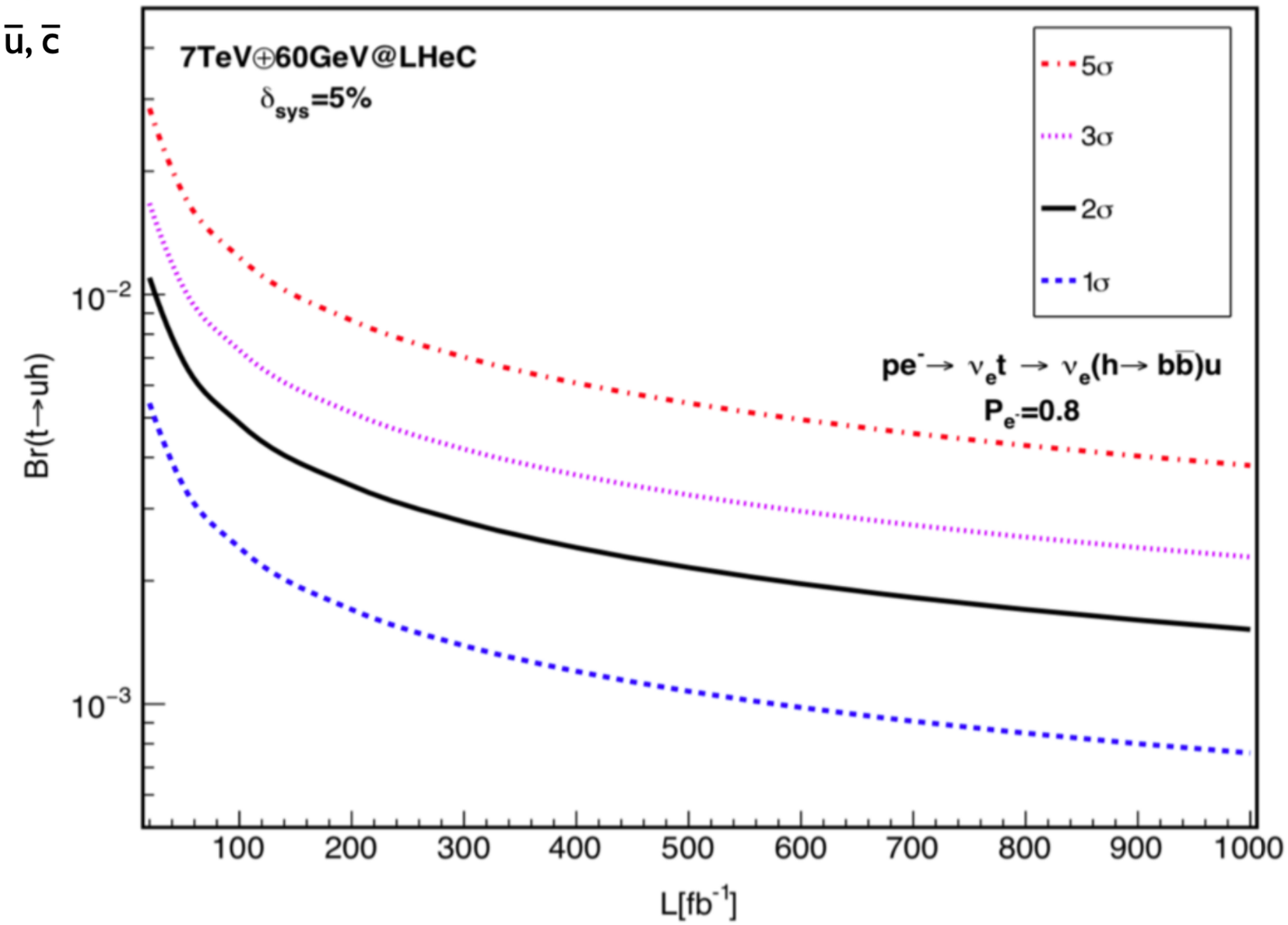
Expected sensitivities on FCNC

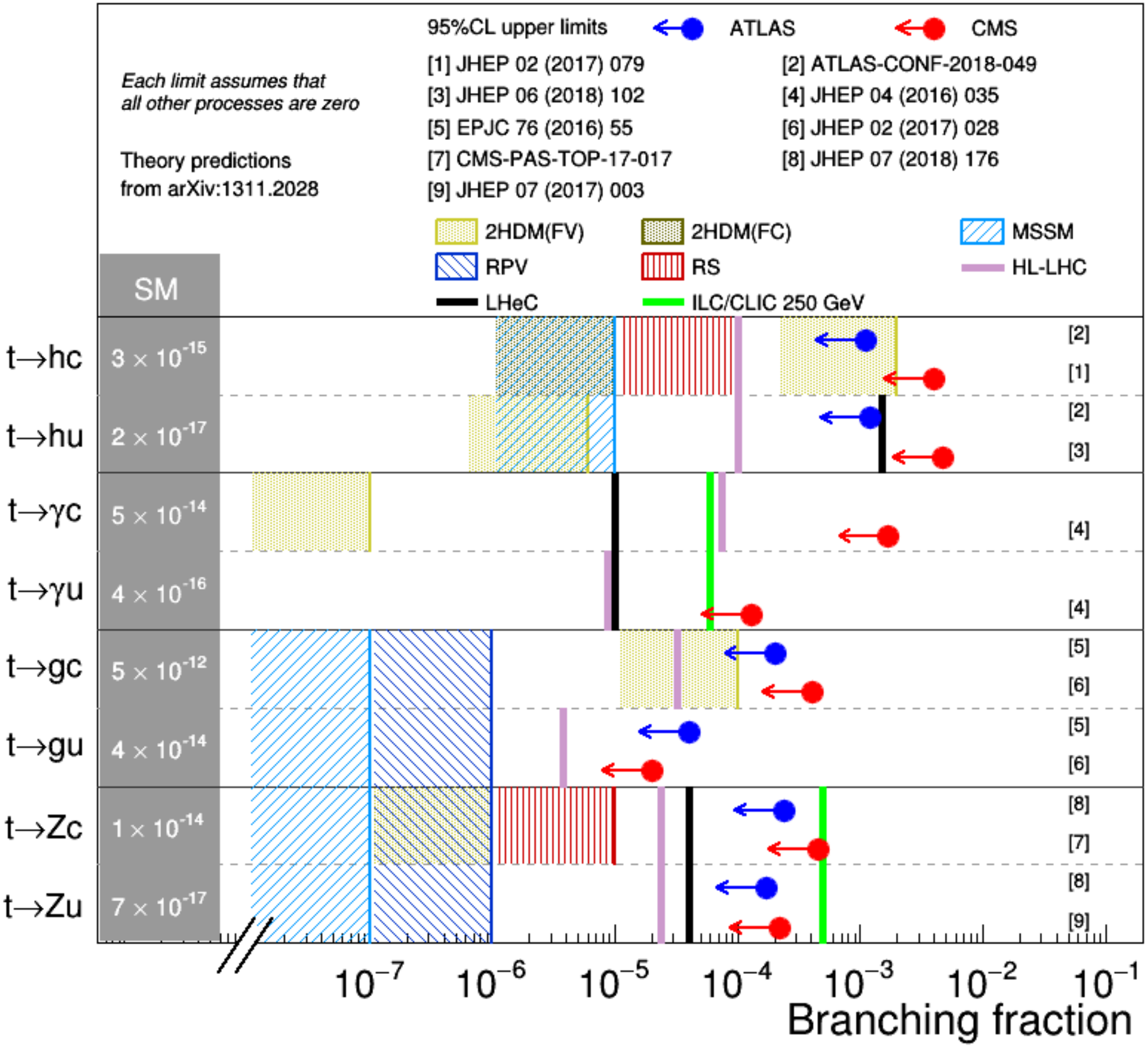




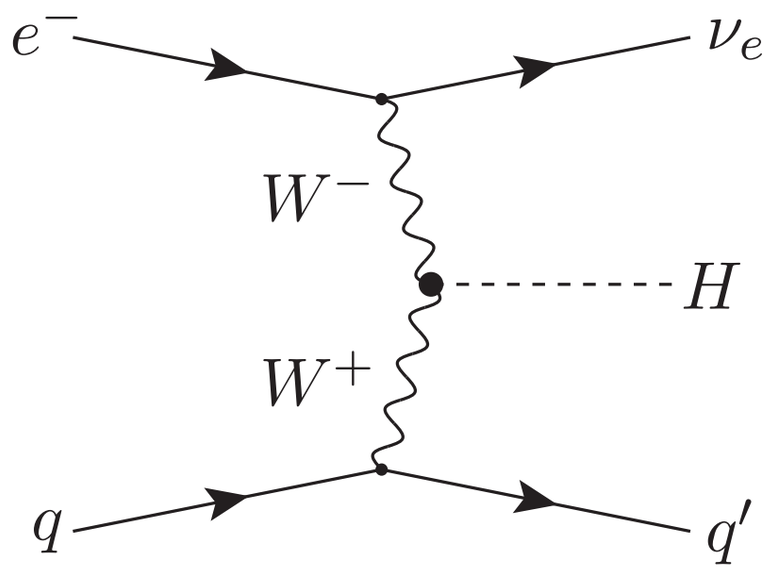
FCNC tqH couplings

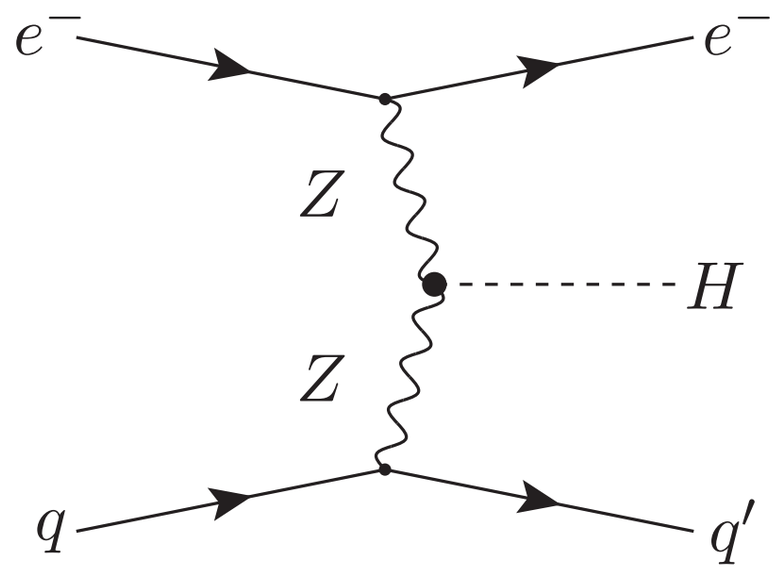





95%CL upper limits
ATLAS
CMS
Each limit assumes that all other processes are zero
Theory predictions from arXiv:1311.2028
[1] JHEP 02 (2017) 079
[2] ATLAS-CONF-2018-049
[3] JHEP 06 (2018) 102
[4] JHEP 04 (2016) 035
[5] EPJC 76 (2016) 55
[6] JHEP 02 (2017) 028
[7] CMS-PAS-TOP-17-017
[8] JHEP 07 (2018) 176
[9] JHEP 07 (2017) 003
2HDM(FV)
2HDM(FC)
MSSM
RPV
RS
HL-LHC
LHeC
ILC/CLIC 250 GeV
SM
t→hc
3 × 10^-15
t→hu
2 × 10^-17
t→γc
5 × 10^-14
t→γu
4 × 10^-16
t→gc
5 × 10^-12
t→gu
4 × 10^-14
t→Zc
1 × 10^-14
t→Zu
7 × 10^-17
[2]
[1]
[2]
[3]
[4]
[4]
[5]
[6]
[5]
[6]
[8]
[7]
[8]
[9]
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
Branching fraction

3. Higgs Physics:
bb and cc modes

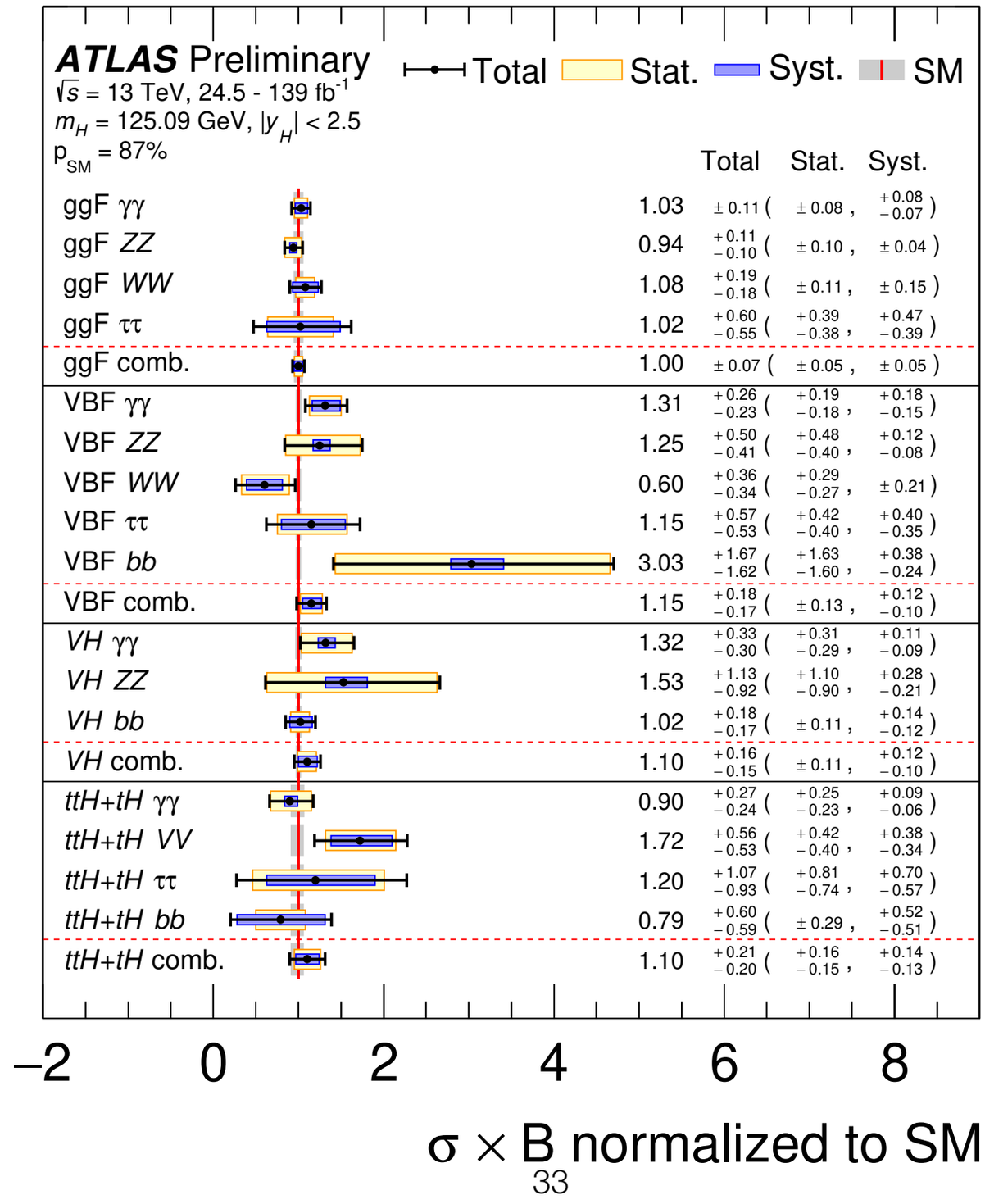




Higgs production cross section in fb

Parameter	Unit	LHeC	HE-LHeC	FCC-eh	FCC-eh
E_p	TeV	7	13.5	20	50
$\sqrt{s}$	TeV	1.30	1.77	2.2	3.46
σ_{CC} $(P = -0.8)$	fb	197	372	516	1038
σ_{NC} $(P = -0.8)$	fb	24	48	70	149
σ_{CC} $(P = 0)$	fb	110	206	289	577
σ_{NC} $(P = 0)$	fb	20	41	64	127
HH in CC	fb	0.02	0.07	0.13	0.46

Higgs precision at the LHC



Higgs precision test at the other future colliders

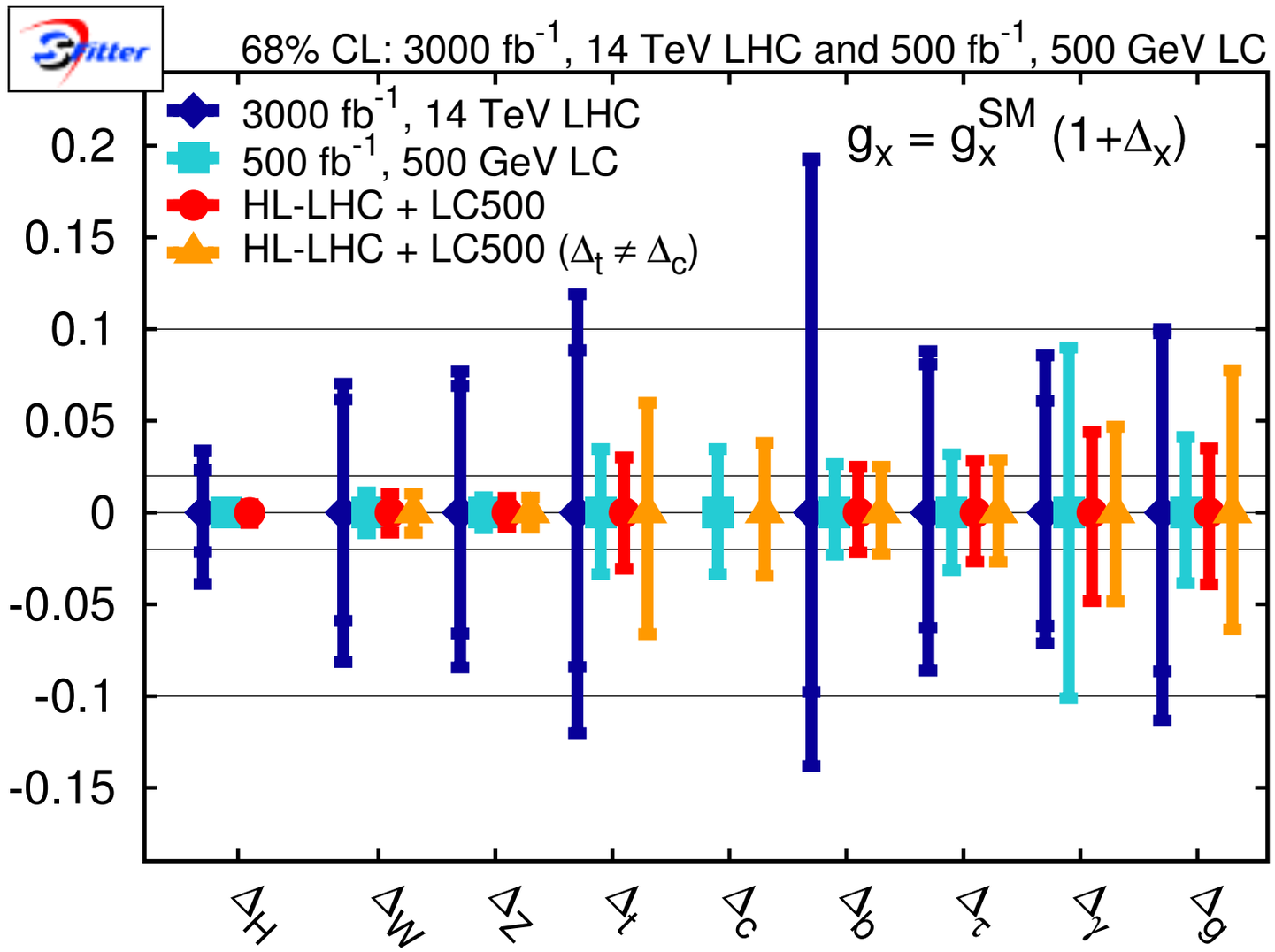
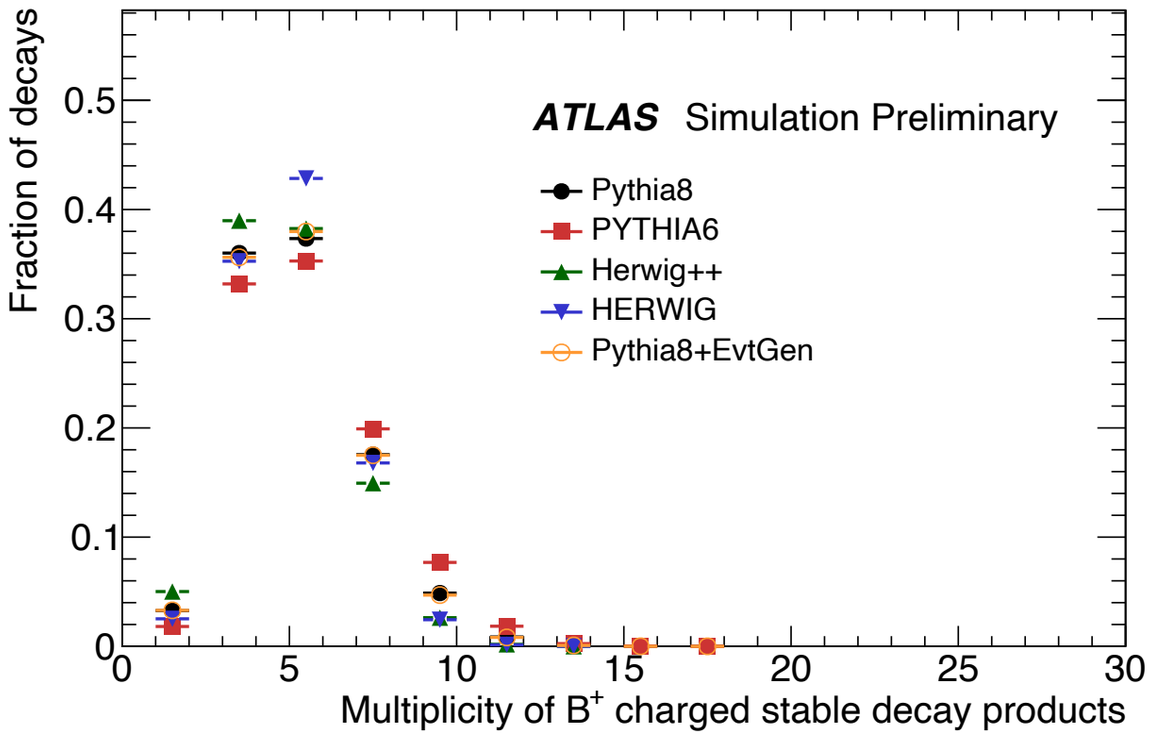


Figure 3. Expected precision for Higgs couplings from a high-luminosity LHC, a 500 GeV ILC, and their combination. For the LHC we also show a scenario with improved systematic uncertainties. Figure from Ref. [31].

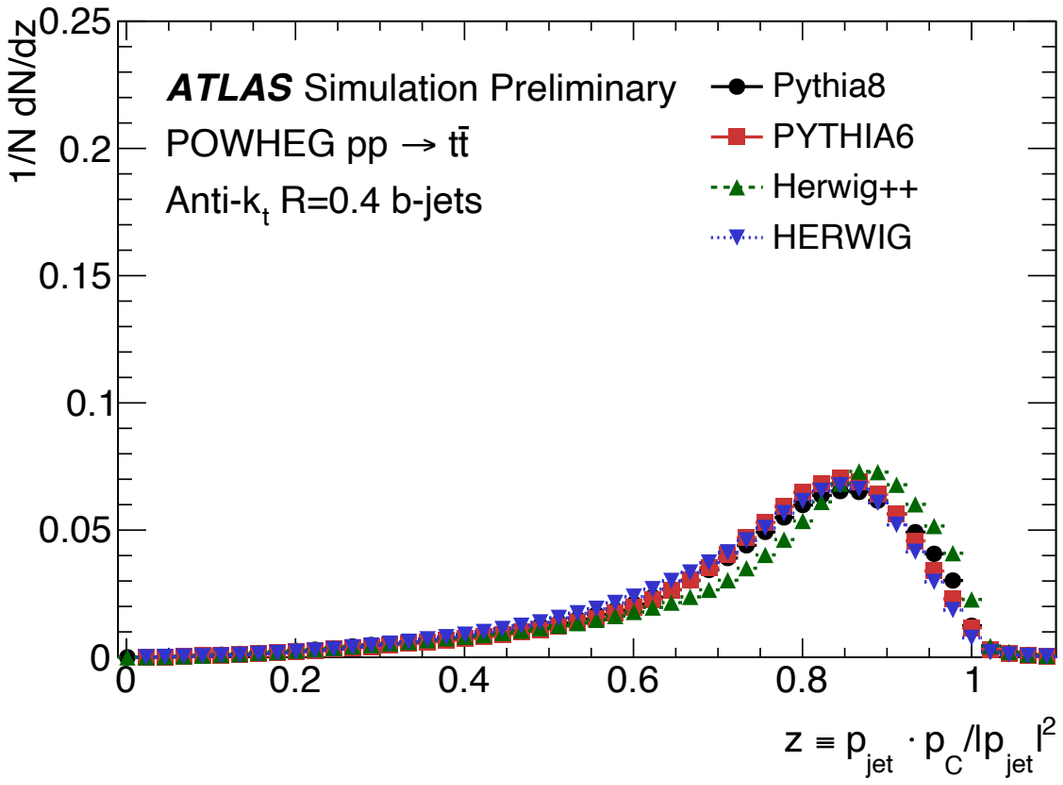
arXiv:1301.1322

Properties of B hadrons

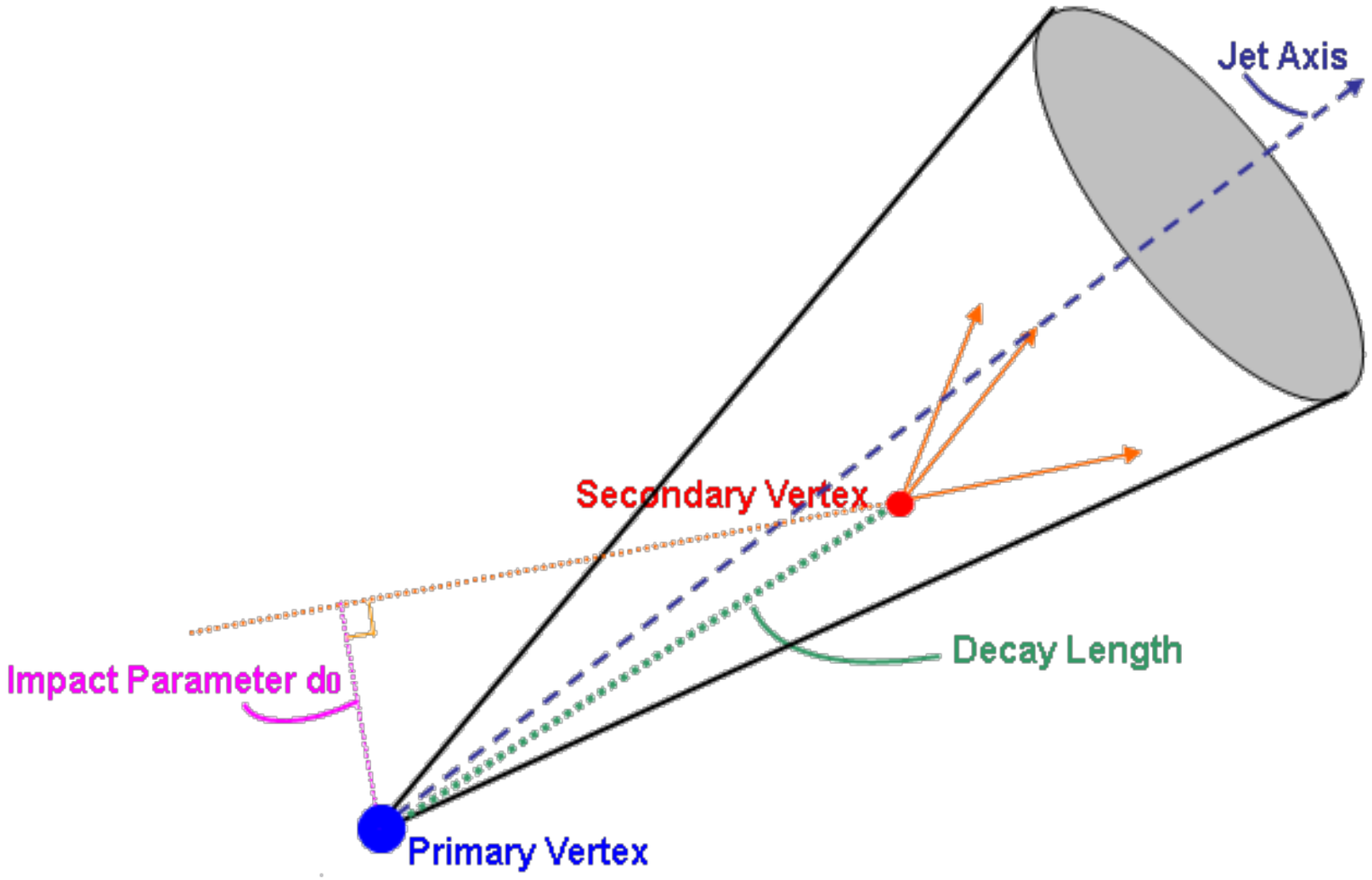
- **Lifetime:** Long enough to lead to a measureable decay length (around 5mm for a 50 GeV boost)
- **Mass:** Weakly decaying b-hadrons have masses around 5 GeV, leading to high decay product multiplicities (average of 5 charged particles per decay)
- **Fragmentation:** Much harder than jets initiated by other species (b-hadrons carry around 75% of jet energy, on average)



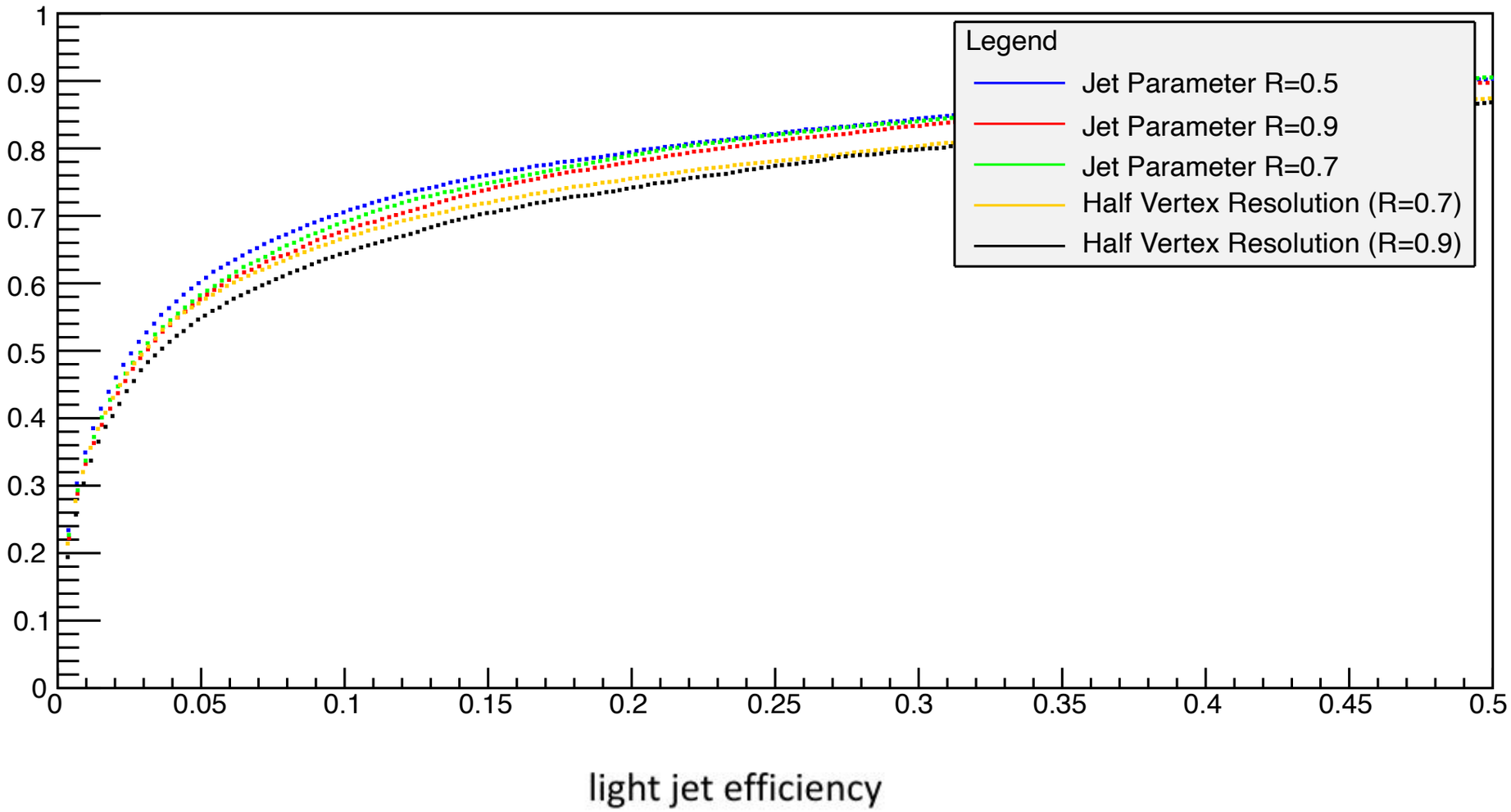
Left: Mean charged multiplicity in B^+ mesons decays



Right: b-quark fragmentation function



- B-tagging algorithms are used to tag the b-jets originating from b quarks. In first data, three algorithms are going to be used:
  - TrackCounting: use tracks with large impact parameter.
  - JetProb: calculate the probability of a track to be from light jet.
  - Secondary Vertex Reconstruction (SV0): use the signed decay length significance of the secondary vertex .


B-jet efficiency vs light-jet efficincy
Legend
Jet Parameter R=0.5
Jet Parameter R=0.9
Jet Parameter R=0.7
Half Vertex Resolution (R=0.7)
Half Vertex Resolution (R=0.9)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
light jet efficiency

Eur. Phys. J. C (2021) 81:178
https://doi.org/10.1140/epjc/s10052-020-08677-2

THE EUROPEAN PHYSICAL JOURNAL C

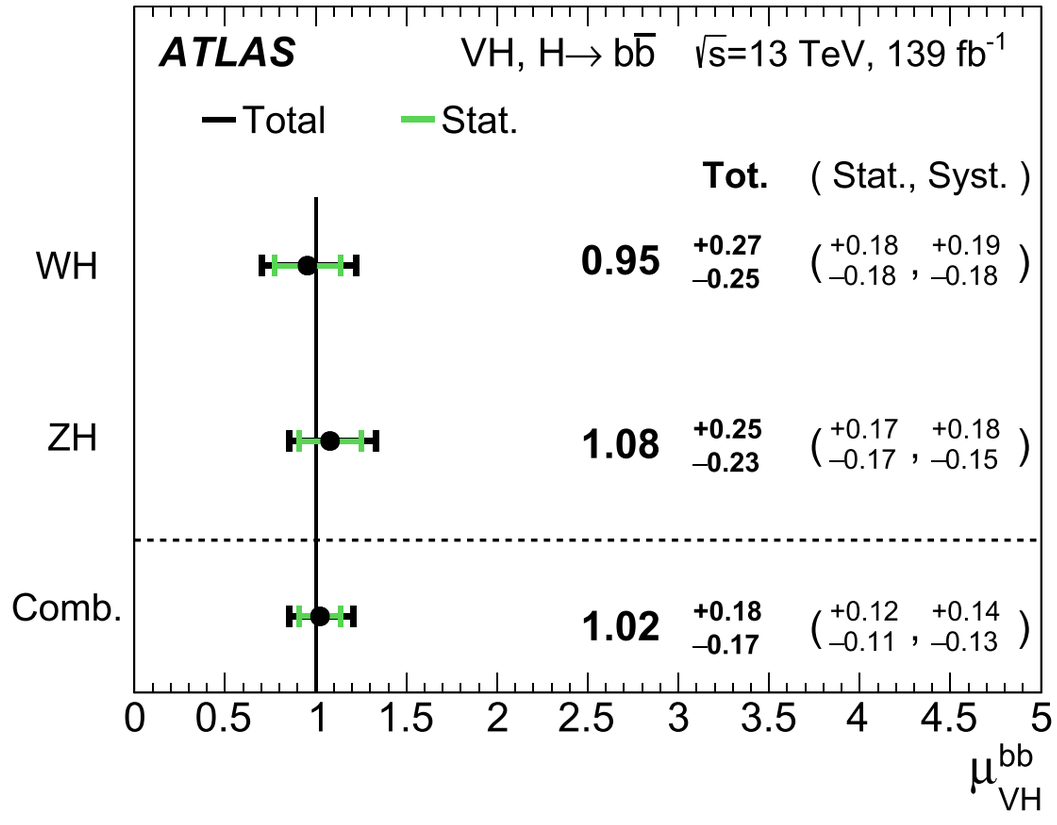
Regular Article - Experimental Physics

139/fb

Measurements of WH and ZH production in the $H \to b\bar{b}$ decay channel in pp collisions at 13 TeV with the ATLAS detector

ATLAS Collaboration*

$$\mu_{VH}^{bb} = 1.02^{+0.18}_{-0.17} = 1.02^{+0.12}_{-0.11}(\text{stat.})^{+0.14}_{-0.13}(\text{syst.}).$$



2007.02873

Physics Letters B 816 (2021) 136204

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Measurement of the associated production of a Higgs boson decaying into b-quarks with a vector boson at high transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration *

VH with pTW>250 GeV and 139/fb

$$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.}).$$

2008.02508

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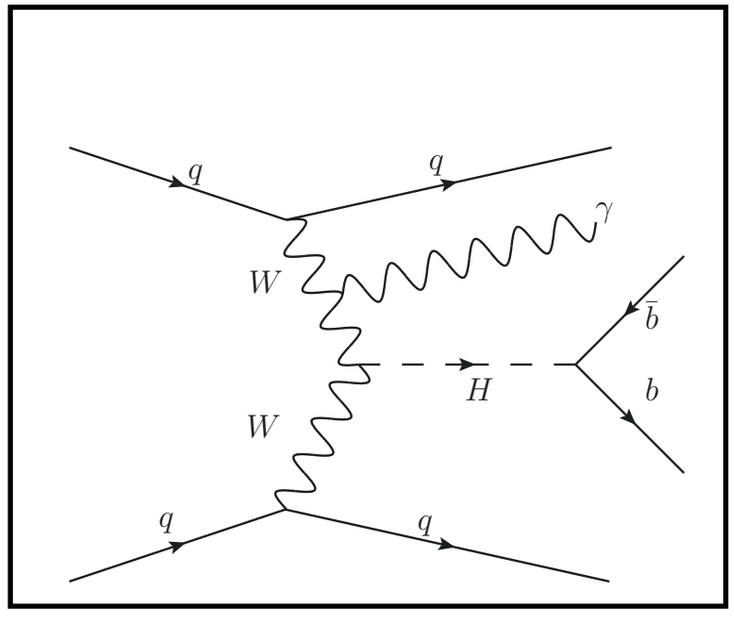
Search for Higgs boson production in association with a high-energy photon via vector-boson fusion with decay into bottom quark pairs at $\sqrt{s} = 13$ TeV with the ATLAS detector

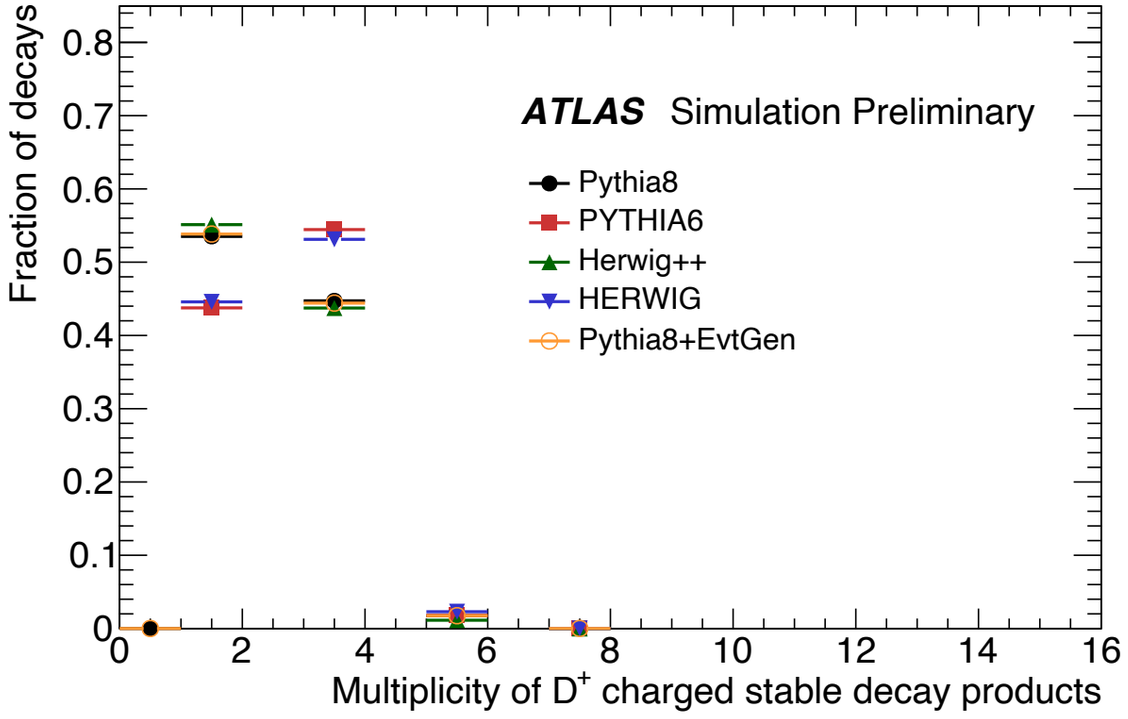


$$\boxed{\mu_H = 1.3 \pm 1.0.}$$

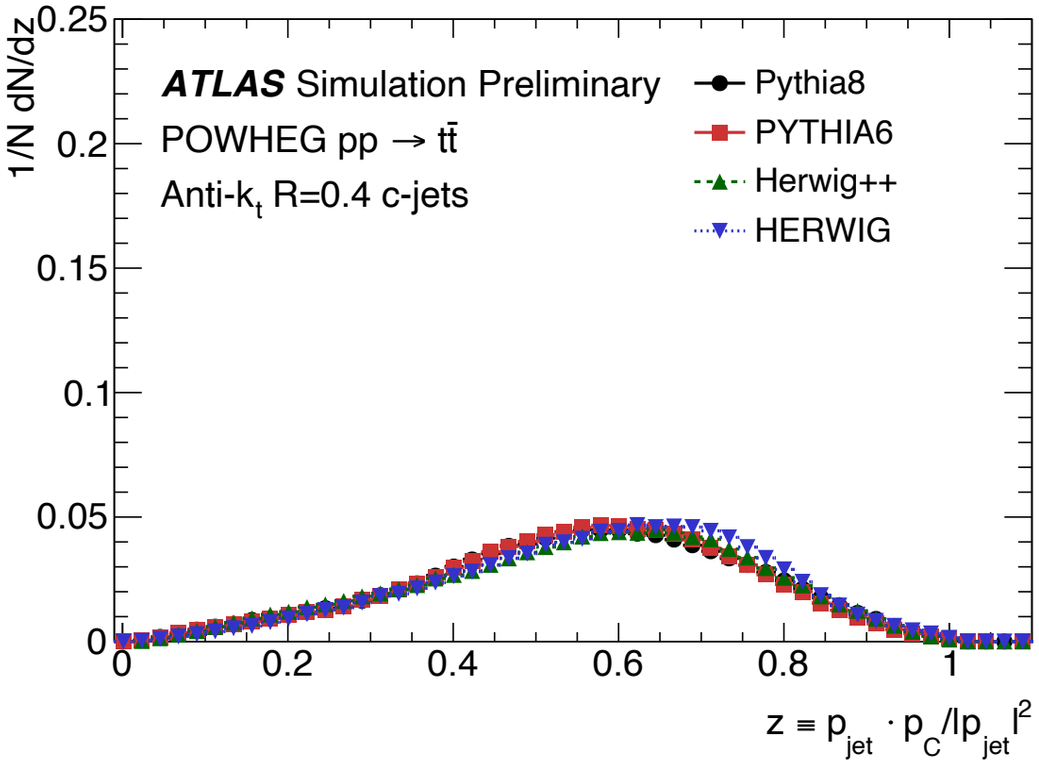
2010.13651

Properties of C hadrons

- **Lifetime:** Shorter than the *b*-hadrons by around a factor of 2-3, still enough for measureable decay length (around 1-3mm for a 50 GeV boost)
- **Mass:** Weakly decaying *c*-hadrons have masses around 2 GeV, around 2–3$\times$ lower than *b*-hadrons (mean of $\approx$ 2 charged particles per decay)
- **Fragmentation:** Softer than *b*-jets, but still harder than jets initiated by light species (*c*-hadrons carry around 55% of jet energy, on average)

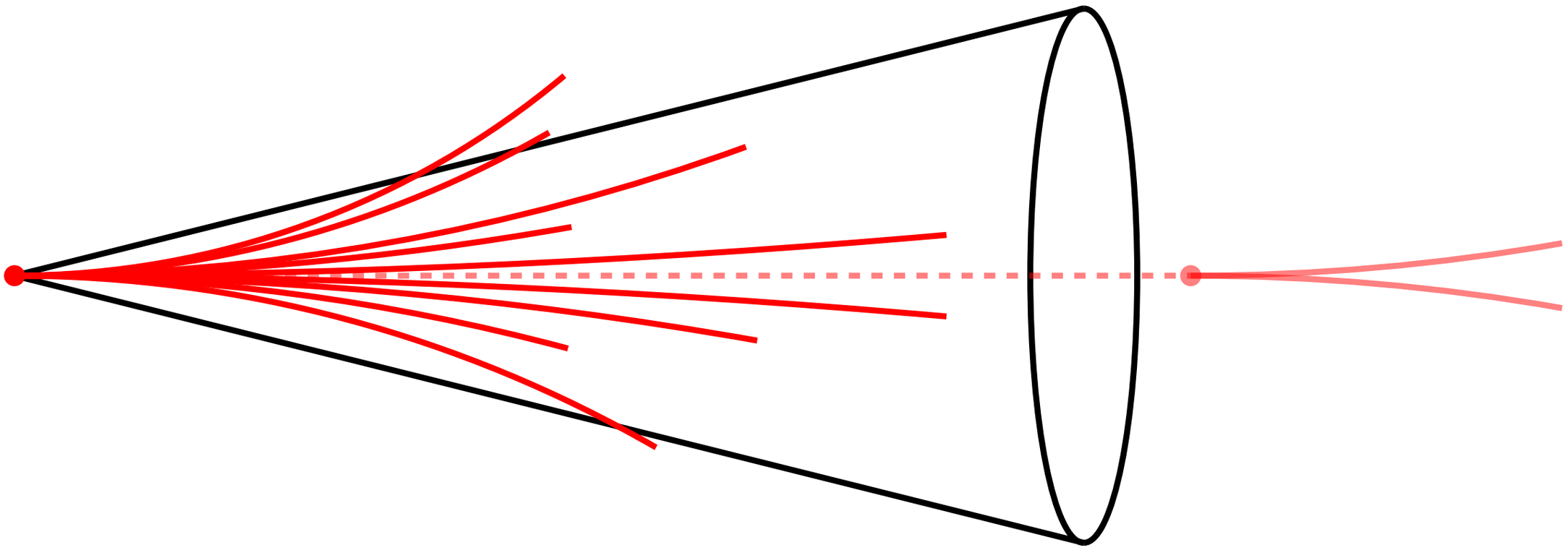


Left: Mean charged multiplicity in D^+ mesons decays



Right: *c*-quark fragmentation function

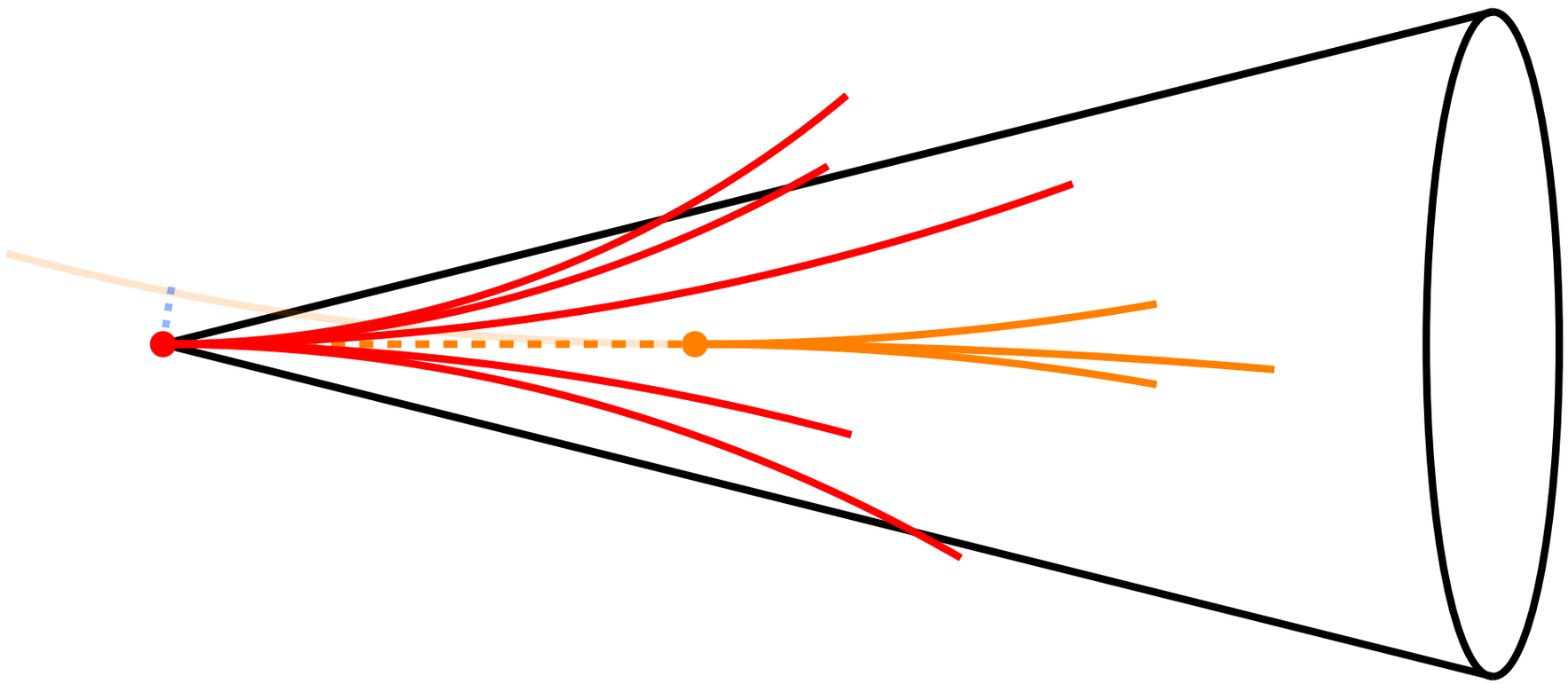
Anatomy of a light flavour (u, d, s) jet



Typical Experimental Signature

- **Light-quarks hadronise into many light hadrons which share the jet energy**
- **Tracks from this vertex often have impact parameters consistent with zero**
- **Long-lived light hadrons (e.g. K_S^0, Λ^0) can be produced, though they are more likely to decay very far (many cm) from the primary *pp* vertex**

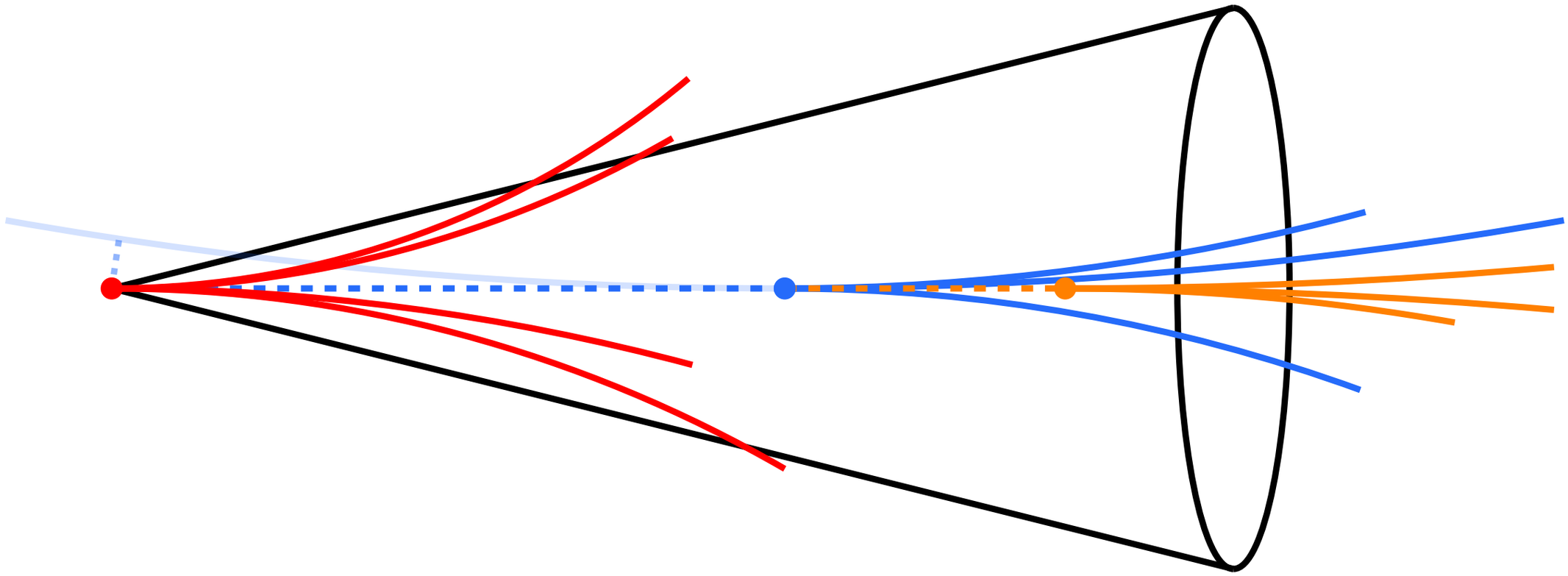
Anatomy of a c-jet



Typical Experimental Signature

- *c*-quark fragments into a *c*-hadron which carries around half of the jet energy
- *c*-hadron decay vertex often displaced from the primary *pp* vertex by a few mm
- Tracks from this vertex can often have large impact parameters

Anatomy of a b-jet



Typical Experimental Signature

- *b*-quark fragments into a *b*-hadron which carries most of the jet energy
- Most *b*-hadrons ($\approx 90\%$) decay into *c*-hadrons
- *b*-hadron decay vertex often displaced from the primary *pp* vertex by a few mm
- Subsequent *c*-hadron decay vertex often displaced by a further few mm
- Tracks from both of these vertices often have large impact parameters

- If a b hadron is found the jet is labeled as a b jet.
- If no b hadron is found, but a c hadron is present, then the jet is labeled as a c jet.
- Otherwise the jet is labeled as a light-flavor jet.

Introduction to charm jet tagging

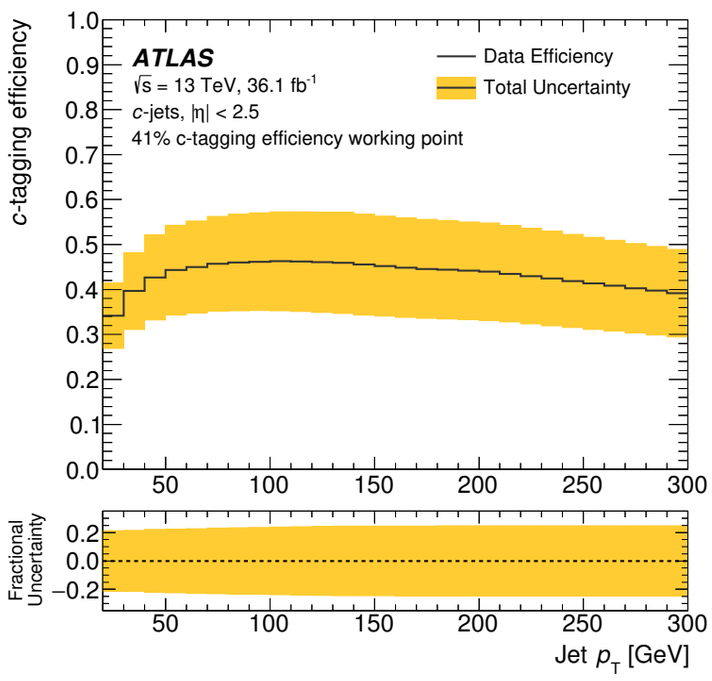
"Exclusive" charm jet tagging

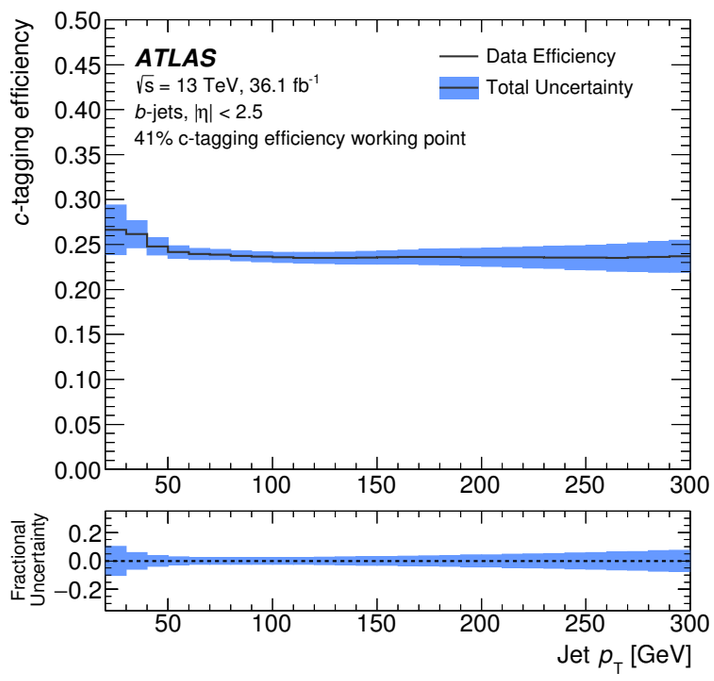
- Focus on the full reconstruction of exclusive c-hadron decay chains (e.g. $D^{\star\pm} \to D^0(K^-\pi^+)\pi^\pm$) or leptons from semi-leptonic c-hadron decays
- ✓ Can often provide a very pure sample of jets containing c-hadrons
- ✗ The efficiency is typically low $\mathcal{O}(1\%)$, limited by the c-hadron branching fractions of interest

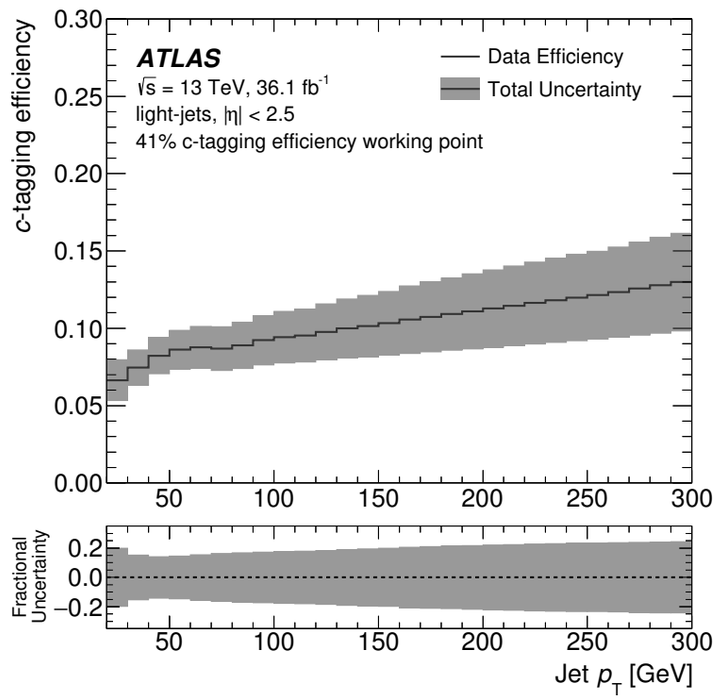
"Inclusive" charm jet tagging

- An alternative approach is to to exploit more "inclusive" observables, such as track impact parameters or secondary vertices
- ✓ The efficiency of this approach is typically very high $\mathcal{O}(10\%)$)
- ✗ The c-jet purity is often lower than these "traditional" approaches
- More suited for use with machine learning (ML) techniques

Performance of the ATLAS c-tagger





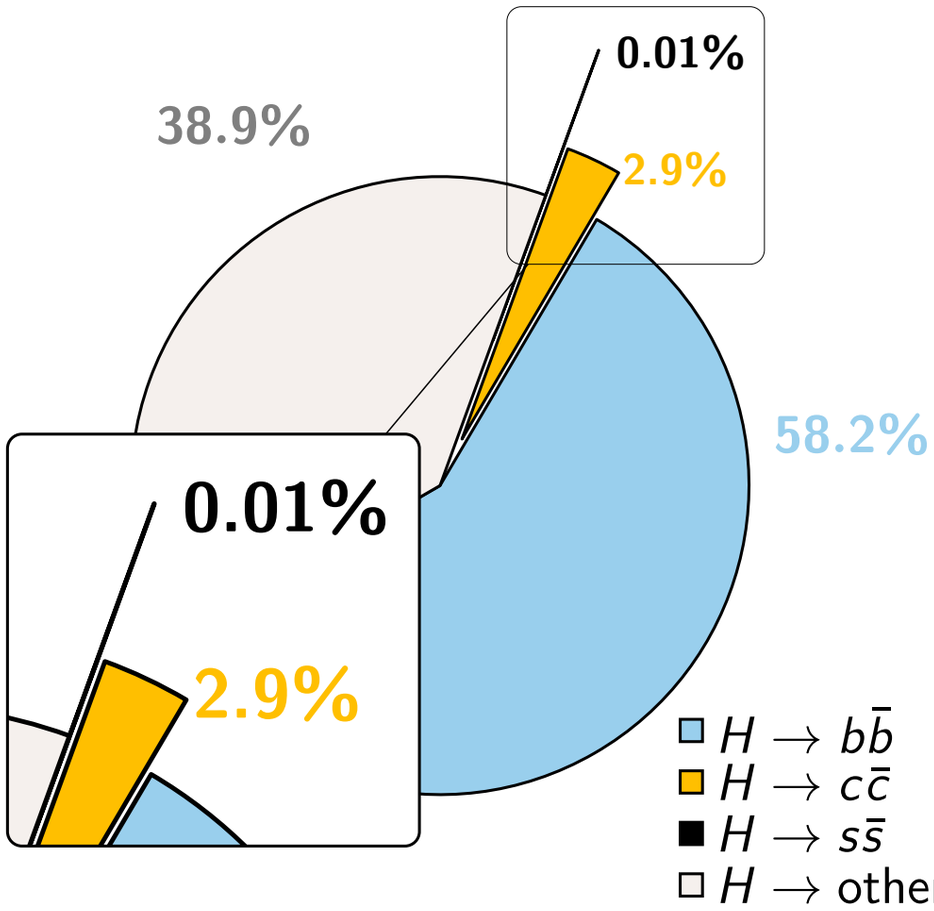


***c*-jets** ***b*-jets** **light flavour (u, d, s, g) jets**

c-tagging efficiency for b-, c- and light flavour jets measured in data ↑

- Working point for $H \to c\bar{c}$ exhibits a c-jet tagging efficiency of around 40%
- Rejects b-jets by around a factor 4× and light jets by around a factor 10×
- Efficiency calibrated in data with samples of b-jets from $t \to Wb$ decays and c-jets from $W \to cs, cd$ decays (in $t\bar{t}$ events)
- Typical total relative uncertainties of around **25%**, **5%** and **20%** for ***c*-**, ***b*-** and **light** jets, respectively

H > cc



What are the existing <u>indirect</u> constraints?

- Constraints on unobserved Higgs decays impose $\mathcal{B}(H \to c\bar{c}) < 20\%$, while global fits indirectly bound Γ_H leading to $y_c/y_c^{SM} < 6$, **assuming SM production and no BSM decays** (arXiv:1310.7029, arXiv:1503.00290)
- Direct bound of around $\Gamma_H < 1$ GeV from $H \to \gamma\gamma$ and $H \to 4\ell$ lineshapes impose around $y_c/y_c^{SM} < 120$, **but this is model independent** (arXiv:1503.00290)

H > cc at the LHC

Idea 1 - **Exclusive $H \to J/\psi\,\gamma$ decays**

- Rare exclusive radiative Higgs boson decays to vector mesons are sensitive to the $Hq\bar{q}$ couplings (arXiv:1503.00290)
- The $H \to J/\psi\,\gamma$ decay has been proposed as a clean probe of the $Hc\bar{c}$ coupling, though decay width "only" evolves as $(\text{const.} + y_c)^2$ ($\text{const.} \gg y_c$)
- ATLAS pioneered searches in this channel during Run 1 (arXiv:1501.03276)

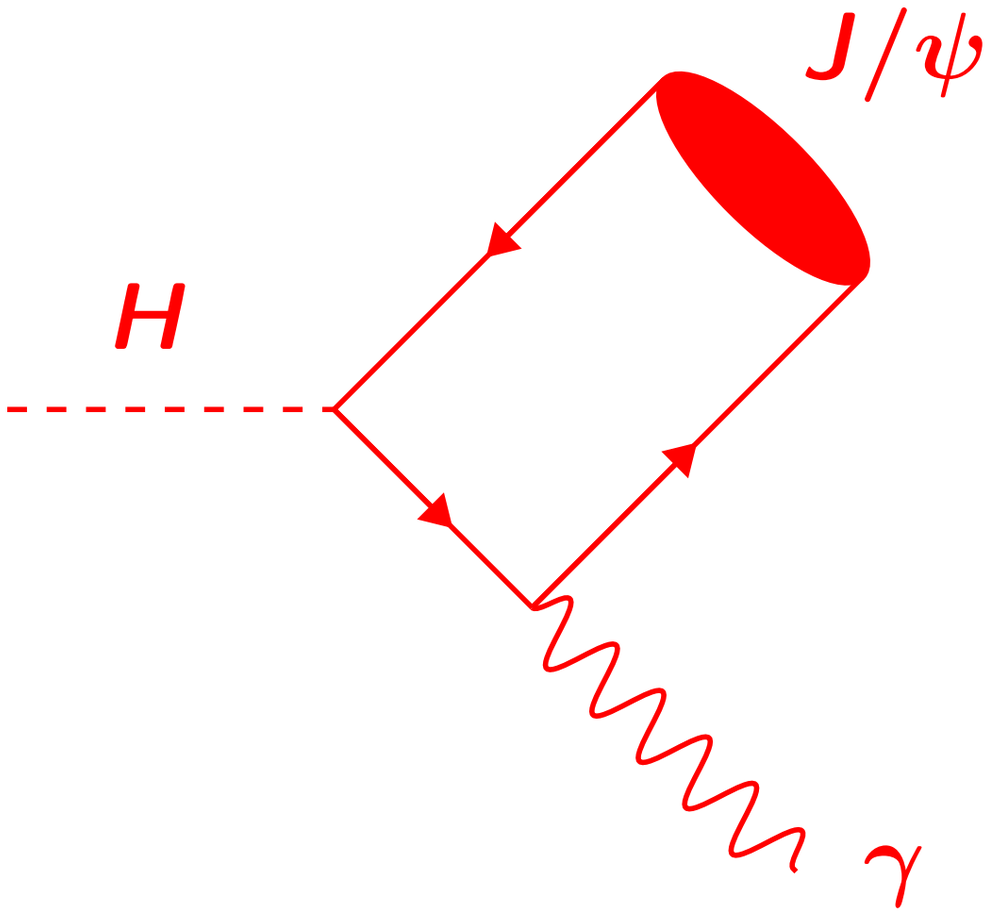
Idea 2 - **Associated production of a Higgs boson and charm quark**

- Tree level sensitivity to $Hc\bar{c}$ coupling (arXiv:1507.02916, arXiv:1606.09253)
- Use jet c-tagging to identify charm quark signature and a suitably "clean" Higgs decay (e.g. $H \to \gamma\gamma$)
- Alternatively, study p_T^H distribution to look for potential shape modifications...

Idea 3 - **Inclusive $H \to c\bar{c}$ decays (The focus of this seminar...)**

- Inclusive $H \to c\bar{c}$ decays are directly sensitive to the $Hc\bar{c}$ coupling, with the decay width evolving as $\Gamma_{H\to c\bar{c}} \propto y_c^2$
- Use double jet c-tagging and focus on VH ($V = W, Z$) production with leptonic V decays to mitigate the large multi-jet backgrounds

H > J/ψ + γ



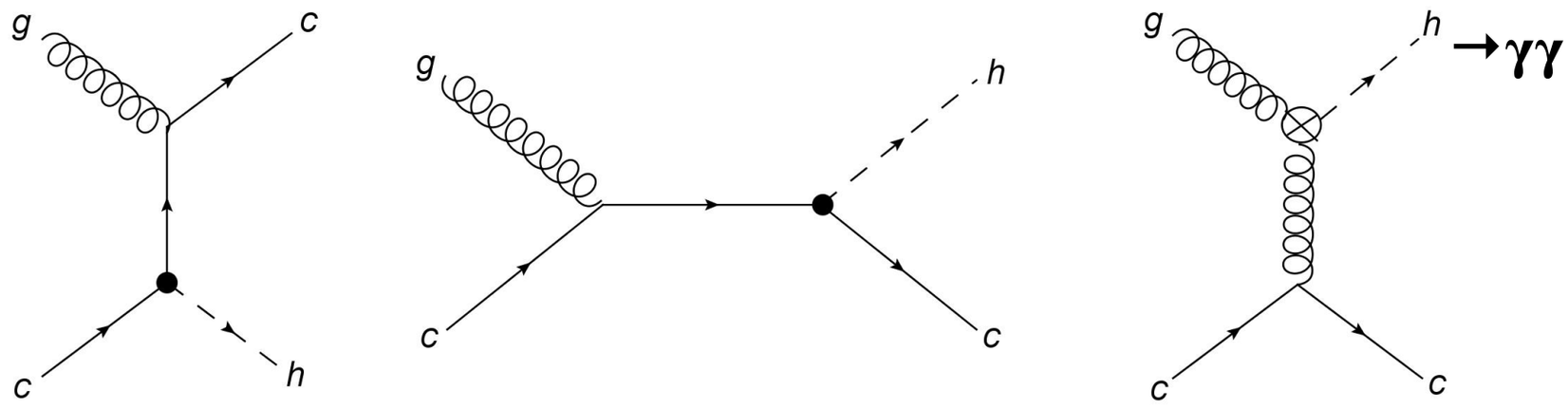
$$\mathcal{B}(H \to J/\psi\,\gamma) = (2.99 \pm 0.16) \times 10^{-6}$$

Expt.	95% CL upper limit on $\mathcal{B}(H \to J/\psi\,\gamma)$		
	Expected	Observed	Obs./$\mathcal{B}_{SM}$
ATLAS†	$(3.0^{+1.4}_{-0.8}) \times 10^{-4}$	3.5×10^{-4}	**117**×
CMS‡	$(5.2^{+2.4}_{-1.6}) \times 10^{-4}$	7.6×10^{-4}	**253**×

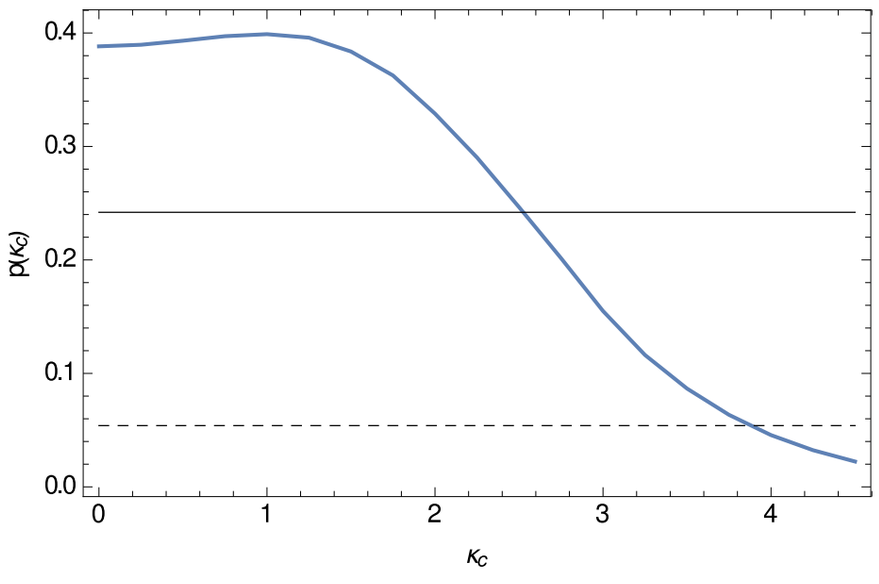
Phys. Lett. B 786 (2018) 134 (arXiv:1807.00802)

Associated Higgs boson + charm quark production

The production of Higgs boson in association with a charm quark is directly sensitive to the charm quark Yukawa coupling

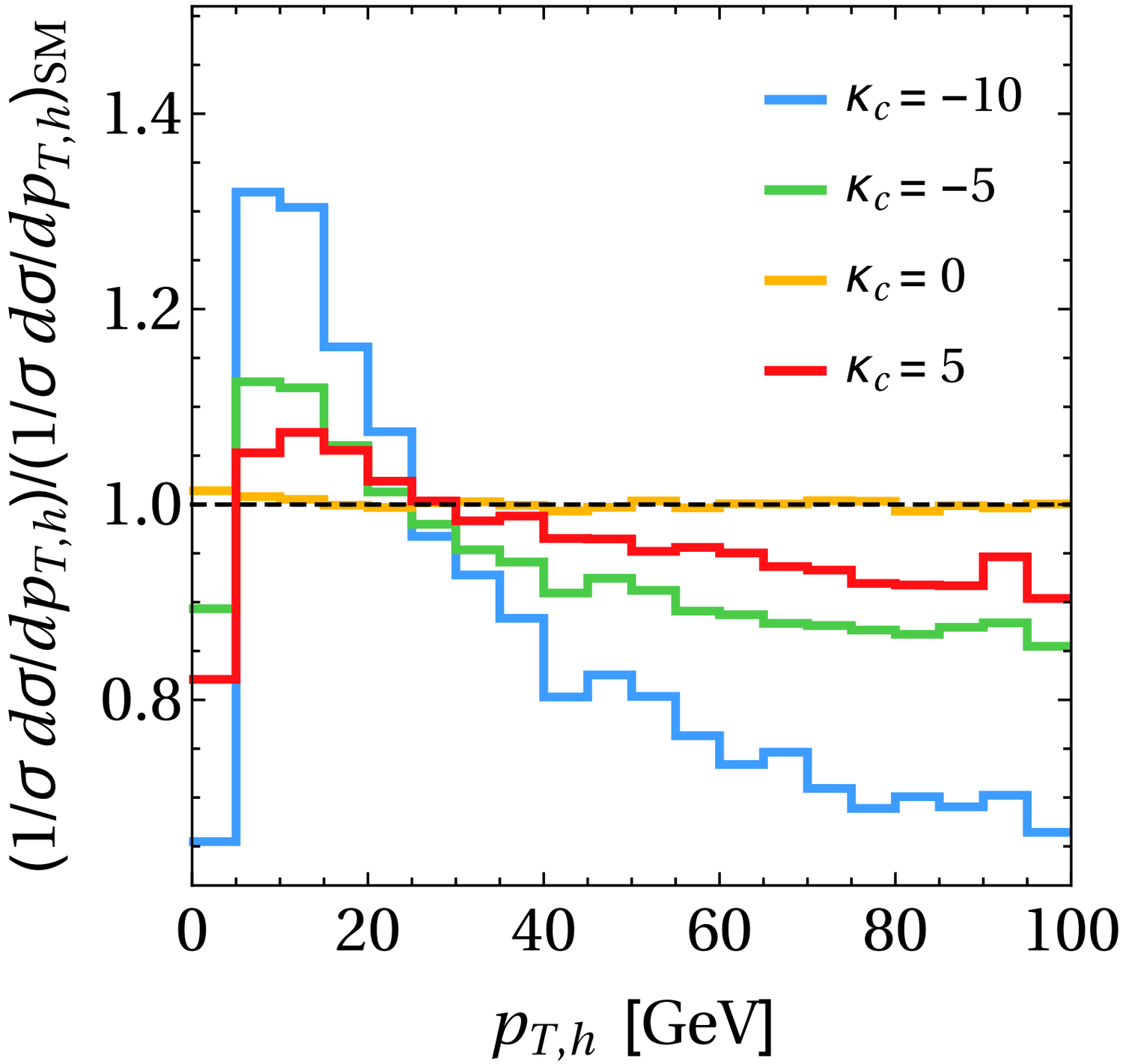


↑ **Examples of "direct" (left and centre) and "indirect" (right) $cg \to Hc$ diagrams (from arXiv:1507.02916)**

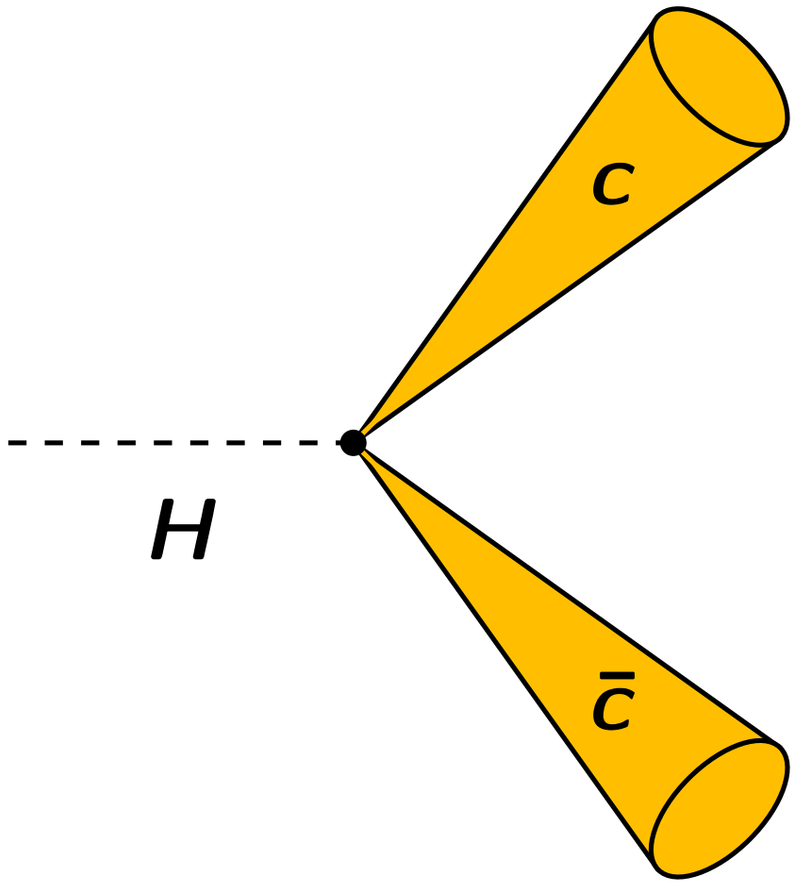


↑ **Expected *p*-value as a function of $\kappa_c = y_c/y_c^{SM}$ (from arXiv:1507.02916)**

- t-channel diagram (left) is expected to dominate the cross-section and is sensitive to the $Hc\bar{c}$ coupling, highly sensitive channel!
- No experimental measurements yet, though the sensitivity at the HL-LHC has been surveyed in the literature (arXiv:1507.02916)
- Assuming a data sample of $3\,\text{ab}^{-1}$ at $\sqrt{s} = 14$ TeV, $\mathcal{O}(1)$ constraints on y_c/y_c^{SM} are expected to be obtained...


$(1/\sigma\, d\sigma/dp_{T,h})/(1/\sigma\, d\sigma/dp_{T,h})_{\mathrm{SM}}$
1.4
1.2
1.0
0.8
$\kappa_c = -10$
$\kappa_c = -5$
$\kappa_c = 0$
$\kappa_c = 5$
0
20
40
60
80
100
$p_{T,h}$ [GeV]

Inclusive H → cc̄ decays

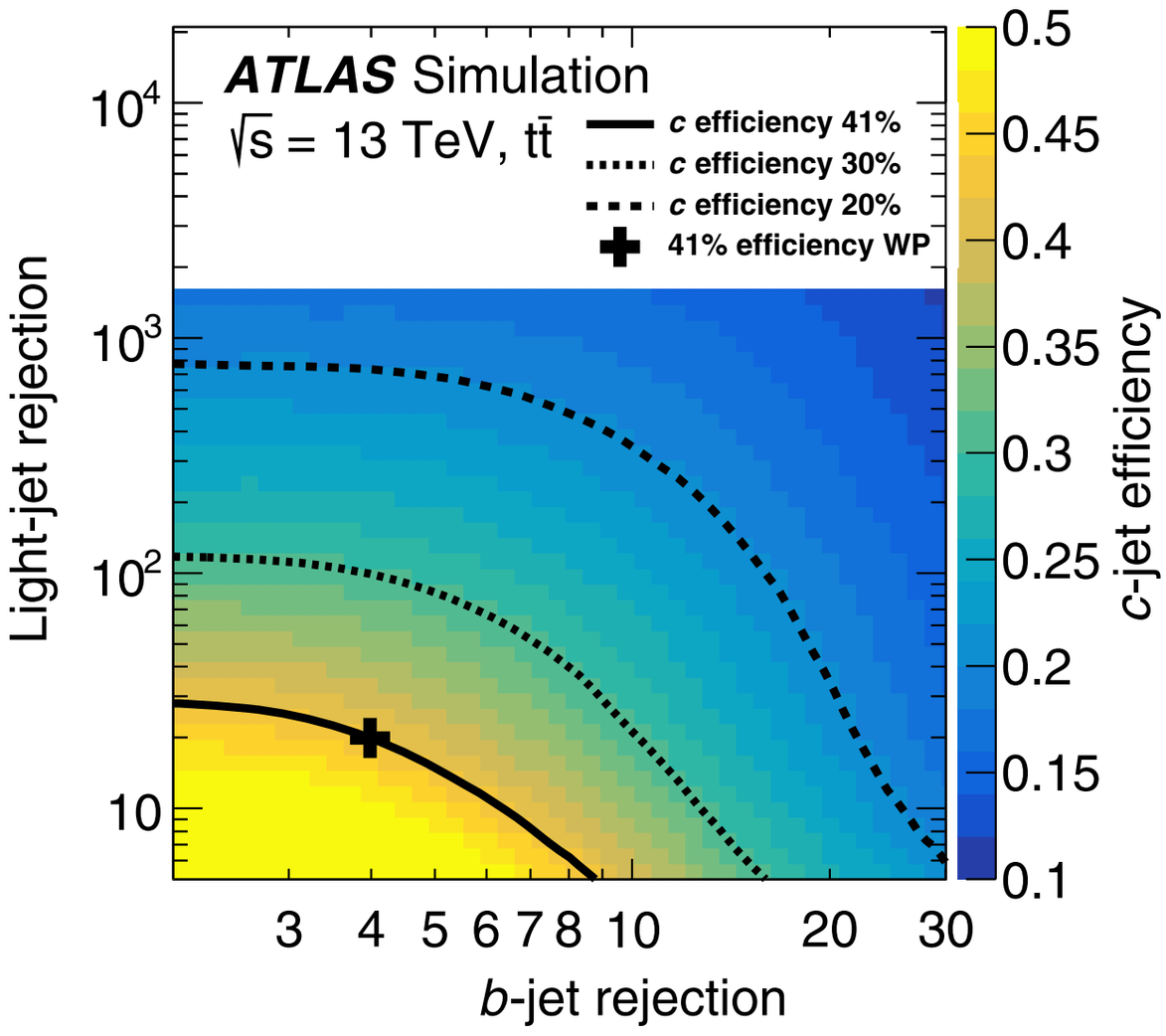


- In $\sqrt{s} = 13$ TeV pp collisions, one expects around 1600 $H \to c\bar{c}$ decays in every $1\,\text{fb}^{-1}$ of data!
- **But**, how can we hope to separate $H \to c\bar{c}$ from the **HUGE** jet background at the LHC?

Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment

M. Aaboud *et al.*[*]
(ATLAS Collaboration)

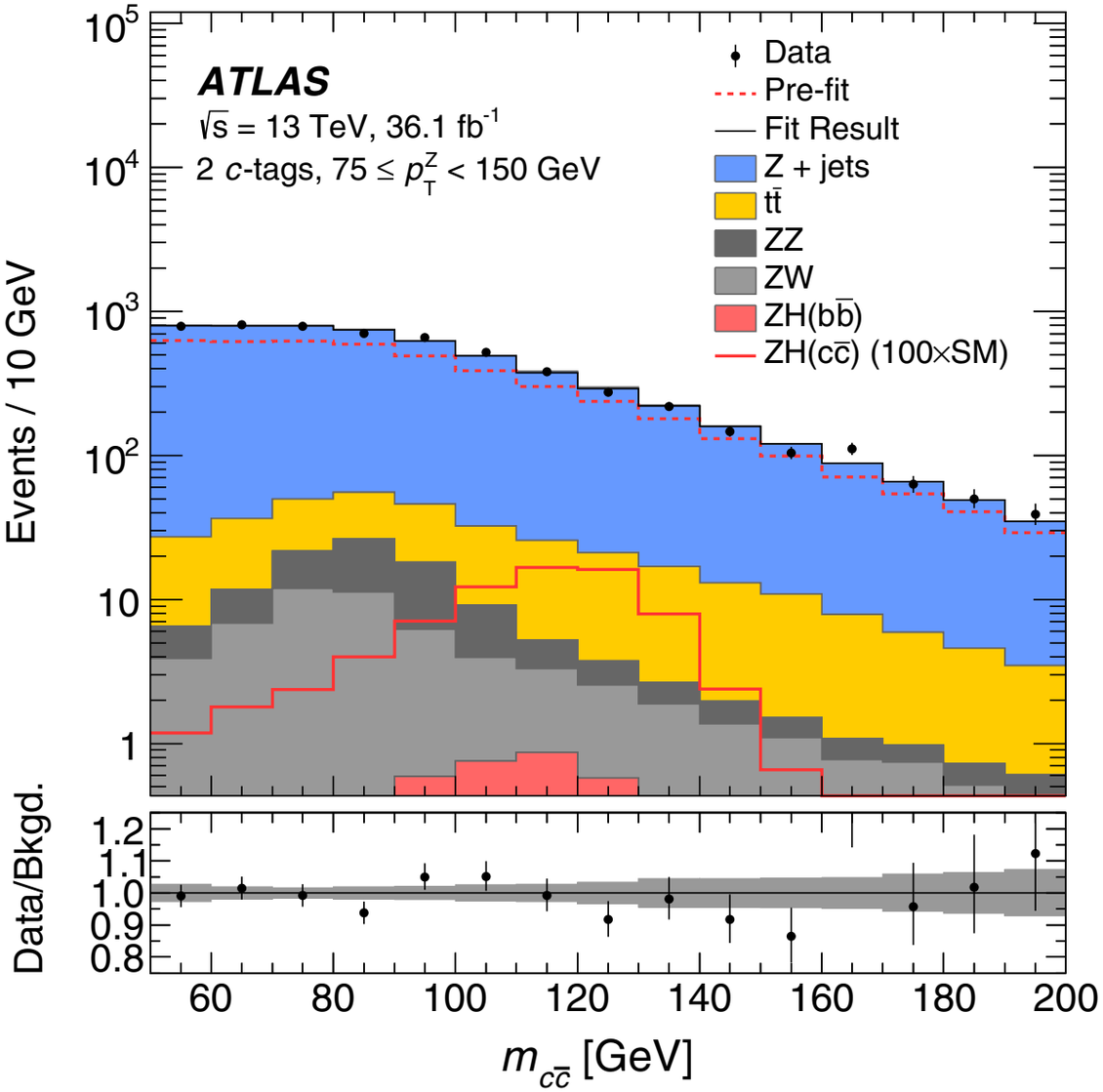
$$ZH \to \ell^+\ell^- c\bar{c}$$

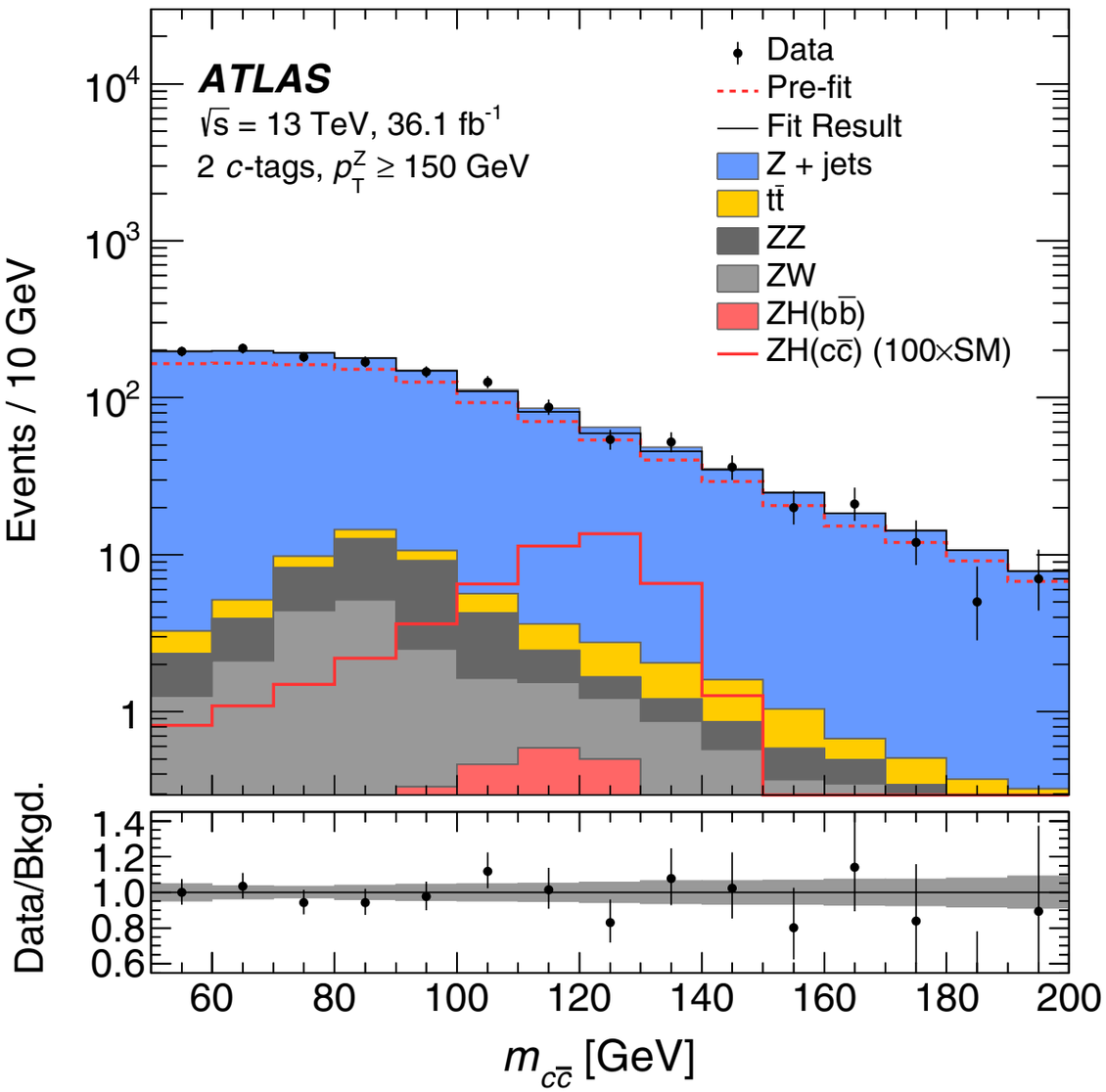


The c-jet-tagging efficiency (colored scale) as a function of the b jet and l jet rejection

TABLE III. Postfit yields for the signal and background processes in each category from the profile likelihood fit. Uncertainties include statistical and systematic contributions. The prefit SM expected $ZH(c\bar{c})$ signal yields are indicated in parenthesis.

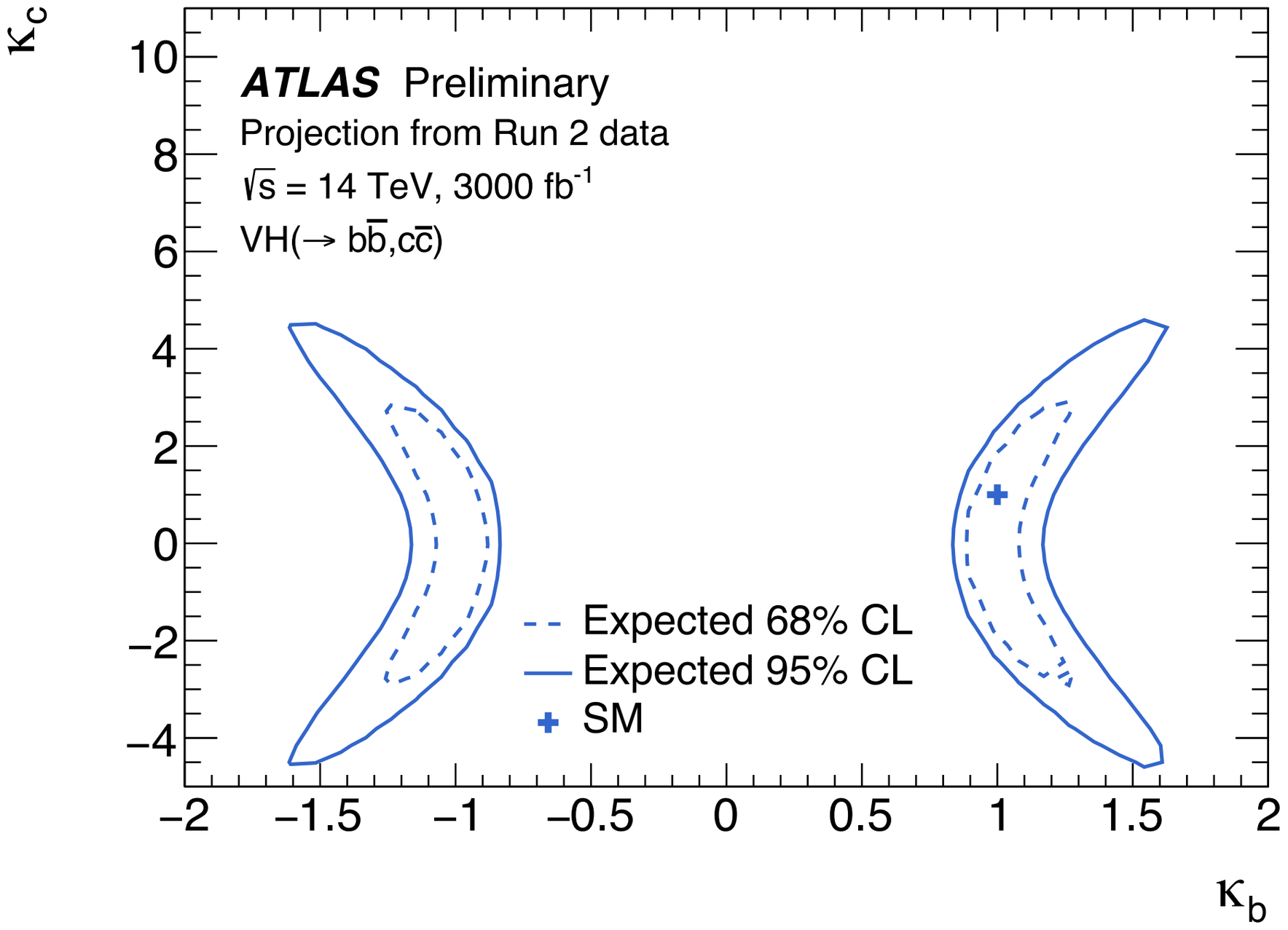
Sample	Yield, 50 GeV $< m_{c\bar{c}} <$ 200 GeV			
	1 c tag		2 c tags	
	$75 \leq p_{\mathrm{T}}^{Z} < 150$ GeV	$p_{\mathrm{T}}^{Z} \geq 150$ GeV	$75 \leq p_{\mathrm{T}}^{Z} < 150$ GeV	$p_{\mathrm{T}}^{Z} \geq 150$ GeV
$Z+$jets	69400 ± 500	15650 ± 180	5320 ± 100	1280 ± 40
ZW	750 ± 130	290 ± 50	53 ± 13	20 ± 5
ZZ	490 ± 70	180 ± 28	55 ± 18	26 ± 8
$t\bar{t}$	2020 ± 280	130 ± 50	240 ± 40	13 ± 6
$ZH(b\bar{b})$	32 ± 2	19.5 ± 1.5	4.1 ± 0.4	2.7 ± 0.2
$ZH(c\bar{c})$ (SM)	$-143 \pm 170\,(2.4)$	$-84 \pm 100\,(1.4)$	$-30 \pm 40\,(0.7)$	$-20 \pm 29\,(0.5)$
Total	72500 ± 320	16180 ± 140	5650 ± 80	1320 ± 40
Data	72504	16181	5648	1320





an observed upper limit on μ at the 95% C.L. of 110

ATLAS PUB Note
ATL-PHYS-PUB-2021-039
22nd October 2021

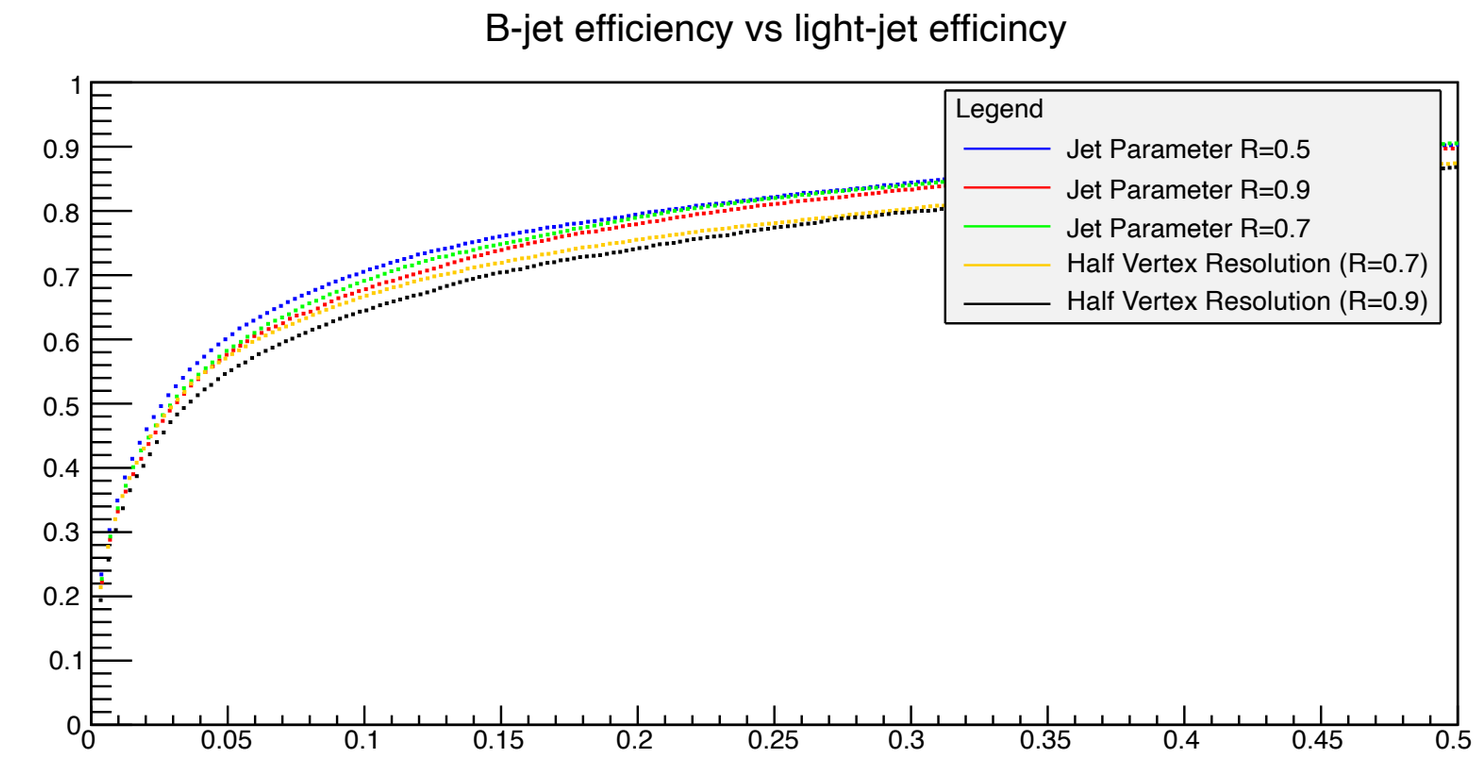


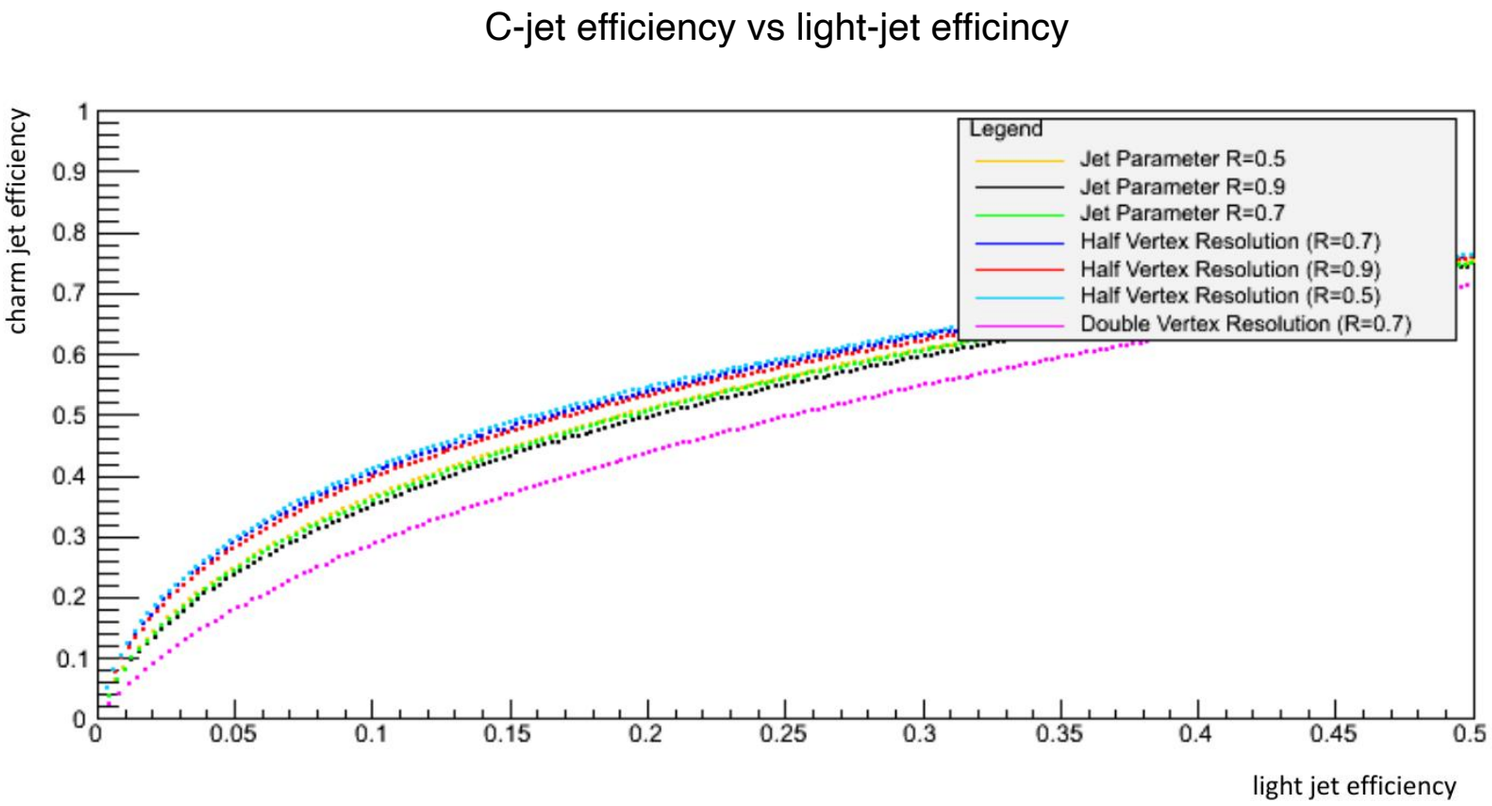
Can LHeC do better?

Higgs at LHeC vs Fcc-eh

		Number of Events			
		Charged Current		Neutral Current	
Channel	Fraction	LHeC	FCC-eh	LHeC	FCC-eh
$b\bar{b}$	0.581	114 500	1 208 000	14 000	175 000
W^+W^-	0.215	42 300	447 000	5 160	64 000
gg	0.082	16 150	171 000	2000	25 000
$\tau^+\tau^-$	0.063	12 400	131 000	1 500	20 000
$c\bar{c}$	0.029	5700	60 000	700	9 000
ZZ	0.026	5 100	54 000	620	7 900
$\gamma\gamma$	0.0023	450	5 000	55	700
$Z\gamma$	0.0015	300	3 100	35	450
$\mu^+\mu^-$	0.0002	40	410	5	70
σ [pb]		0.197	1.04	0.024	0.15

H →bb, cc





At DELPHES detector level using a CC multi-jet sample and for an integrated luminosity of 100 fb−1. The coloured lines correspond to the choice of the anti-kt distance parameter R and different assumptions in the impact parameter resolution of 10 (5) μm (nominal, no text added in legend), 5 (2.5) μm (Half Vertex Resolution), 20 (10) μm (Double Vertex Resolution) for tracks with $0.5 < pT < 5 (> 5)$ GeV within $|\eta| < 3.5$.

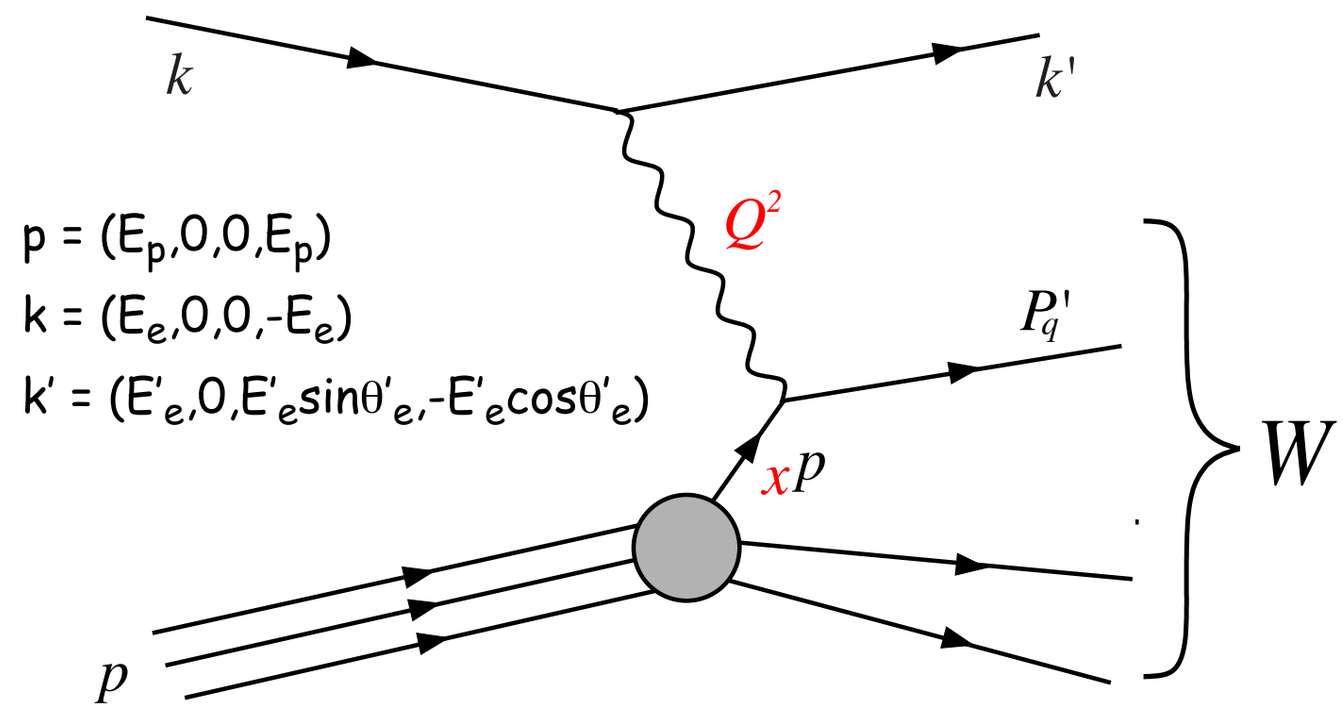
Kinematics at ep

DIS Kinematics

$s = (k+p)^2 = 4E_eE_p$	Centre-of-mass energy squared
$Q^2 = -q^2 = (k-k')^2 = 2E_eE'_e(1-\cos\theta'_e)$	Negative squared four momentum transfer
$\upsilon = q.p/M_p$	Energy transfer in proton rest frame
$\upsilon_{max} = s/(2M_p)$	Maximum energy transfer
$y = (q.p)/(k.p) = \upsilon/\upsilon_{max}$	Fraction of energy transfer
$x = Q^2/(2q.p)$	Bjorken scaling variable
$W^2 = (p+q)^2 = M_p - Q^2 + 2M_p\upsilon$	Invariant mass of total hadronic system

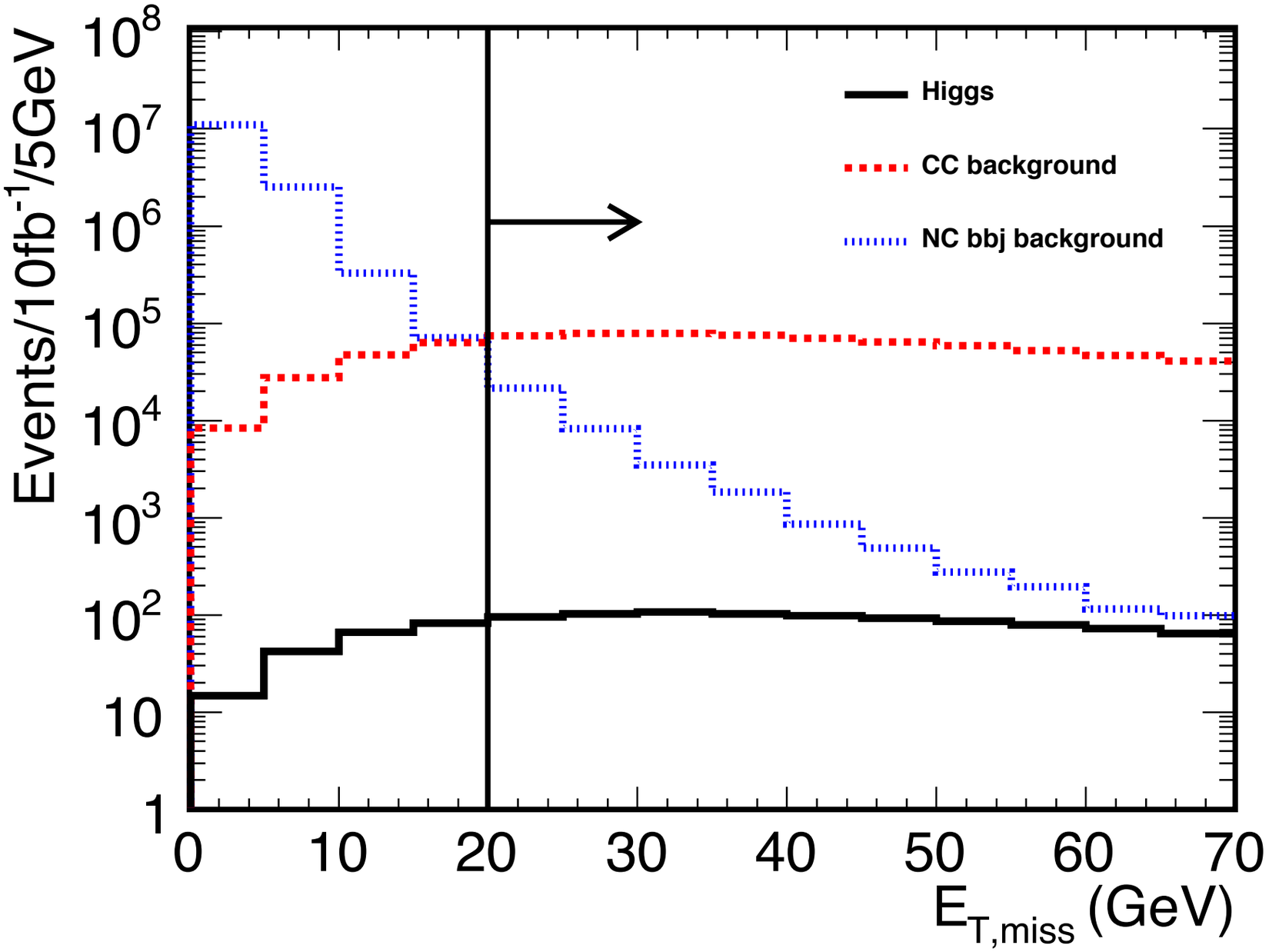
$$Q^2 = sxy$$

At fixed s only two independent variables



CDR-1: h>bb through CC

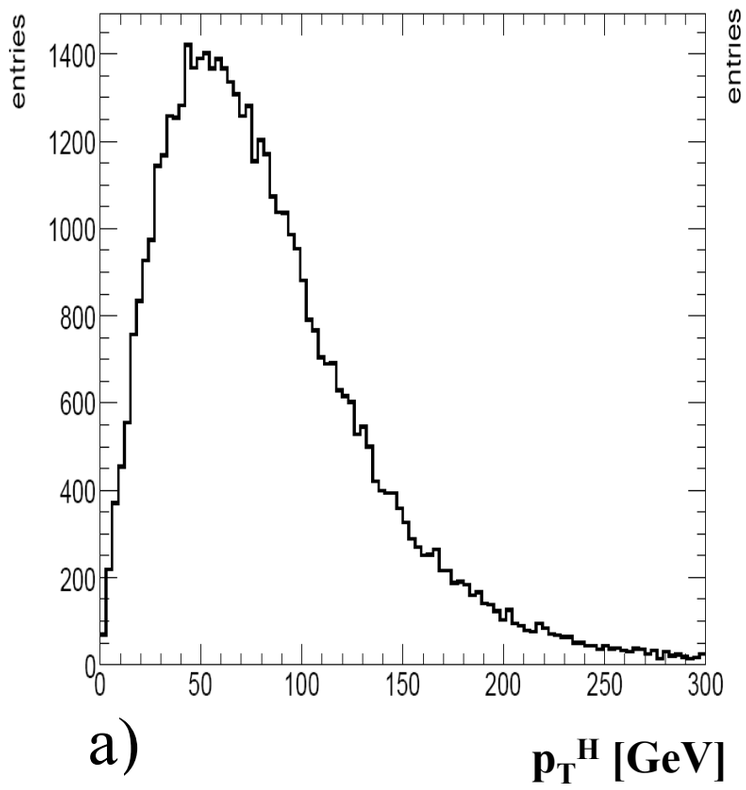
- **cut (1): Primary cuts**
  - Exclude electron-tagged events
  - $E_{T,miss} > 20\,\mathrm{GeV}$
  - $N_{jet}(P_{T,jet} > 20\,\mathrm{GeV}) \geq 3$
  - $E_{T,total} > 100\,\mathrm{GeV}$
  - $y_{JB} < 0.9$, where $y_{JB} = \Sigma(E - p_z)/2E_e$, as shown in Fig. 5.27 c)
  - $Q^2_{JB} > 400\,\mathrm{GeV}$, where $Q^2_{JB} = E^2_{T,miss}/(1 - y_{JB})$, as shown in Fig. 5.27 d)

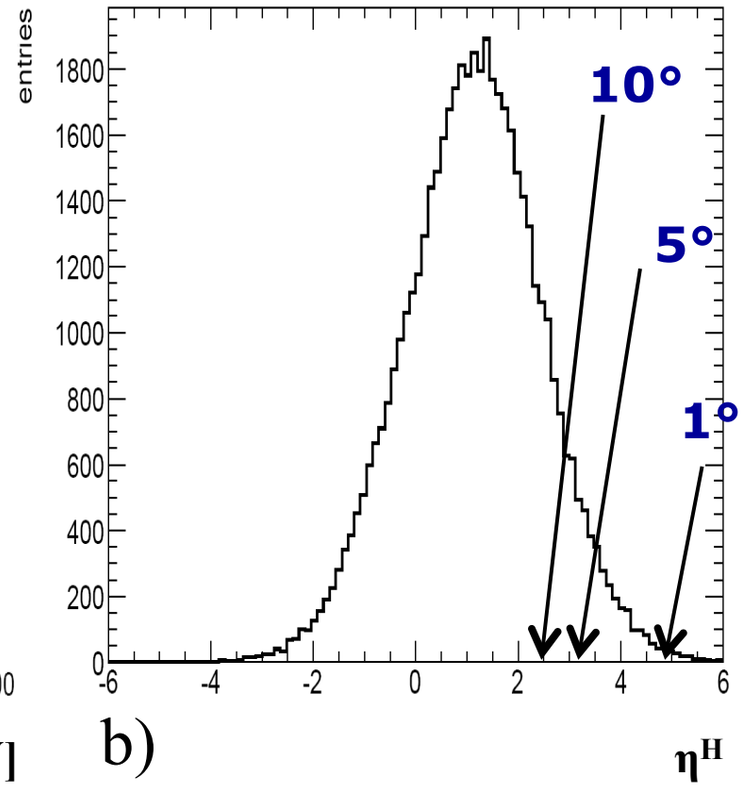

Events/10fb^{-1}/5GeV
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
0
10
20
30
40
50
60
70
$E_{T,miss}$ (GeV)
Higgs
CC background
NC bbj background

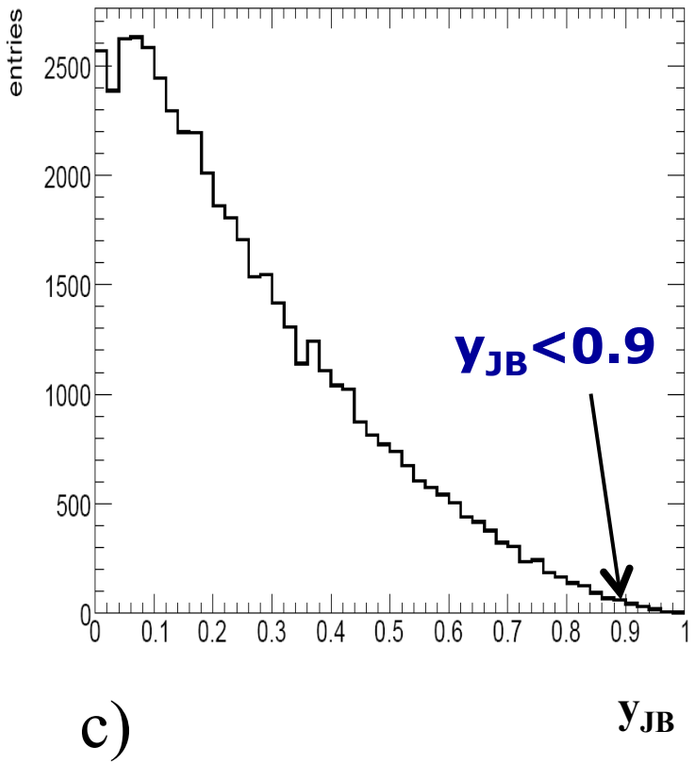
CDR-1: h>bb through CC

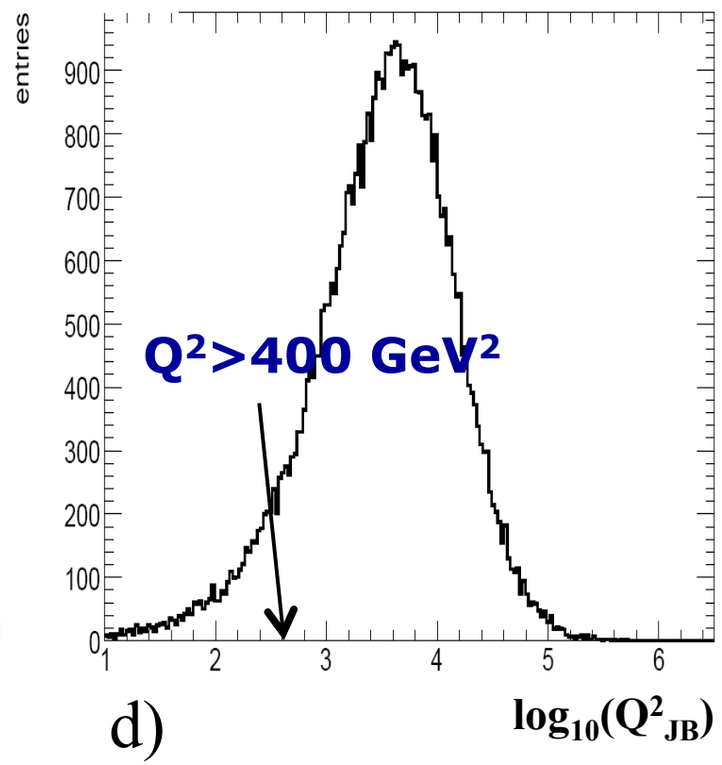
- **cut (1): Primary cuts**
  - Exclude electron-tagged events
  - $E_{T,miss} > 20\,\mathrm{GeV}$
  - $N_{jet}(P_{T,jet} > 20\,\mathrm{GeV}) \geq 3$
  - $E_{T,total} > 100\,\mathrm{GeV}$
  - $y_{JB} < 0.9$, where $y_{JB} = \Sigma(E - p_z)/2E_e$, as shown in Fig. 5.27 c)
  - $Q^2_{JB} > 400\,\mathrm{GeV}$, where $Q^2_{JB} = E^2_{T,miss}/(1 - y_{JB})$, as shown in Fig. 5.27 d)

Kinematics of the Higgs boson at LHeC





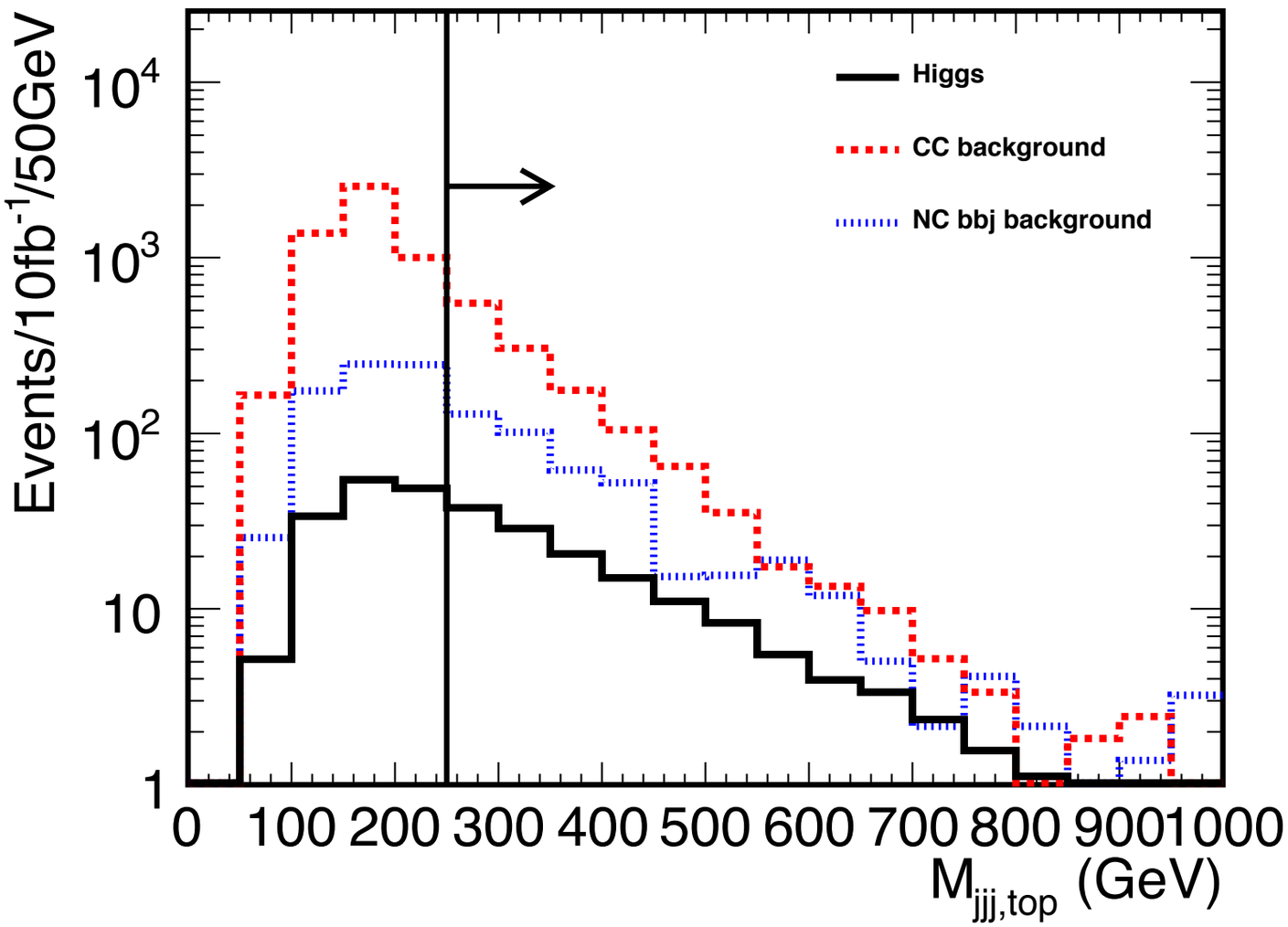




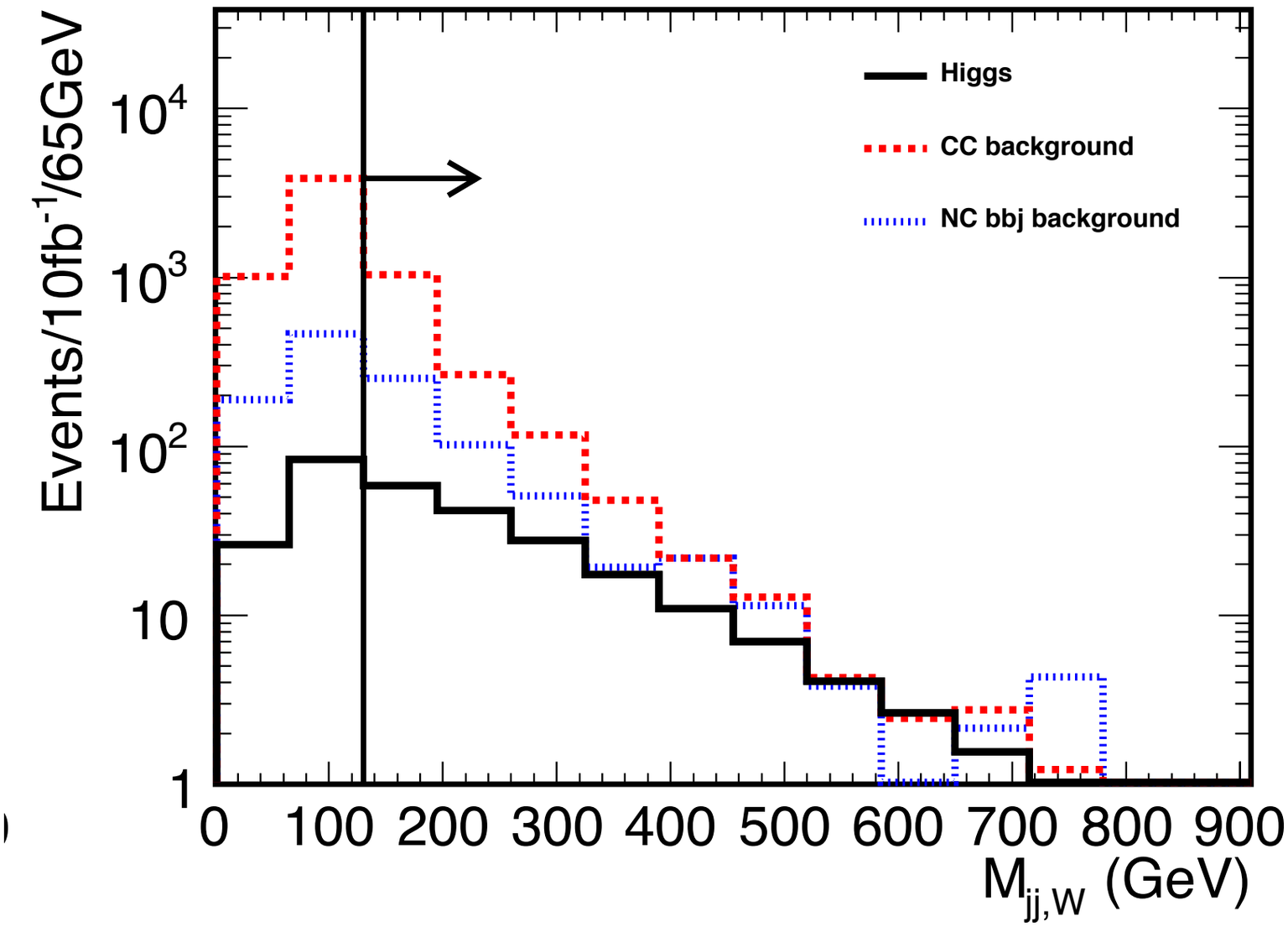
- **cut (2): b-tag requirement**
  - $N_{b\text{-}jet}(P_{T,jet} > 20\,\mathrm{GeV}) \geq 2$, where b-jet means a b-tagged jet
- **cut (3): Higgs invariant mass cut**
  - $90 < M_H < 120\,\mathrm{GeV}$; due to the energy carried by the neutrino from b decays, the mass peaks are slightly lower than the true Higgs mass

- **cut (4): Rejection of single top production** Single top events result in a final state with one b-jet and a W boson decaying into two light-quark jets. The following cuts are found to be efficient in suppressing this background.

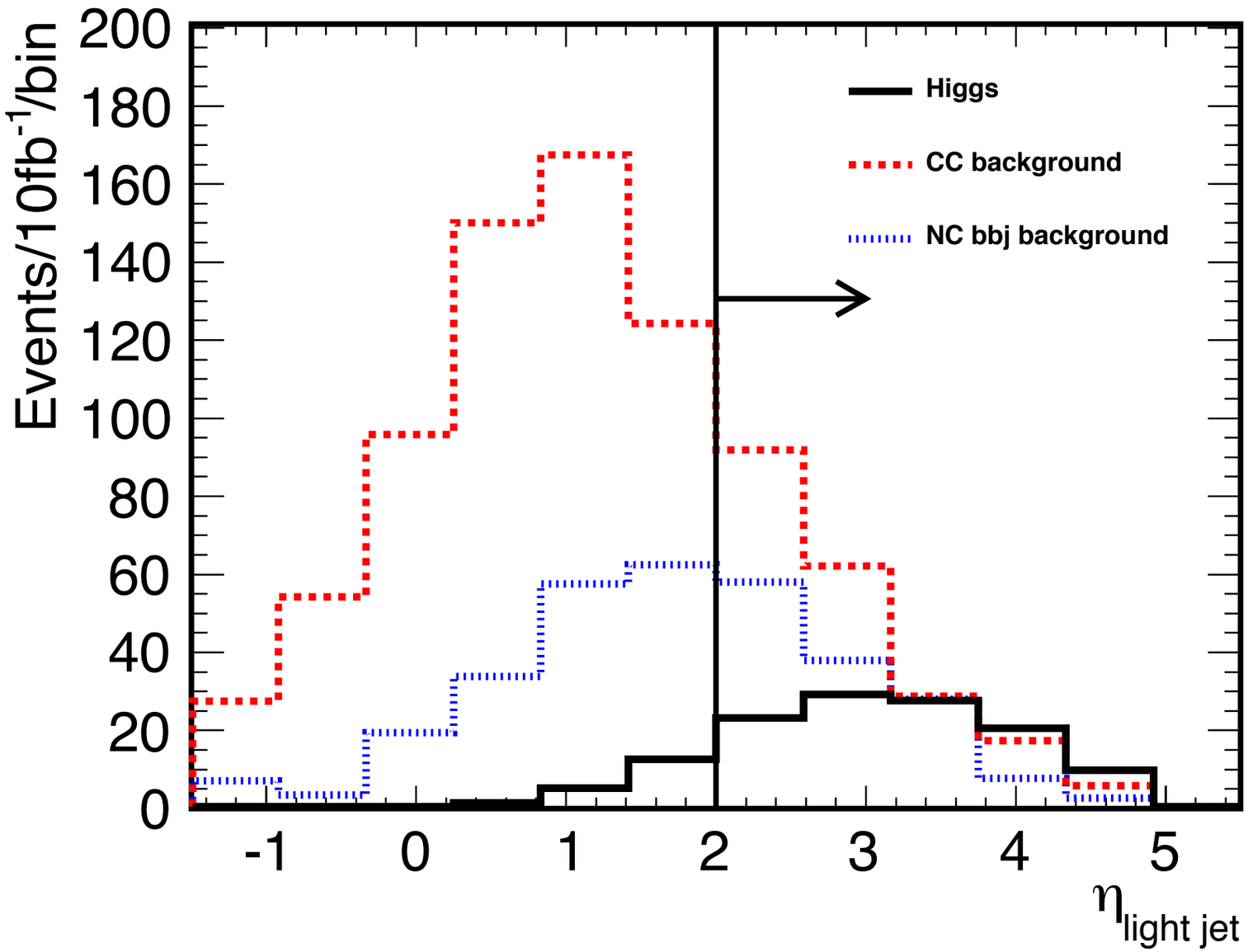
  - $M_{jjj,top} > 250\,\mathrm{GeV}$, where the three-jet invariant mass ($M_{jjj,top}$) is reconstructed from three mainly centrally produced jets using two b-tagged jets with the lowest η and any third jet with the lowest η (b-tag not required for the third jet)

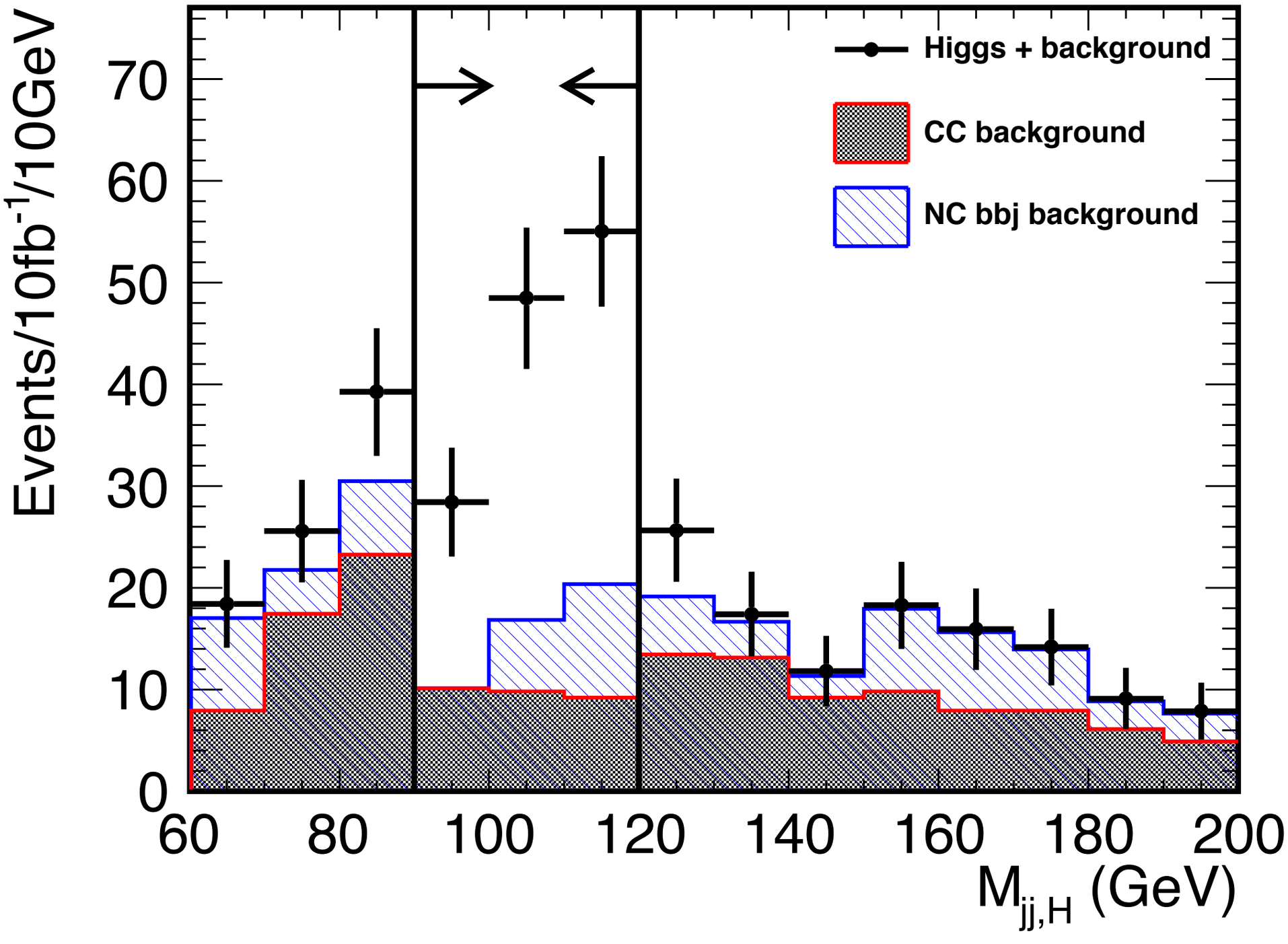


– $M_{jj,W} > 130\,\text{GeV}$, where the di-jet invariant mass ($M_{jj,W}$) is reconstructed from one b-tagged jet with the lowest η and any second jet with the lowest η regardless of b-tag but excluding the second lowest η b-jet



- **cut (5): Forward jet tagging**
  - $\eta_{jet} > 2$ for the jet with the lowest pseudorapidity (lowest-η jet) but excluding the two b-tagged jets used to reconstruct the Higgs boson candidate

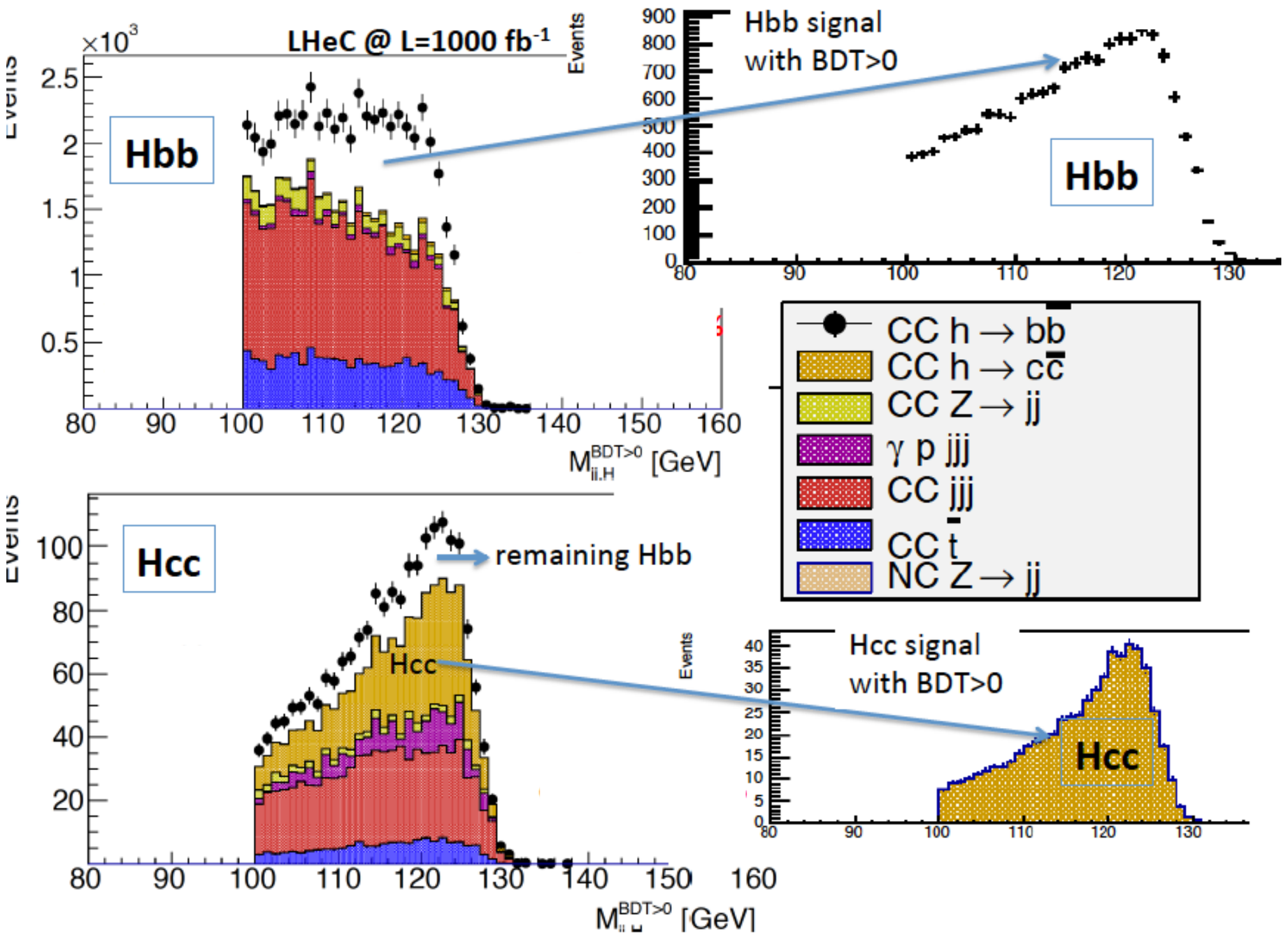



Higgs + background
CC background
NC bbj background
Events/10fb^{-1}/10GeV
0
10
20
30
40
50
60
70
60
80
100
120
140
160
180
200
$M_{jj,H}$ (GeV)

CDR 2020: h>bb

- CC DIS kinematic cuts of $Q_h^2 > 500$ GeV^2, $y_h < 0.9$, missing energy $E_T^{\text{miss}} > 30$ GeV, and no electrons in the final state to reject NC DIS;
- at least three anti-kt $R = 0.7$ jets with $p_T > 20$ GeV which are subject to further b-tagging requirements;
- a Higgs candidate from two b-tagged jets with b-tagging efficiencies of 60 to 75 %, charm (light quark) misidentification efficiencies of 10 to 5 % (1 %) ;
- rejection of single-top events via requiring a dijet W candidate mass of greater than 130 GeV and a three-jet top candidate mass of larger than 250 GeV using a combination with one of the b-jets of the Higgs mass candidate;
- a forward scattered jet with $\eta > 2$, and a large $\Delta\phi_{b,MET} > 0.2$ between the b-tagged jet and the missing energy.

The dominant backgrounds are CC DIS multijet and single top production.
The background due to multijets from photoproduction, where Q2 ~ 0, can be reduced considerably due to the tagging of the small angle scattered electron with an electron tagger.

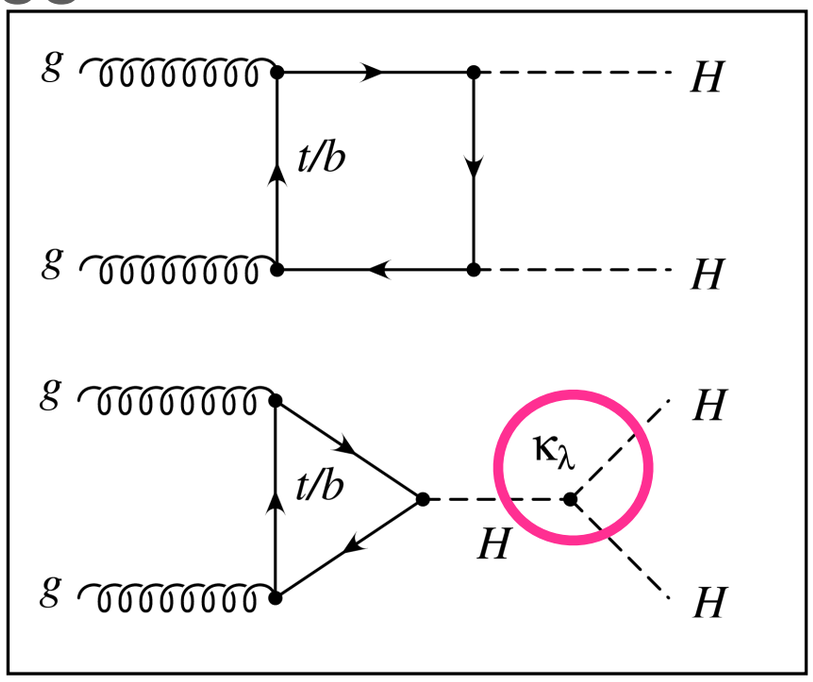

LHeC @ L=1000 fb-1
×10^3
Events
Hbb
M_ll,H^BDT>0 [GeV]
Hbb signal
with BDT>0
Hbb
CC h → bb
CC h → cc̄
CC Z → jj
γ p jjj
CC jjj
CC t
NC Z → jj
Hcc
remaining Hbb
Hcc
M_ll,□^BDT>0 [GeV]
Hcc signal
with BDT>0
Hcc

5. Why is the ep collider better for HHWW?

HH: very challenging

Dominant!

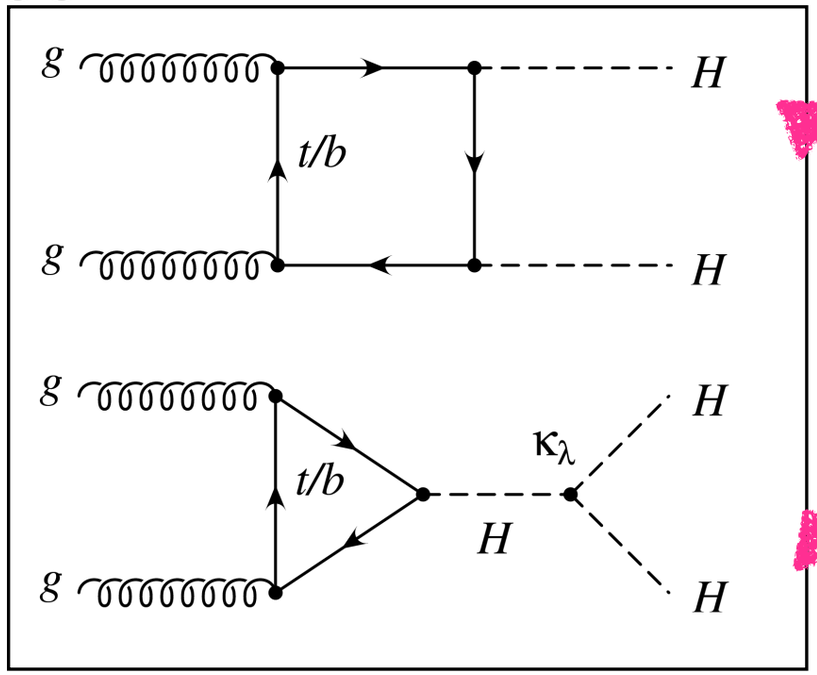
ggHH LO PRODUCTION



- ggHH sensitive to λ

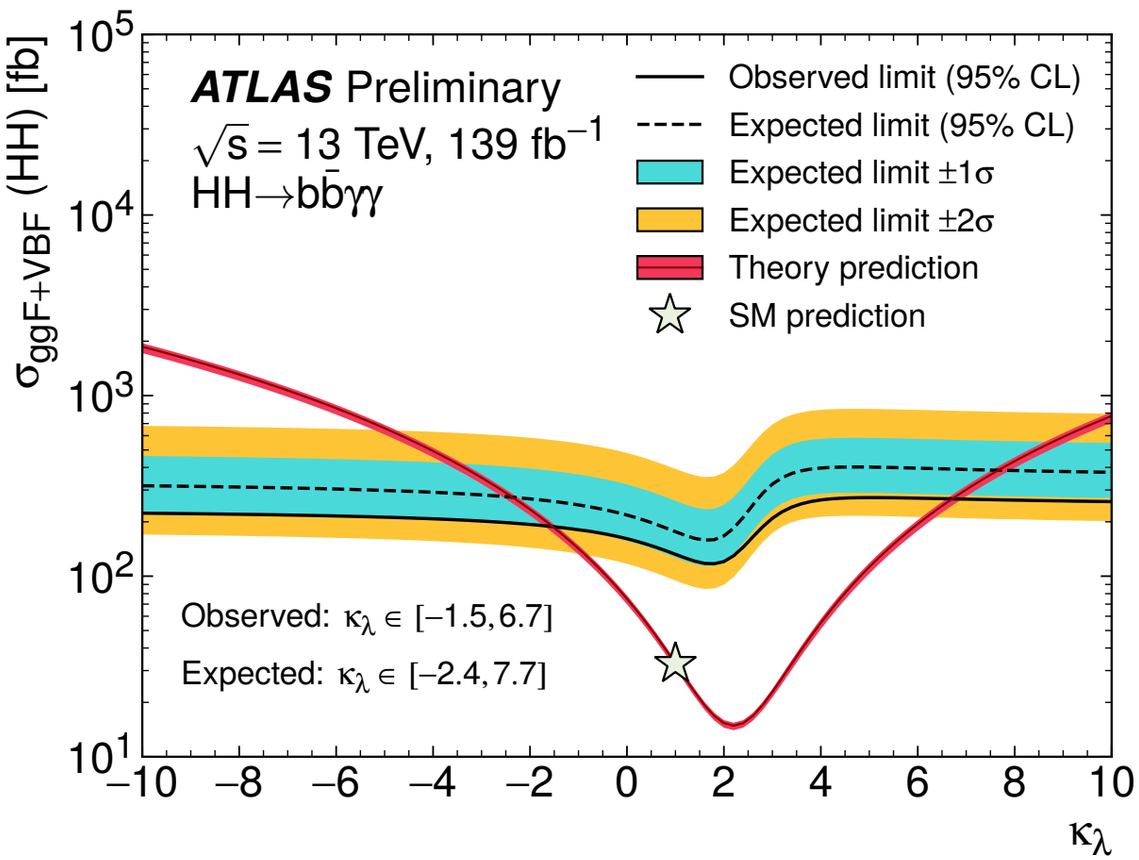
HH: very challenging

ggHH LO PRODUCTION



In the SM

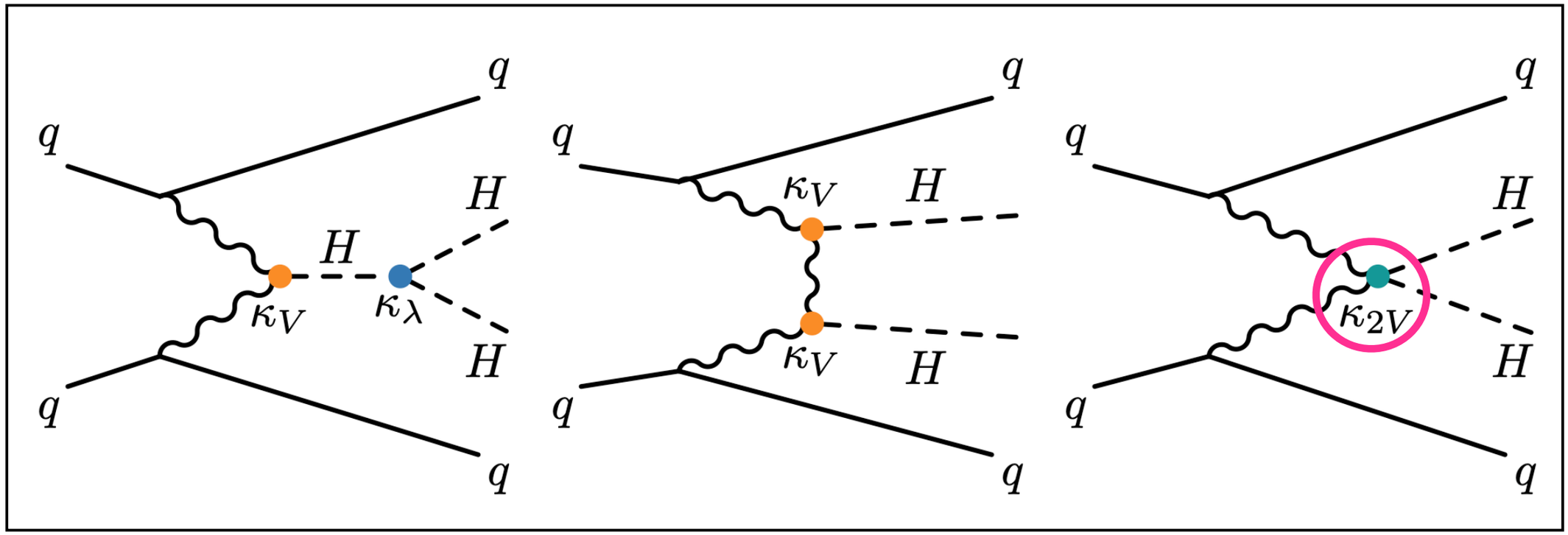
Destructive interference b/w box and triangle



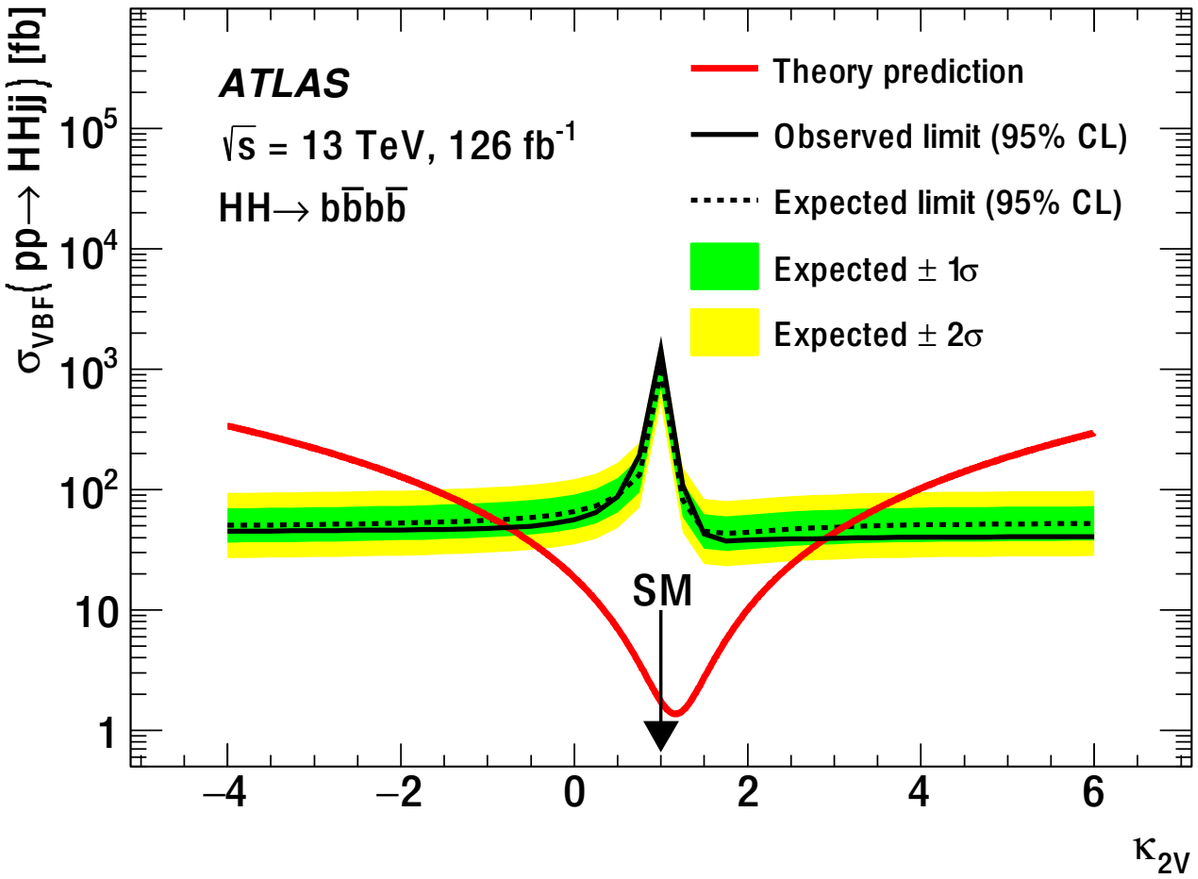
ATLAS-CONF-21-016

ATLAS measurement of κ_{2V}: limited

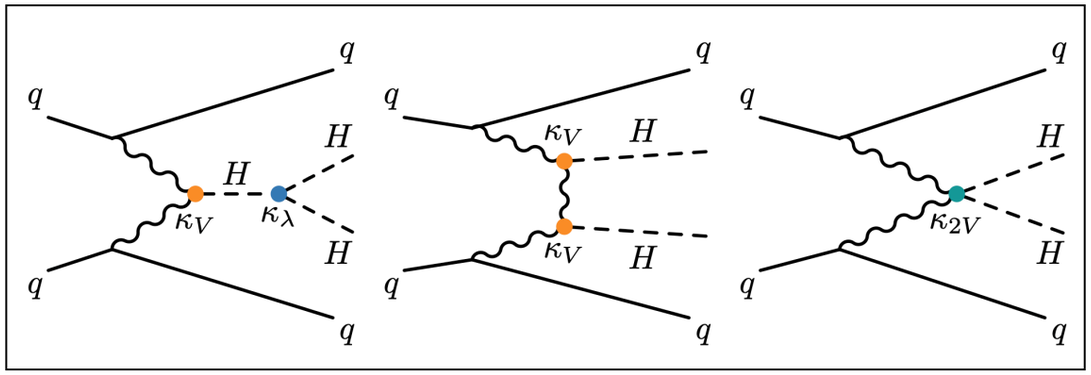
VBF HH PRODUCTION



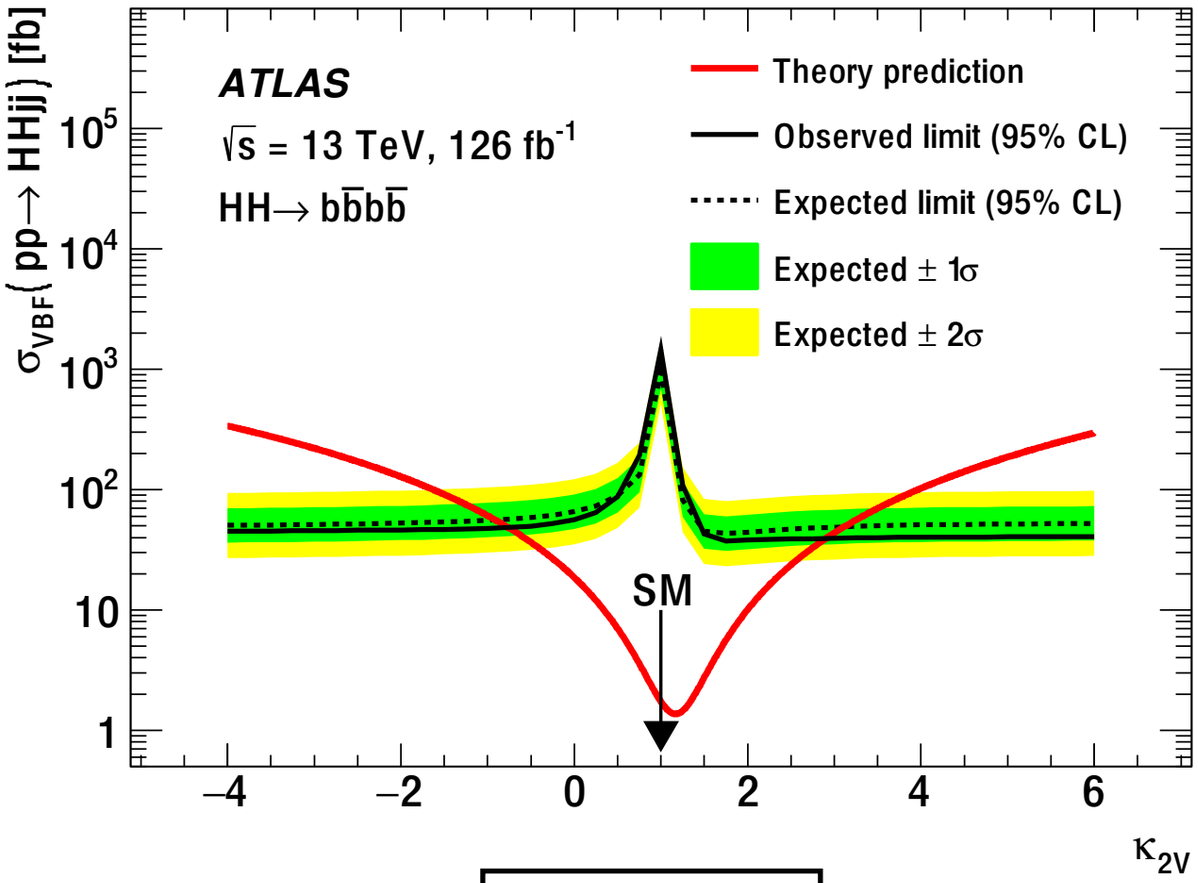
ATLAS measurement of κ_{2V}: limited



VBF HH PRODUCTION

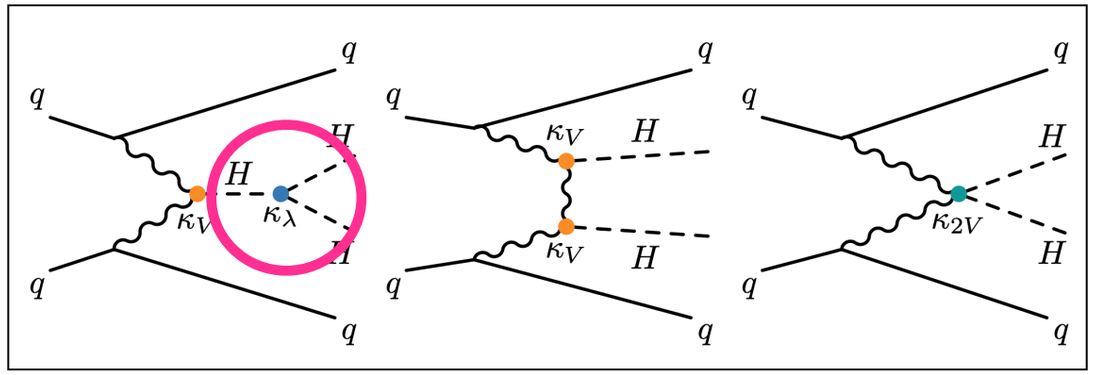


ATLAS measurement of κ_{2V}: limited

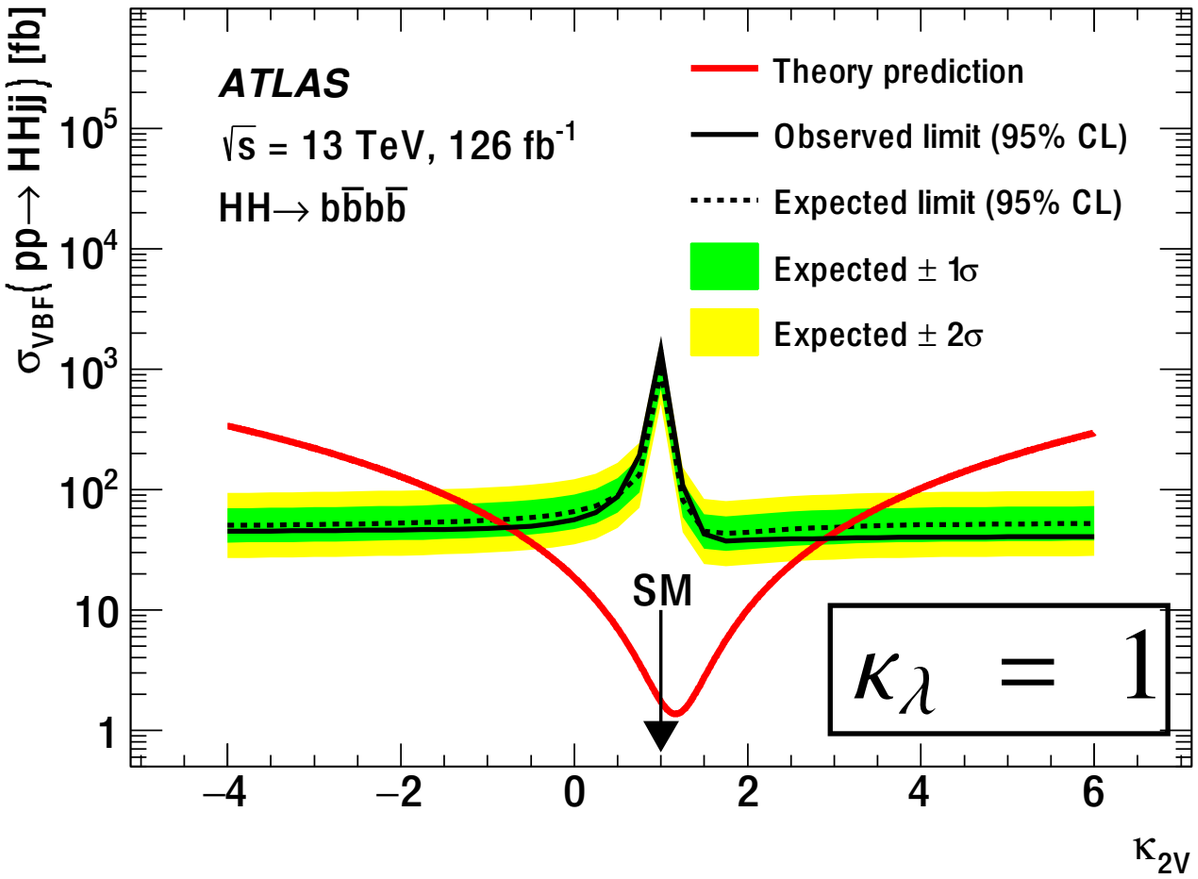


Assumption! $\kappa_\lambda = 1$

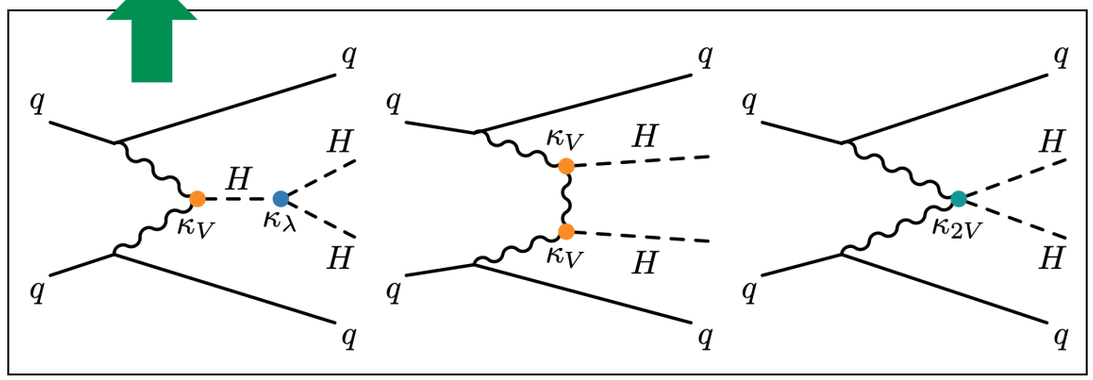
VBF HH PRODUCTION



ATLAS measurement of κ_{2V}: limited



VBF HH PRODUCTION



IF $(\kappa_\lambda \neq 1)$

With large NLO

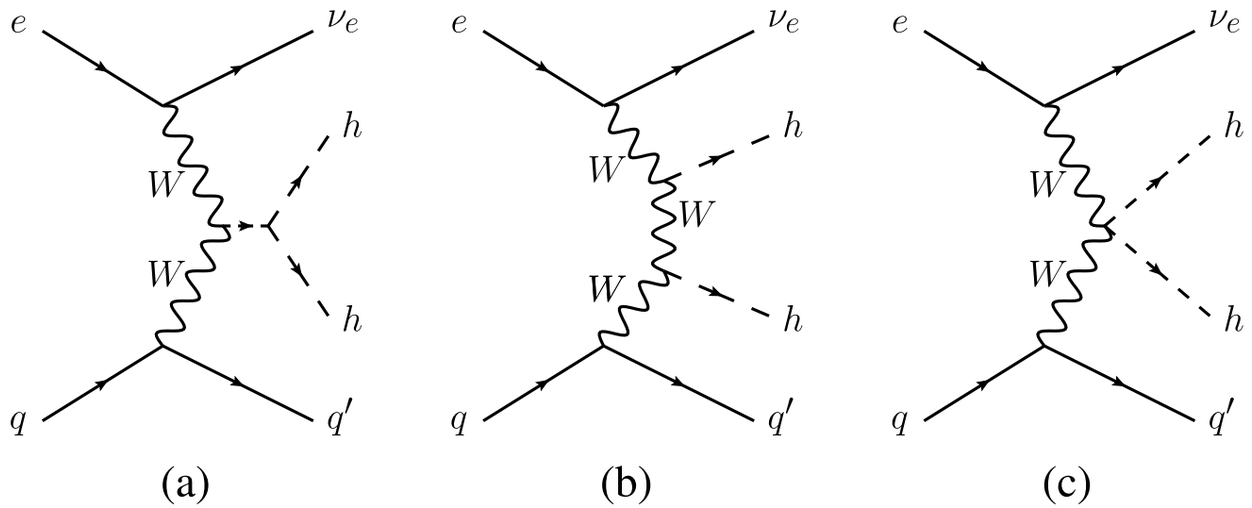
- Gluon fusion pollution becomes severe!

$gg \rightarrow HHjj$

electron-proton collider is better for κ_{2V}

- Gluon fusion pollution becomes severe!

$$gg \to HHjj$$



Consider

LHeC:	$E_e = 50$ GeV,	$E_p = 7$ TeV,
FCC-he:	$E_e = 60$ GeV,	$E_p = 50$ TeV,

Basic setup

Single Higgs couplings are SM-like.

$$\boxed{\kappa_{Hij} = 1}$$

Double and triple Higgs couplings are free.

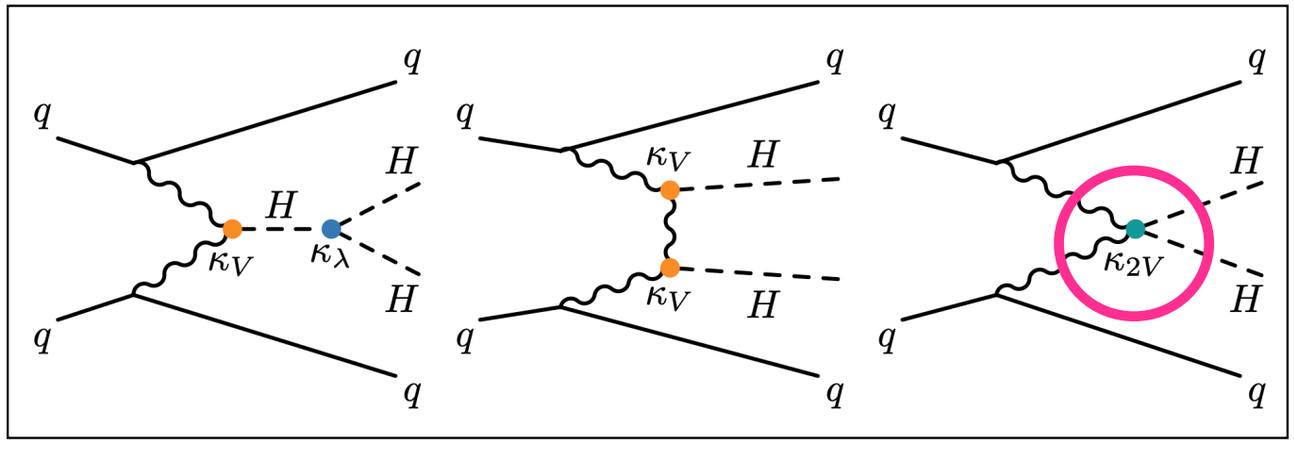
$$\boxed{\mathscr{L} \supset \kappa_{2V} \frac{g^2}{4} W^{+\mu} W^{-}_{\mu} H^2 - \kappa_{\lambda} \frac{3 m_H^2}{v} H^3}$$

Conspiracy? Also suppressed in the SM

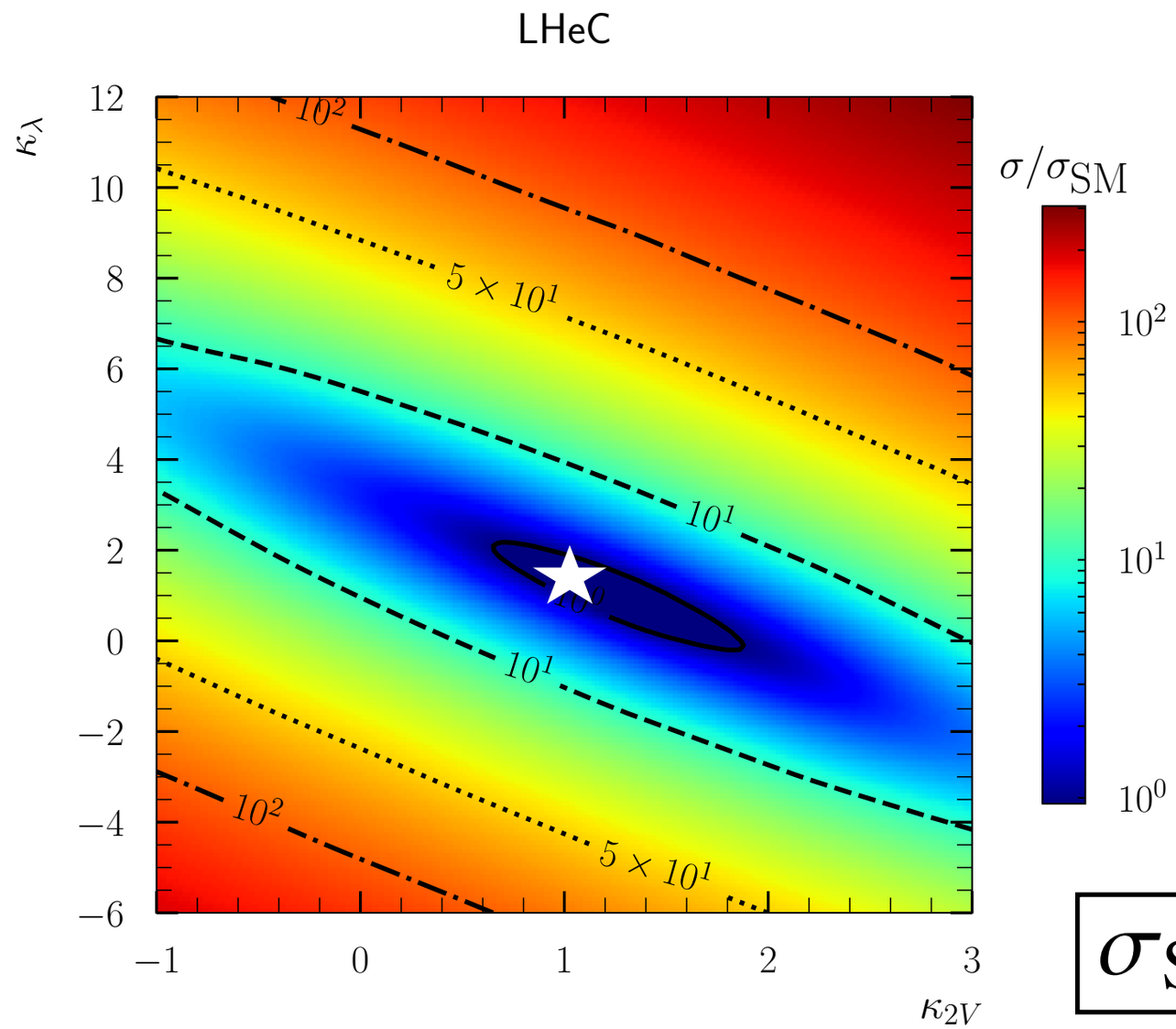
Zero in the SM

$$\frac{1}{g^2}\mathcal{M}(W_L^+W_L^- \to HH) = \left(\kappa_{2V} - \kappa_V^2\right)\frac{s}{4m_W^2} + \kappa_\lambda \frac{3m_H^2}{4m_W^2}$$
$$+\kappa_V^2\left[1 - \frac{m_H^2}{2m_W^2} - \frac{2}{\sin^2\theta^*}\right]$$
$$-\frac{\kappa_{2V}}{2} + \mathcal{O}\left(\frac{m_{W,H}^2}{s}\right),$$

VBF HH PRODUCTION

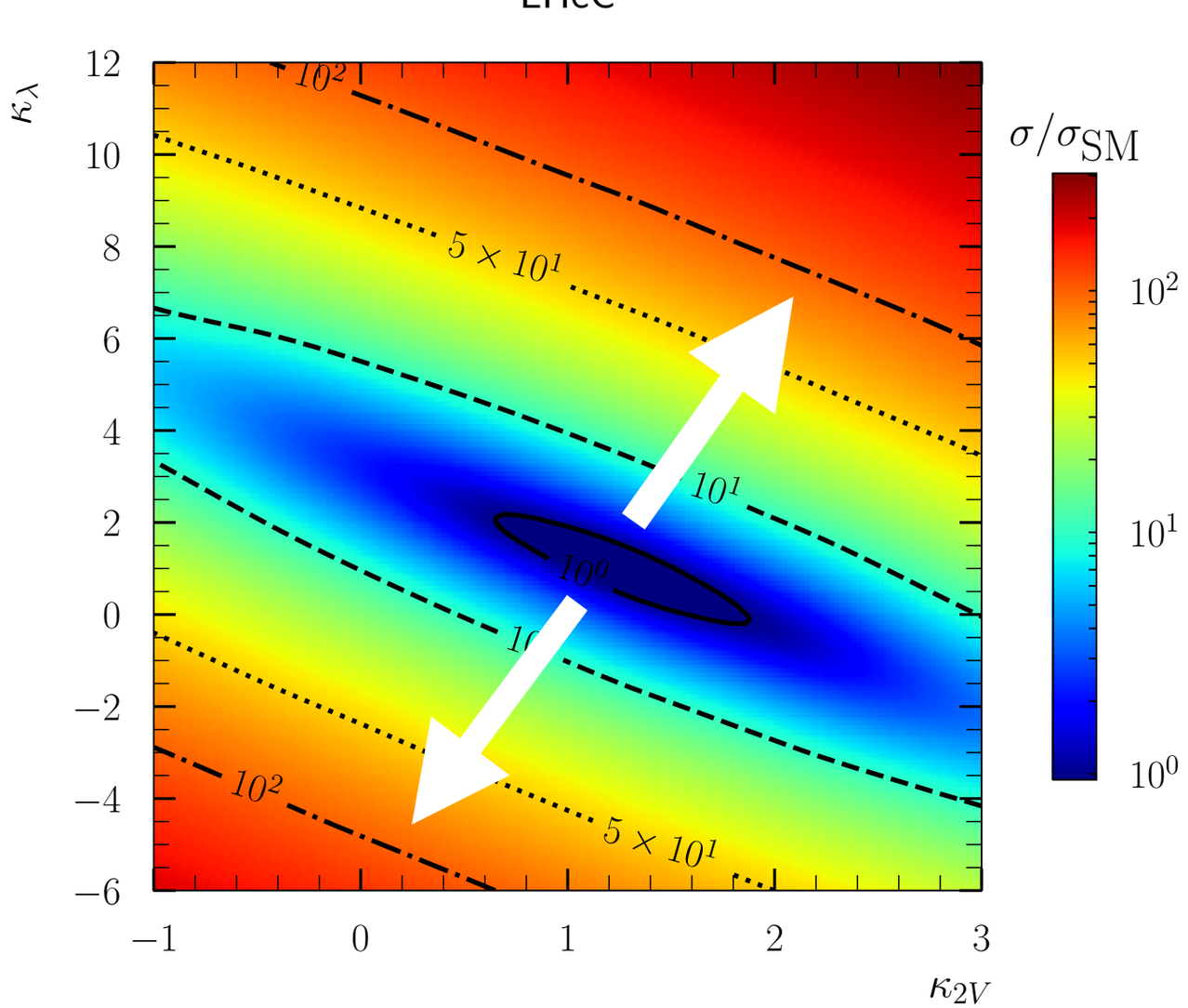


Signal cross sections at the parton level



$\sigma_{\rm SM} = 5.97$ ab

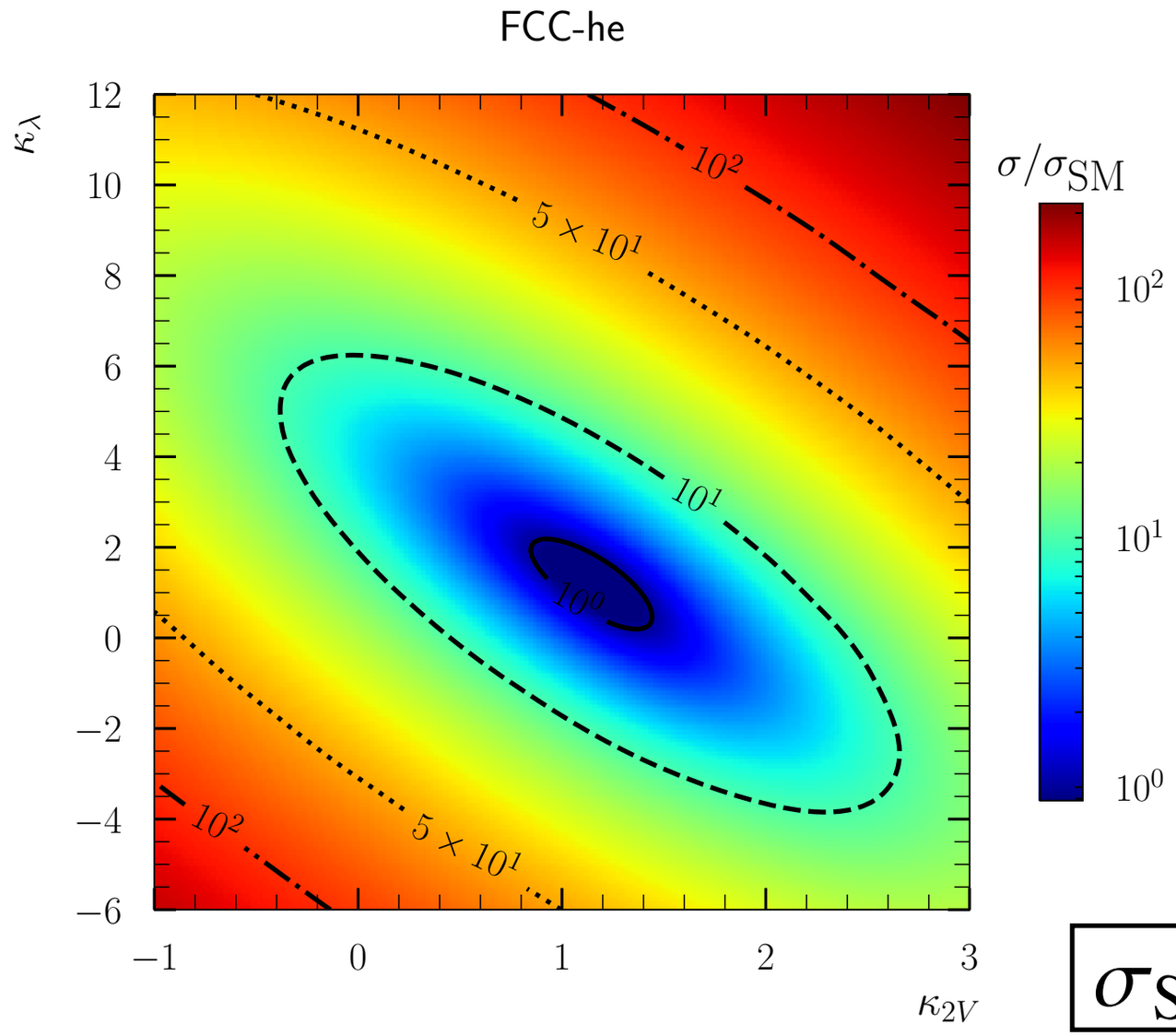
- SM (star mark): almost minimize the signal rate.
- Rapidly increasing with non-SM κ_λ and κ_{2V}



$$\mathcal{M} \sim \left(\kappa_{2V} - \kappa_V^2\right) \frac{s}{4m_W^2} + \kappa_\lambda \frac{3m_H^2}{4m_W^2}$$

- Same-sign κ_λ and κ_{2V} enhance the cross section.

Signal cross sections at the parton level



$\sigma_{\rm SM} = 233.77$ ab

- FCC-ep is more sensitive to κ_{2V}

LO cross-sections for the backgrounds

Process	σ_{CC} [ab]	
	LHeC	FCC-he
$b\bar{b}jj + j_f\nu_e$	1.00×10^5 $^{+57.9\%}_{-33.9\%}$	7.18×10^5 $^{+51.7\%}_{-31.6\%}$
$ZZ + j_f\nu_e$	9.37×10^2 $^{+6.95\%}_{-5.45\%}$	2.24×10^4 $^{+3.65\%}_{-3.26\%}$
$Zb\bar{b} + j_f\nu_e$	5.38×10^2 $^{+27.5\%}_{-19.9\%}$	4.77×10^3 $^{+22.6\%}_{-17.1\%}$
$ZH + j_f\nu_e$	1.23×10^2 $^{+7.29\%}_{-6.27\%}$	3.45×10^3 $^{+3.99\%}_{-3.58\%}$
$b\bar{b}b\bar{b} + j_f\nu_e$	1.82×10^2 $^{+53.8\%}_{-32.4\%}$	7.11×10^2 $^{+50.9\%}_{-31.4\%}$
$Hb\bar{b} + j_f\nu_e$	4.53×10 $^{+28.4\%}_{-20.4\%}$	4.77×10^2 $^{+23.7\%}_{-17.8\%}$
$t\bar{t} + j_f\nu_e$	2.00×10 $^{+29.6\%}_{-21.2\%}$	7.49×10^2 $^{+22.9\%}_{-17.4\%}$

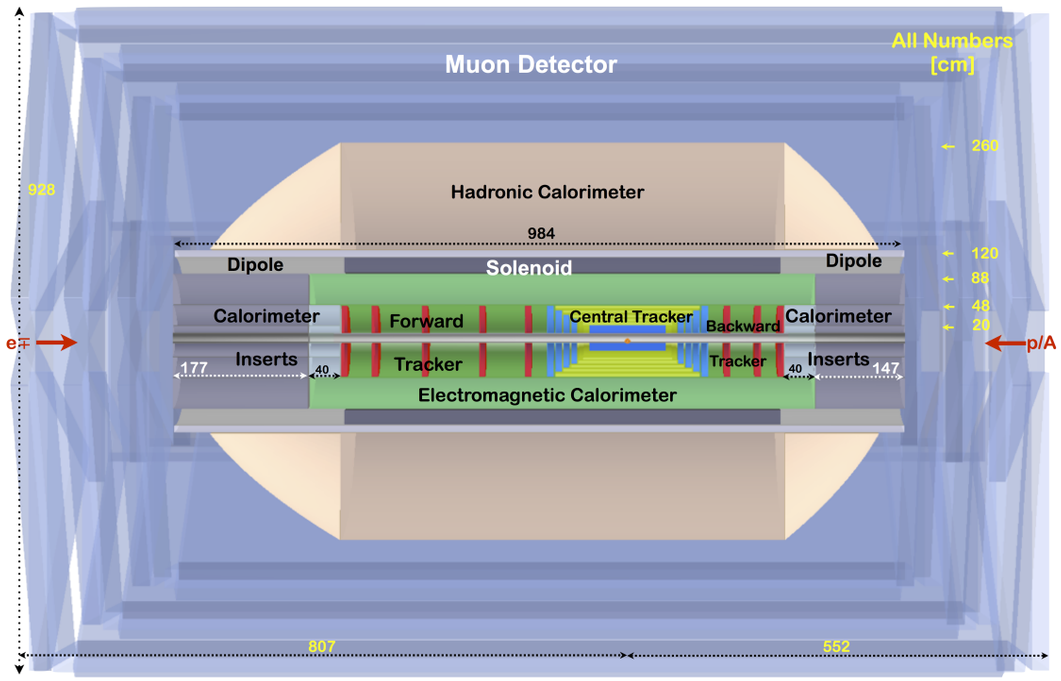
- Uncertainties are from the renormalization and factorization scale variation.

For 4b+(forward j)+nu

Initial
4b-tag
Forward jet
Lepton veto
$E_T^{\text{miss}} > 40$ GeV
Minimum D_{HH}
$X_{HH} < 3.0$

Different forward jet definition

$$p_T^{j_{\text{f}}} > 20 \text{ GeV}, \quad 1.5 < \eta^{j_{\text{f}}} < 7$$



For 4b+(forward j)+nu

Initial
4b-tag
Forward jet
Lepton veto
$E_T^{\text{miss}} > 40$ GeV
Minimum D_{HH}
$X_{HH} < 3.0$

$$D_{HH} = \sqrt{(M_{\text{dijet}}^{\text{lead}})^2 + (M_{\text{dijet}}^{\text{slead}})^2} \times \left| \sin\left(\tan^{-1} \frac{M_{\text{dijet}}^{\text{slead}}}{M_{\text{dijet}}^{\text{lead}}} - \tan^{-1} \frac{116.5 \text{ GeV}}{123.7 \text{ GeV}} \right) \right|$$

To pick up HH

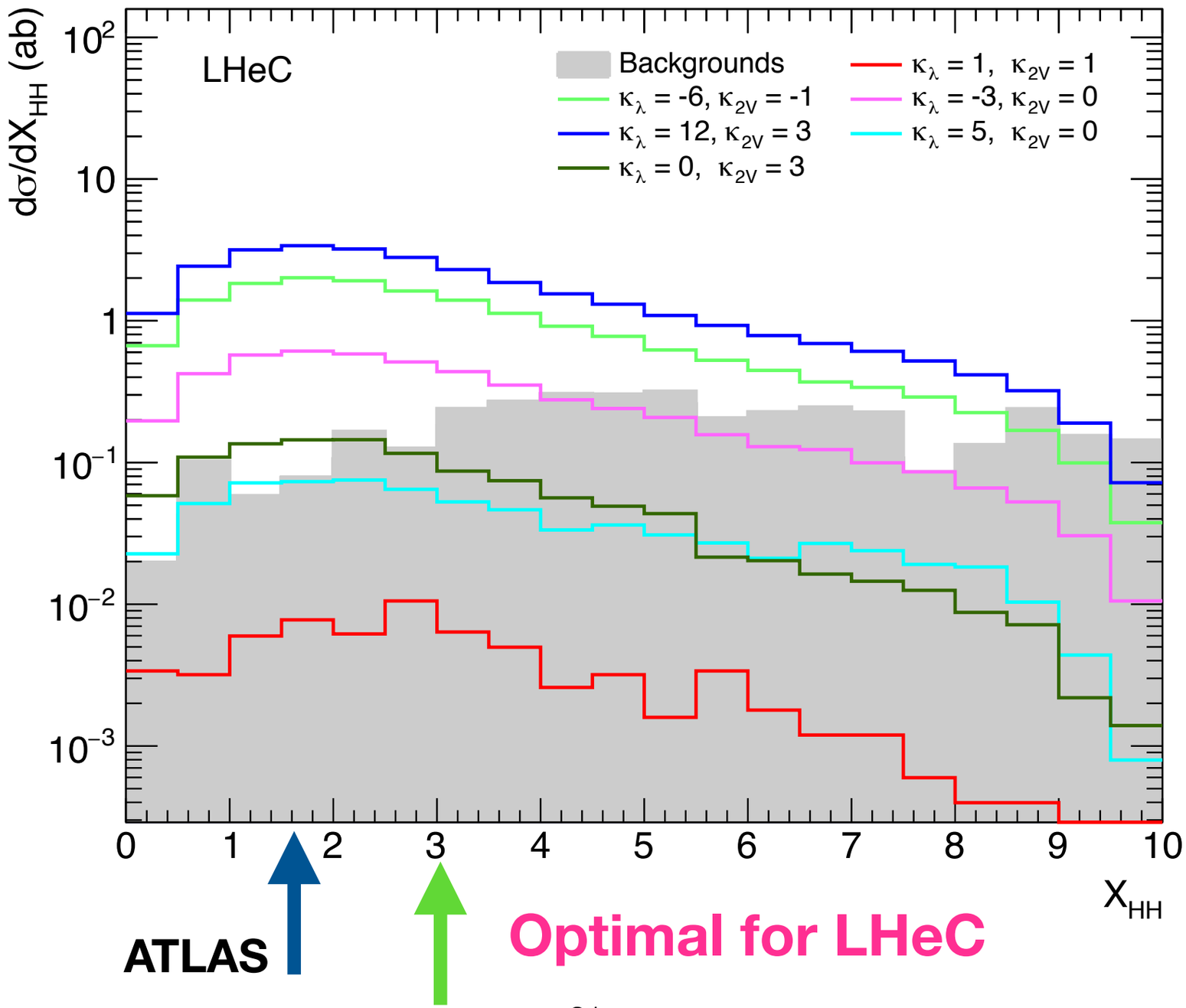
For 4b+(forward j)+nu

Initial
4b-tag
Forward jet
Lepton veto
$E_T^{\text{miss}} > 40$ GeV
Minimum D_{HH}
$X_{HH} < 3.0$

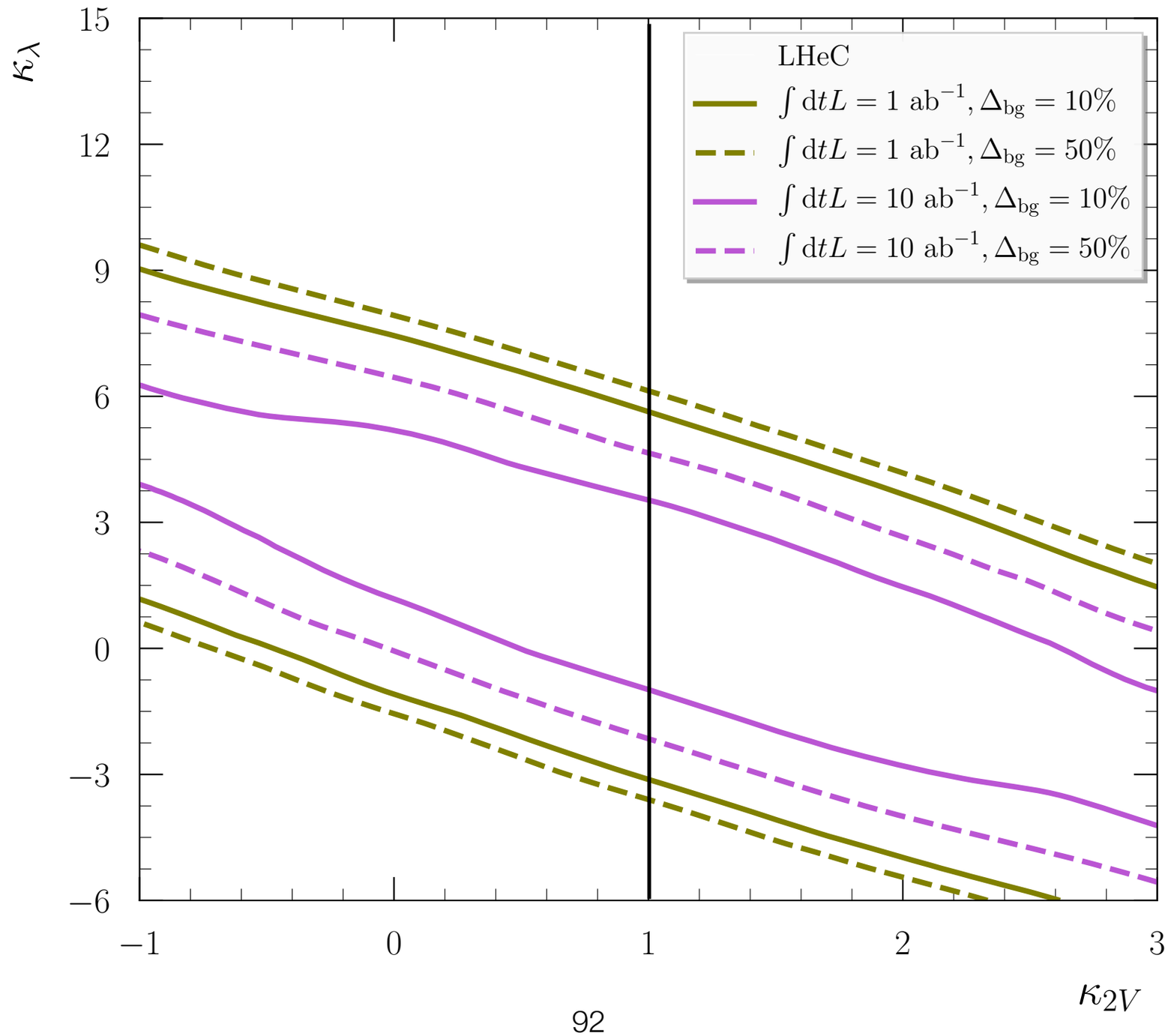
$$X_{HH} \equiv \sqrt{\left(\frac{M_{\text{dijet}}^{\text{lead}} - 123.7\ \text{GeV}}{11.6\ \text{GeV}}\right)^2 + \left(\frac{M_{\text{dijet}}^{\text{slead}} - 116.5\ \text{GeV}}{18.1\ \text{GeV}}\right)^2}$$

To guarantee bb from H

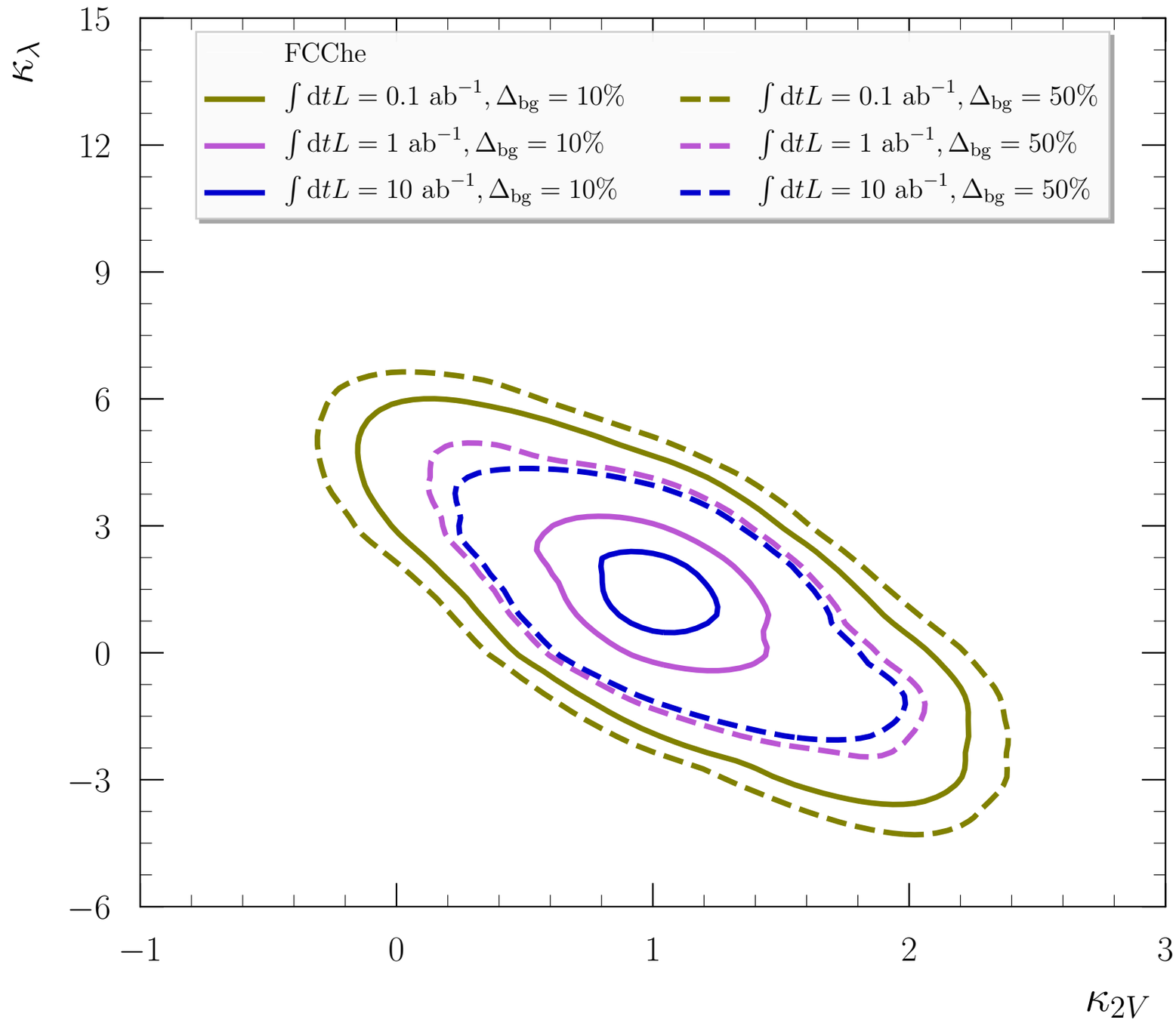
For 4b+(forward j)+nu



The expected exclusions at the LHeC



The expected exclusions at the FCC-he



Conclusions

- HHVV coupling is challenging to probe at the LHC, because of the unknown HHH coupling and the gluon fusion pollution.
- The future electron-proton colliders can be better to probe the HHVV vertex.
- Full detector simulations show that $|\kappa_{2V}|>0.2$ can be excluded at the FCC-he.