Image credit: Marguerite Tonjes

Higgs-charm couplings

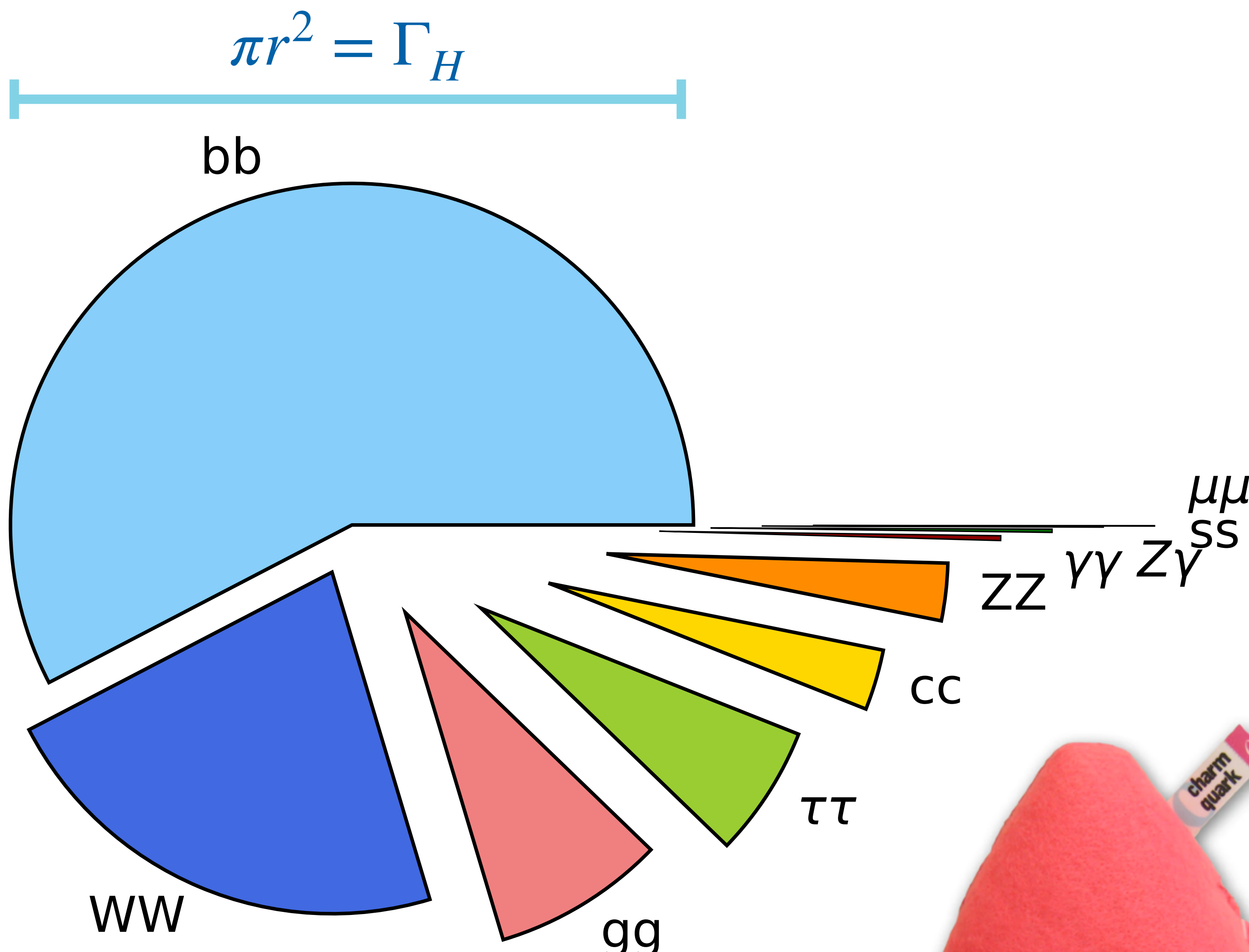
Nick Smith, on behalf of ATLAS+CMS

SM@LHC 2023

12 July, 2023

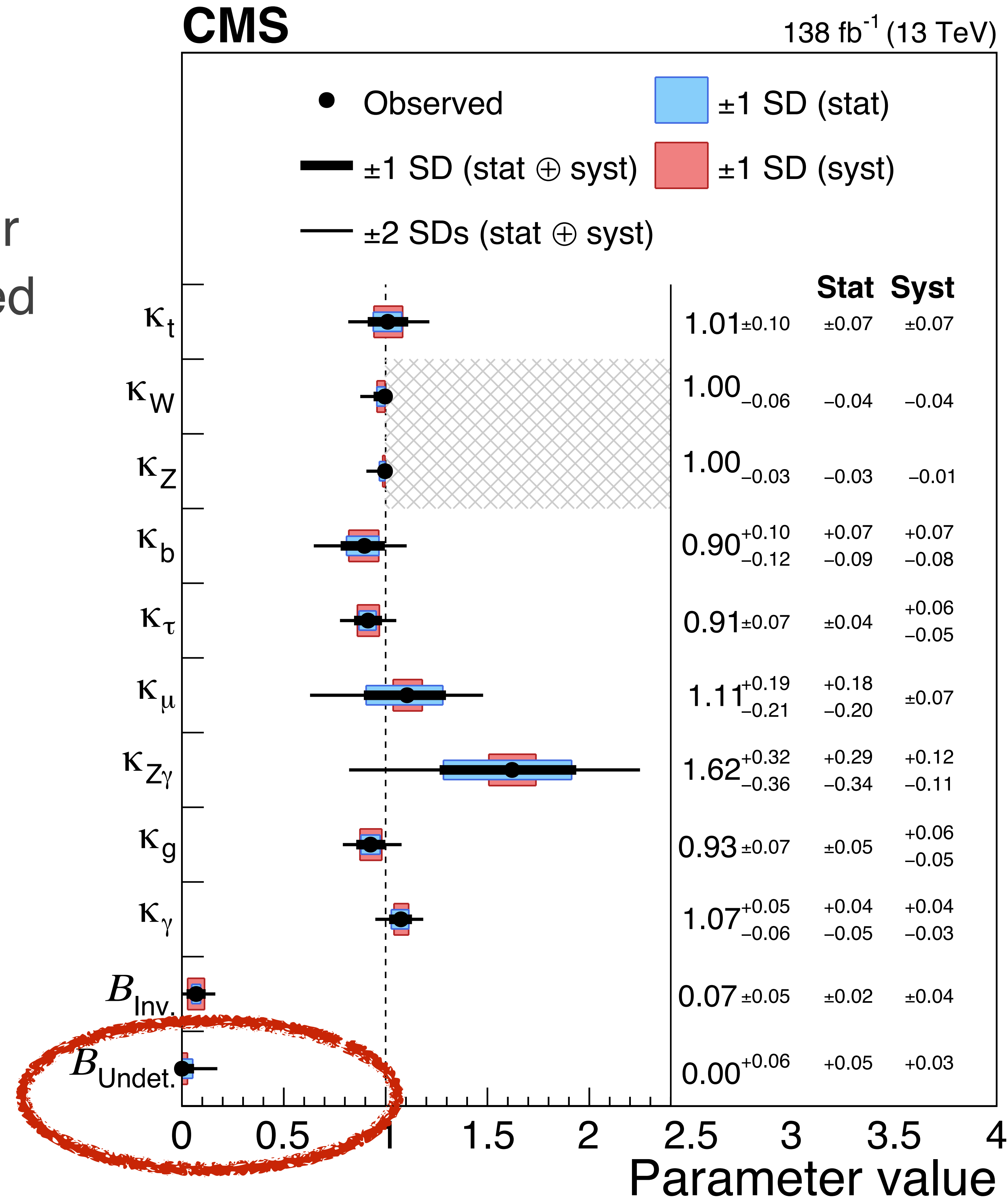
Outline

- Indirect methods
  - Higgs Combination
  - p_T differential
- Direct searches
  - Rare decays
  - VH(cc)
  - ggH(cc)
  - VH(cc) enters combinations
- Outlook for κ_c



H(cc) as what's left of the pie

- Assume $|\kappa_V| \leq 1$ ➜ 95% CL upper limit on branching ratio of undetected decays
  - CMS: ~0.18
  - ATLAS: 0.12



[Nature 607 (2022) 60-68]

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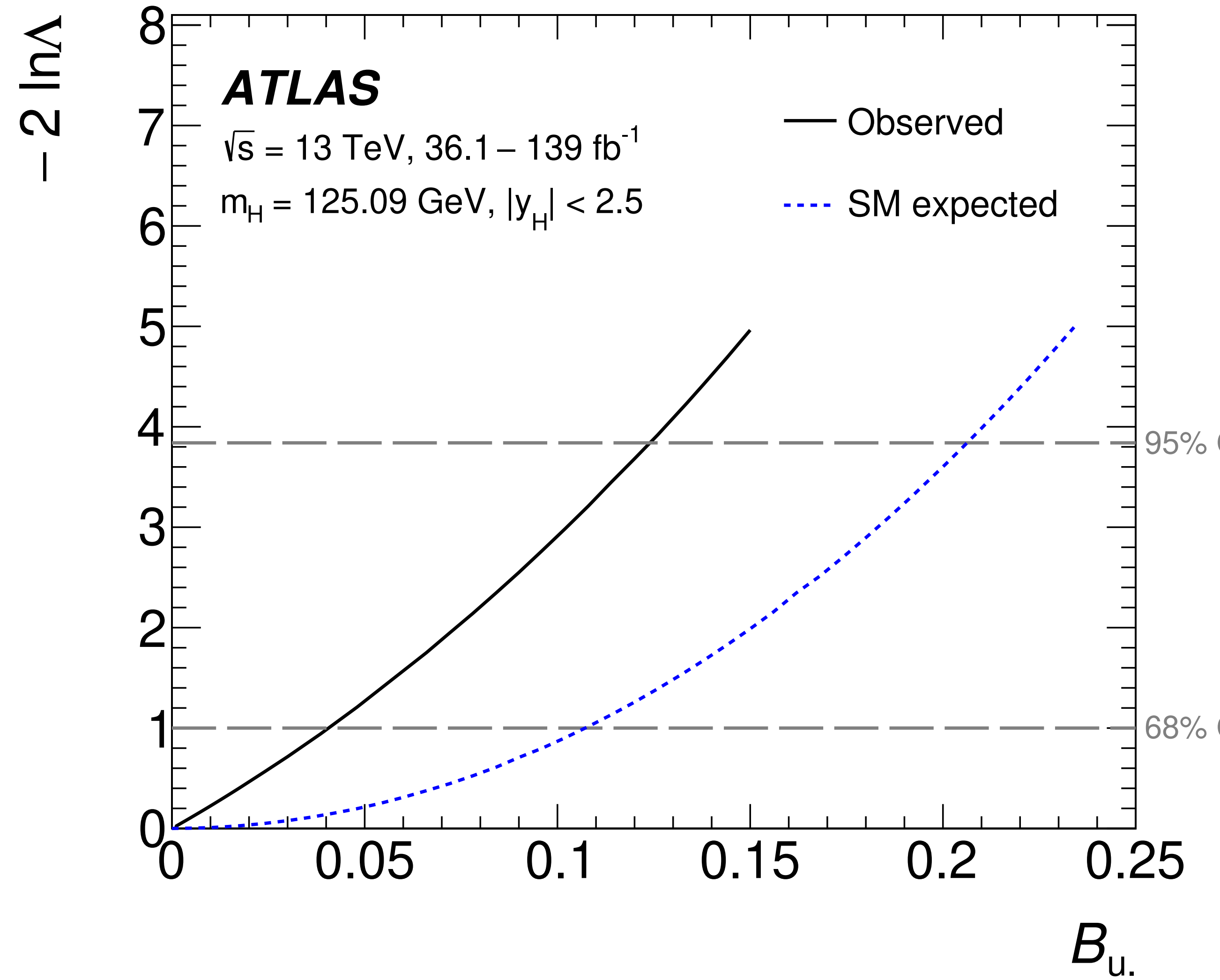

Nature 607, pages 52-59 (2022)

H(cc) as what's left of the pie

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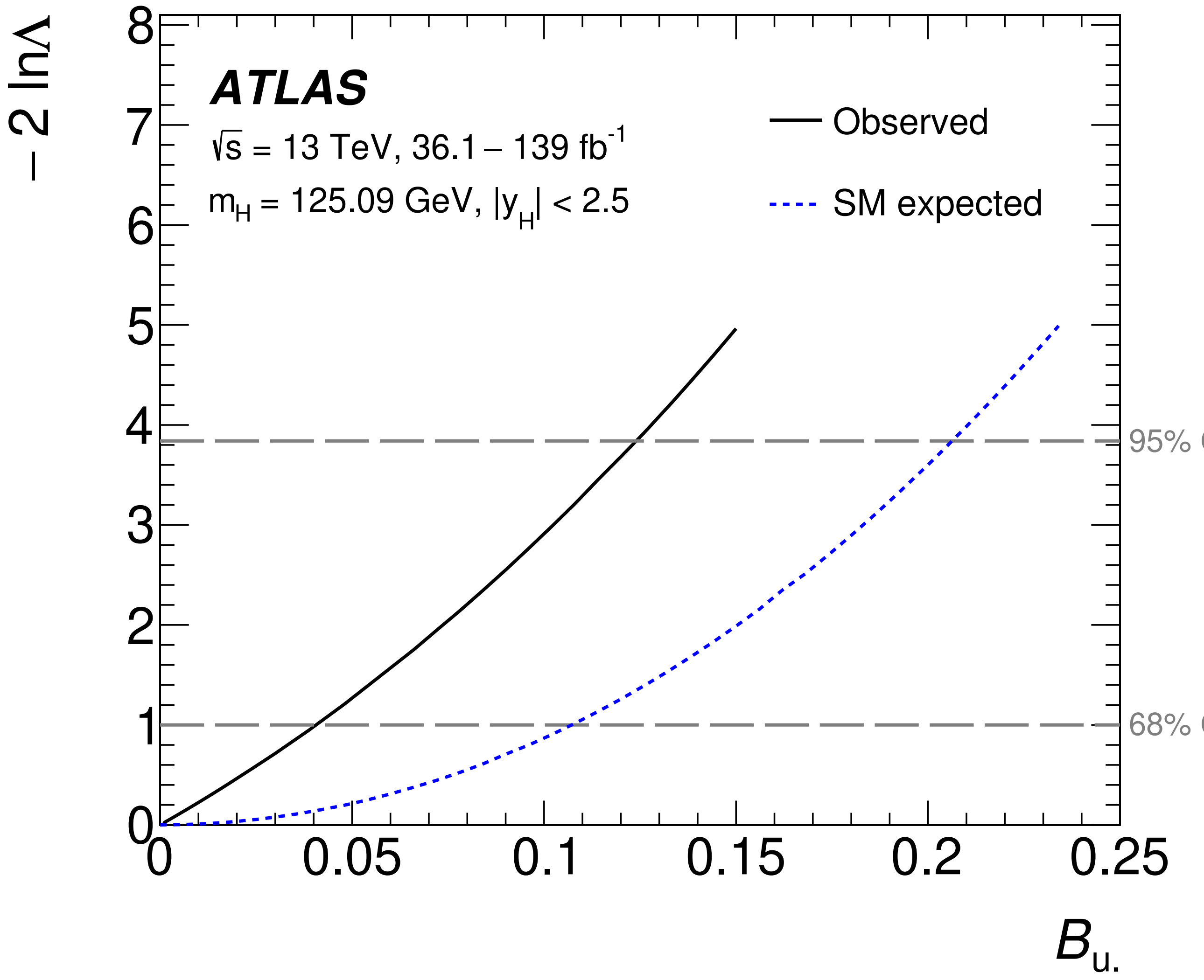
  - $B_{undet} = \dfrac{(\kappa_c^2 - 1)B_{cc}^{SM}}{1 + (\kappa_c^2 - 1)B_{cc}^{SM}}$
  - Implies $\kappa_c \lesssim 2.4$



[Nature 607, pages 52-59 (2022)]

Fermilab

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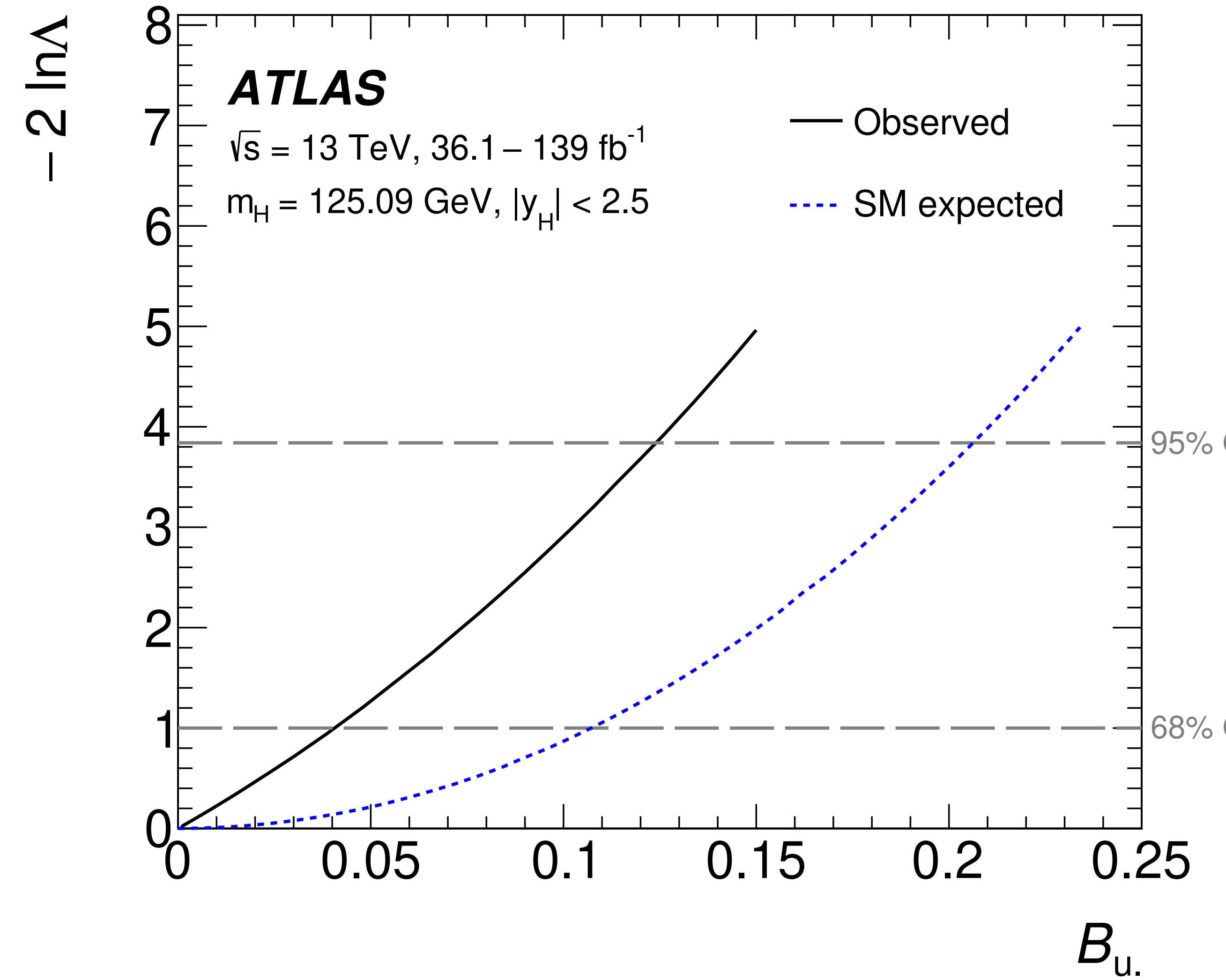
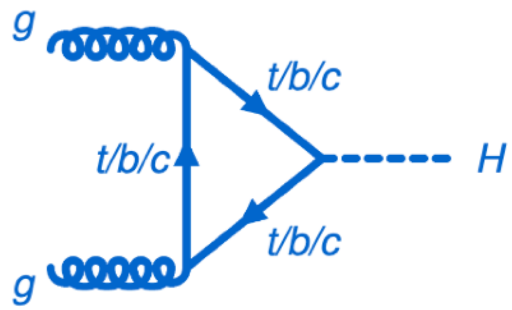
  - Implies $\kappa_c \lesssim 2.4$
- Better: fit with full κ_c dependence, $|\kappa_V| \leq 1, B_{undet} = 0$
  - Or include direct Γ_H constraint (as seen in Ulascan's talk)
    - Bound is ~2x weaker (1905.09360)



Nature 607, pages 52-59 (2022)

Fermilab

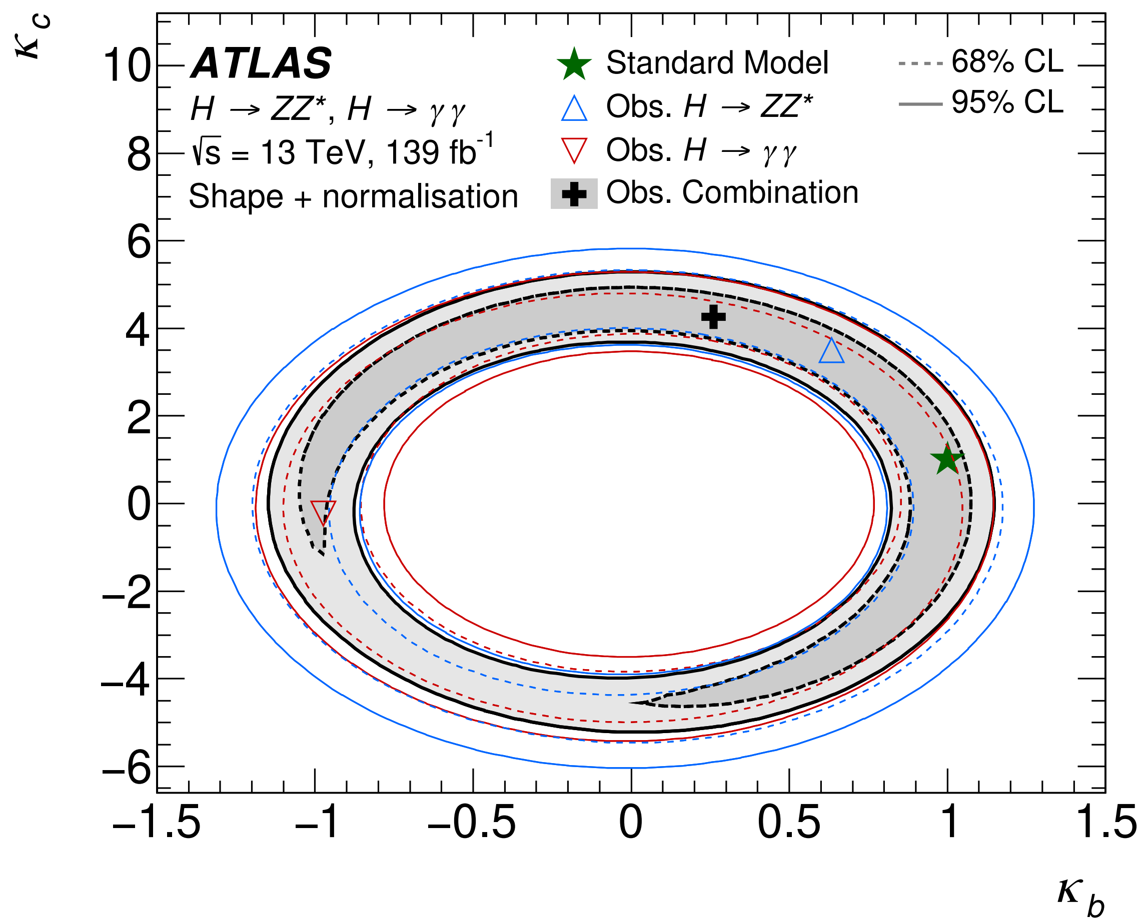
Charm coupling distorts the loop

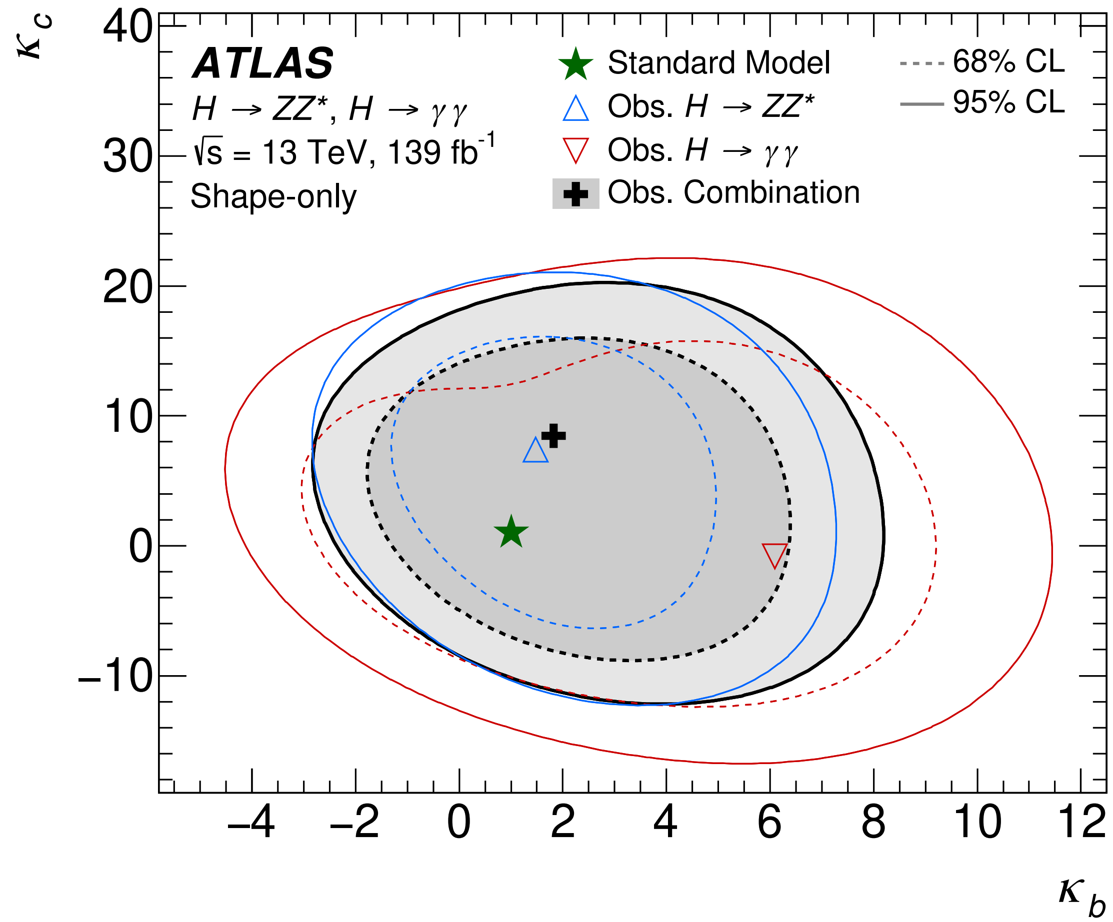


- Higgs p_T measurements can separate c/b contributions to ggH production loop 1606.09253
- ATLAS probed this effect w/full Run-II $H(\gamma\gamma) + H(ZZ^*)$ combination
  - Left: allow couplings to modify total cross section
  - Right: differential shape only
  - Both assume all other $\kappa = 1$

ATLAS JHEP 05 (2023) 028

(CMS partial Run-II: Phys. Lett. B 792 (2019) 369)



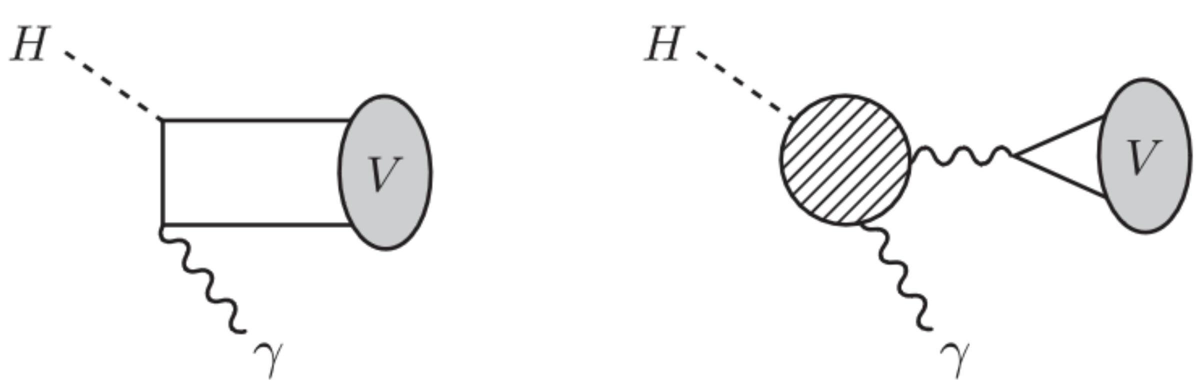


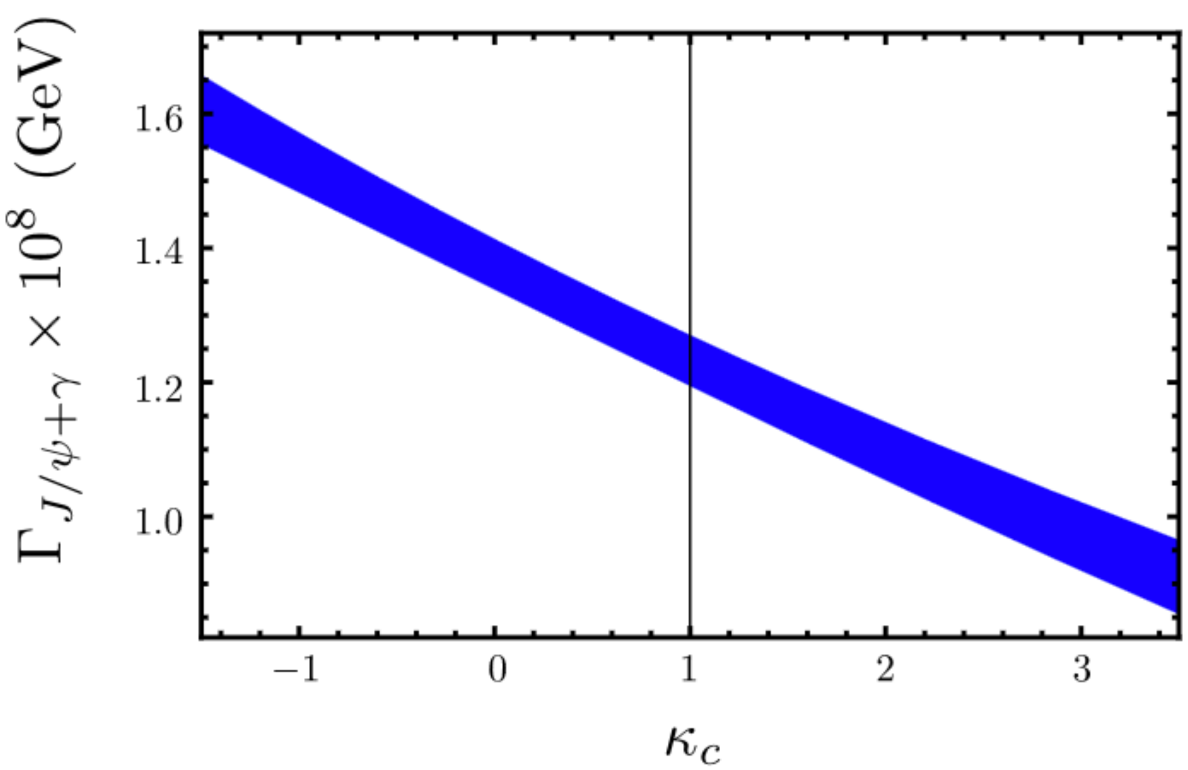
Fermilab

Higgs to γ+meson

- $H \to J/\psi\,\gamma$ decays can probe κ_c
  - SM expected cross section: 3×10^{-6}
  - Contribution from direct H(cc) coupling is sub-leading, hence mild κ_c dependence

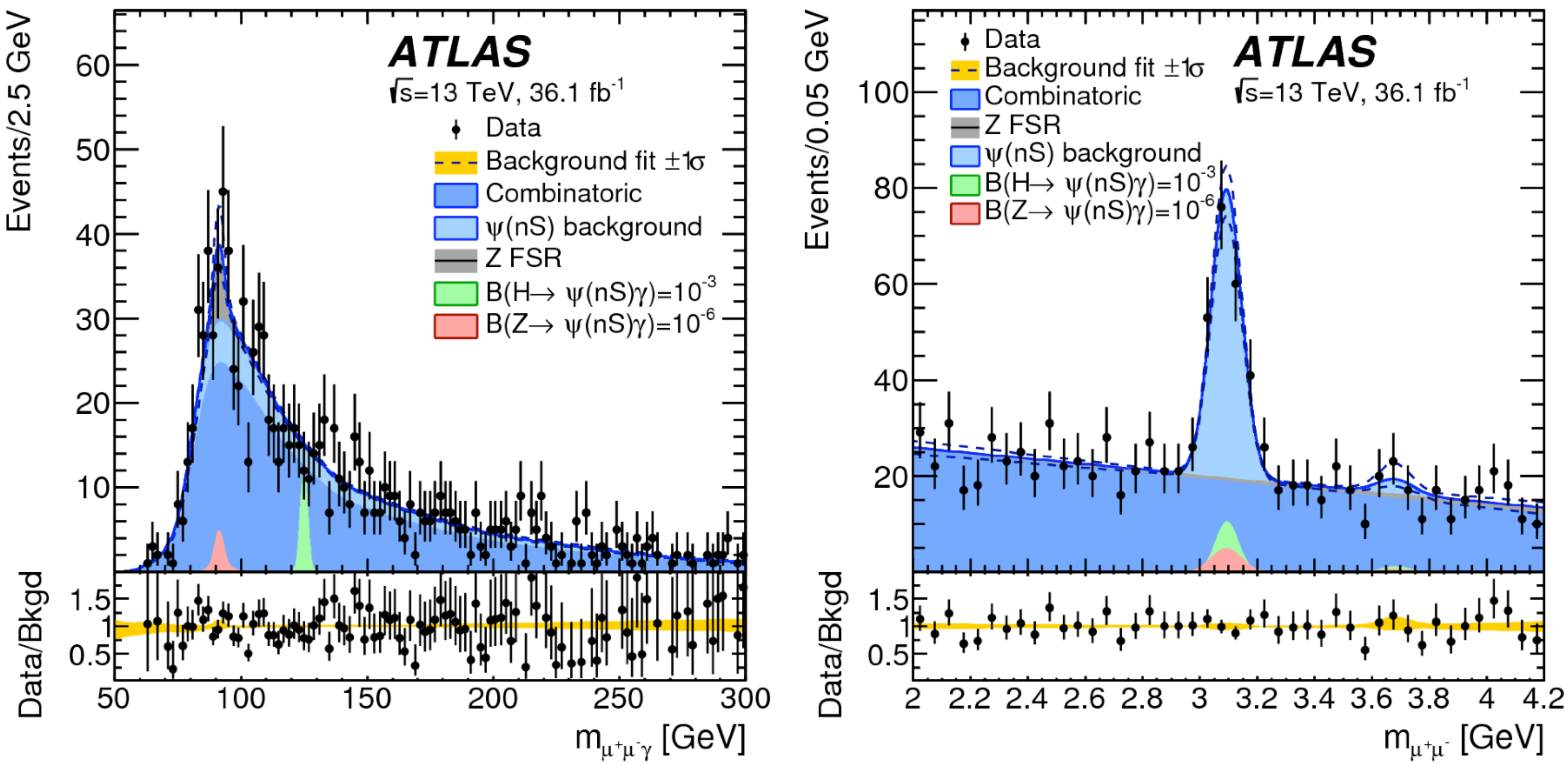
PRD 100, 054038





Higgs to γ+meson

- Both ATLAS & CMS probe several exclusive final states, in particular:
  - ATLAS: $B(H \to J/\psi\,\gamma) < 3.5\,(3.0) \times 10^{-4}$ (Phys. Lett. B 786 (2018) 134)
  - CMS: $B(H \to J/\psi\,\gamma) < 7.6\,(5.2) \times 10^{-4}$ (Eur. Phys. J. C 79 (2019) 94)
  - Corresponds to ~120 times SM expectation

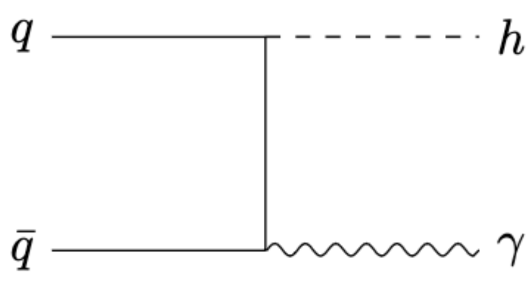


Fermilab

Probing κ_c via the initial state

- WWγ tri-boson with H(WW)γ interpretation (SMP-22-006)
  - Main analysis: SM WWγ observation, dim-8 QGC limits
  - Selection modified to target H(WW) decay ($\Delta\phi_{\ell\ell}$, etc.)
  - Assume other Higgs κ scale to preserve measured BR

Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq 13000$ (16000)
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq 14000$ (17000)
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq 1300$ (1700)
$c\bar{c} \to H + \gamma \to e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq 110$(200)



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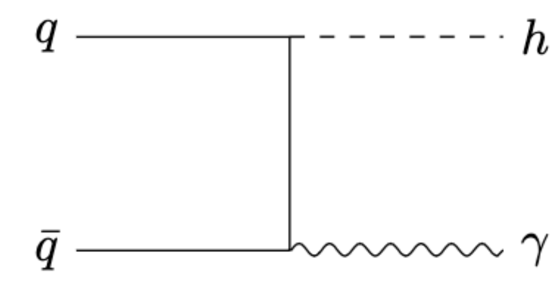
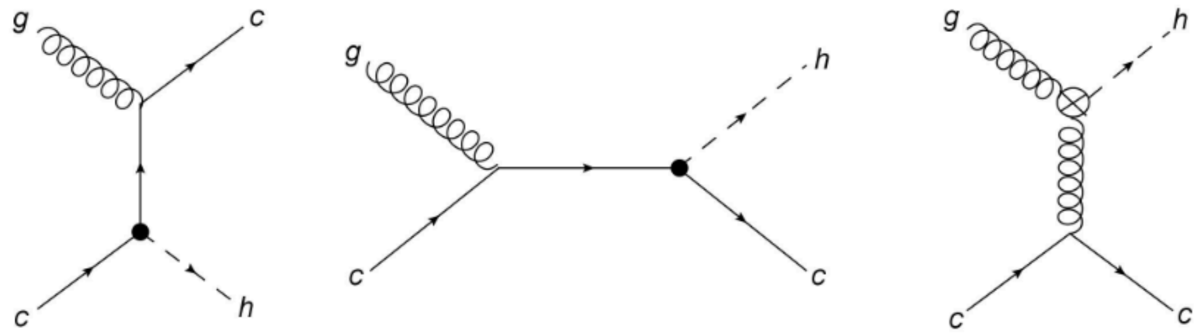


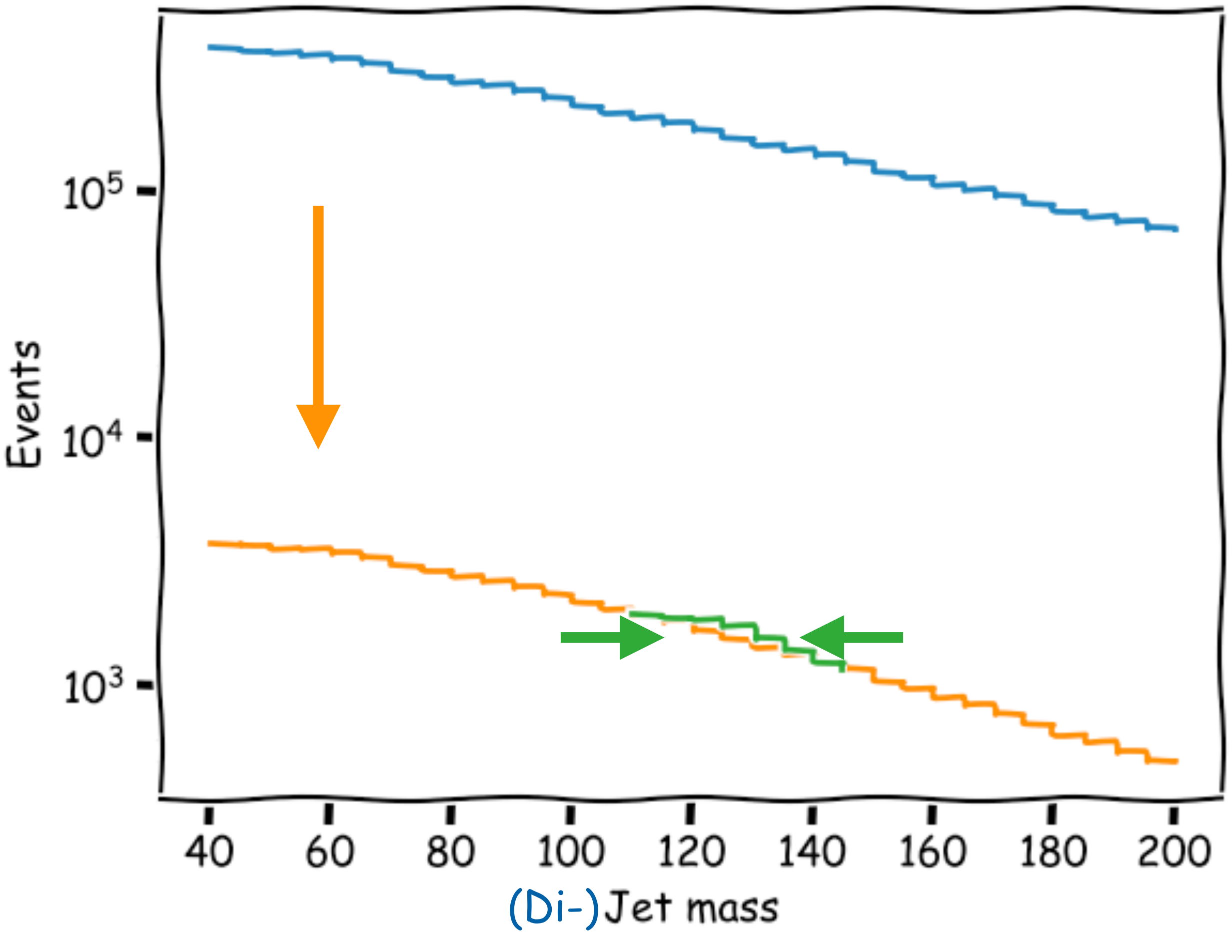
- Higgs+charm
  - Proposed in 1507.02916, expect $|\kappa_c| < 2.6$ (95% CL) with 3/ab HL-LHC data
  - Aside: parton tagging for x+1j EFT searches?



Fermilab

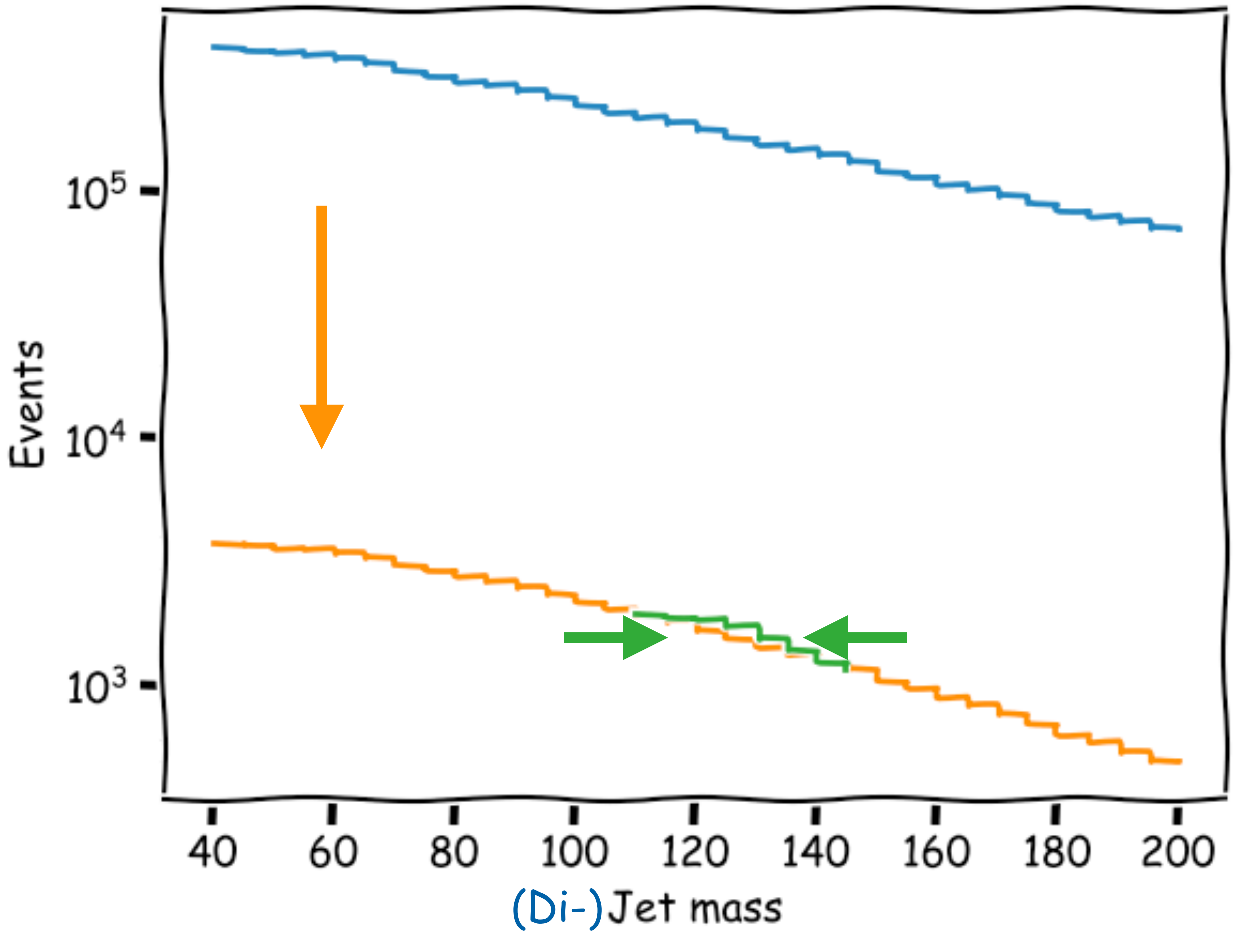
Higgs to cc via jet flavor

- Direct measurement requires:
  - Sharp mass peak with well-understood efficiency
  - Over well-suppressed & well-understood background



Higgs to cc via jet flavor

- Direct measurement requires:
  - Sharp mass peak with well-understood efficiency
  - Over well-suppressed & well-understood background
- Long history of developments for H(bb) largely translate
  - Challenge: mis-tag from two directions



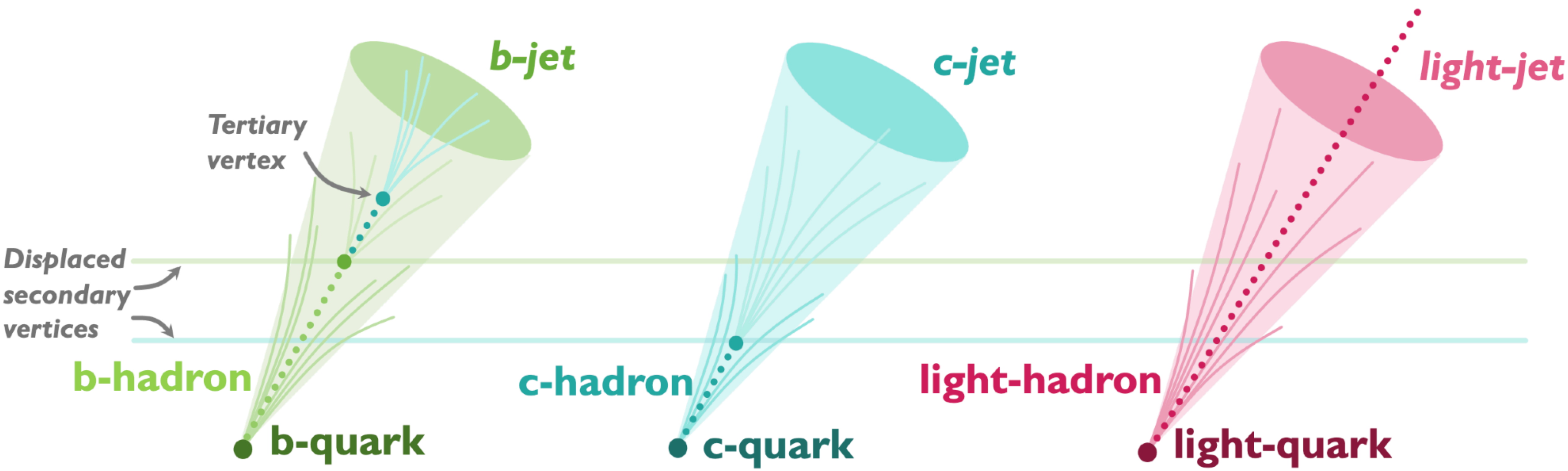
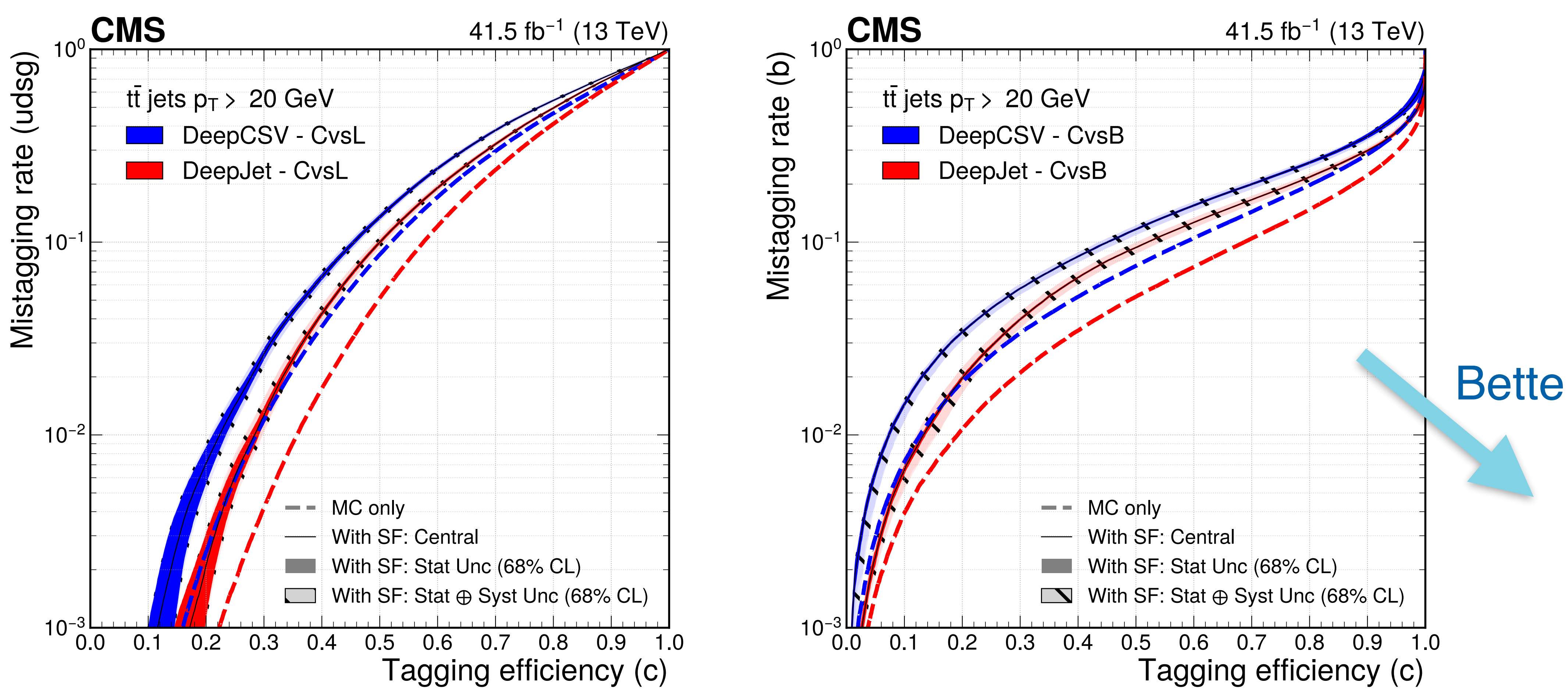


Diagram: Maria Mironova

Fermilab

Charm flavor tagging advances

- As usual, lower-level features + inductive bias = gain
  - *DeepCSV*: MLP on ~70 expert variables ([JINST 13 (2018) P05011])
  - *DeepJet*: CNN+RNN+MLP on ~600 low-level observables ([JINST 15 (2020) P12012])
- ATLAS has NNs too (with less cool names)
  - *MV2* (BDT) for b-tag veto, *DL1* (MLP) for charm-tag ([ATL-PHYS-PUB-2017-013])

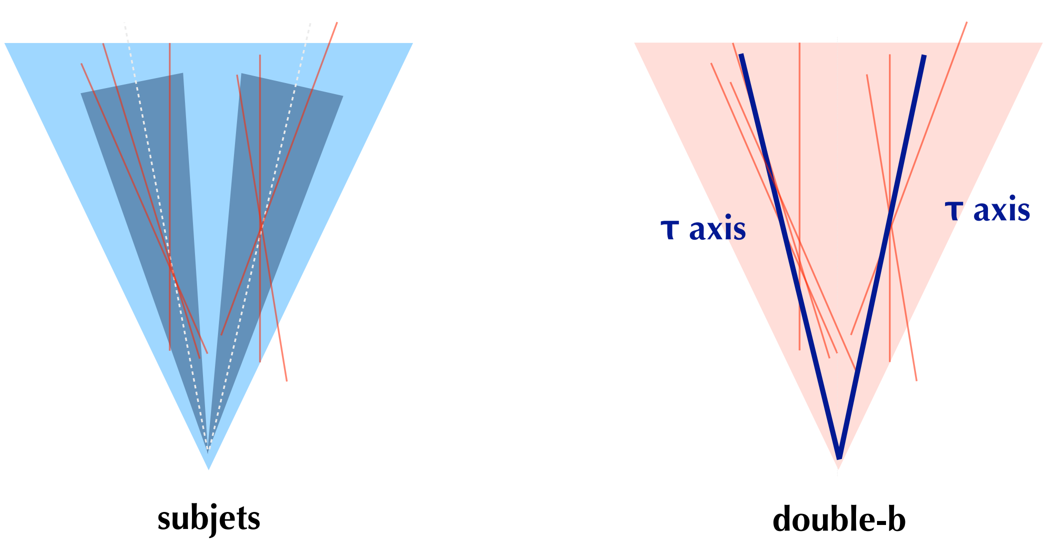


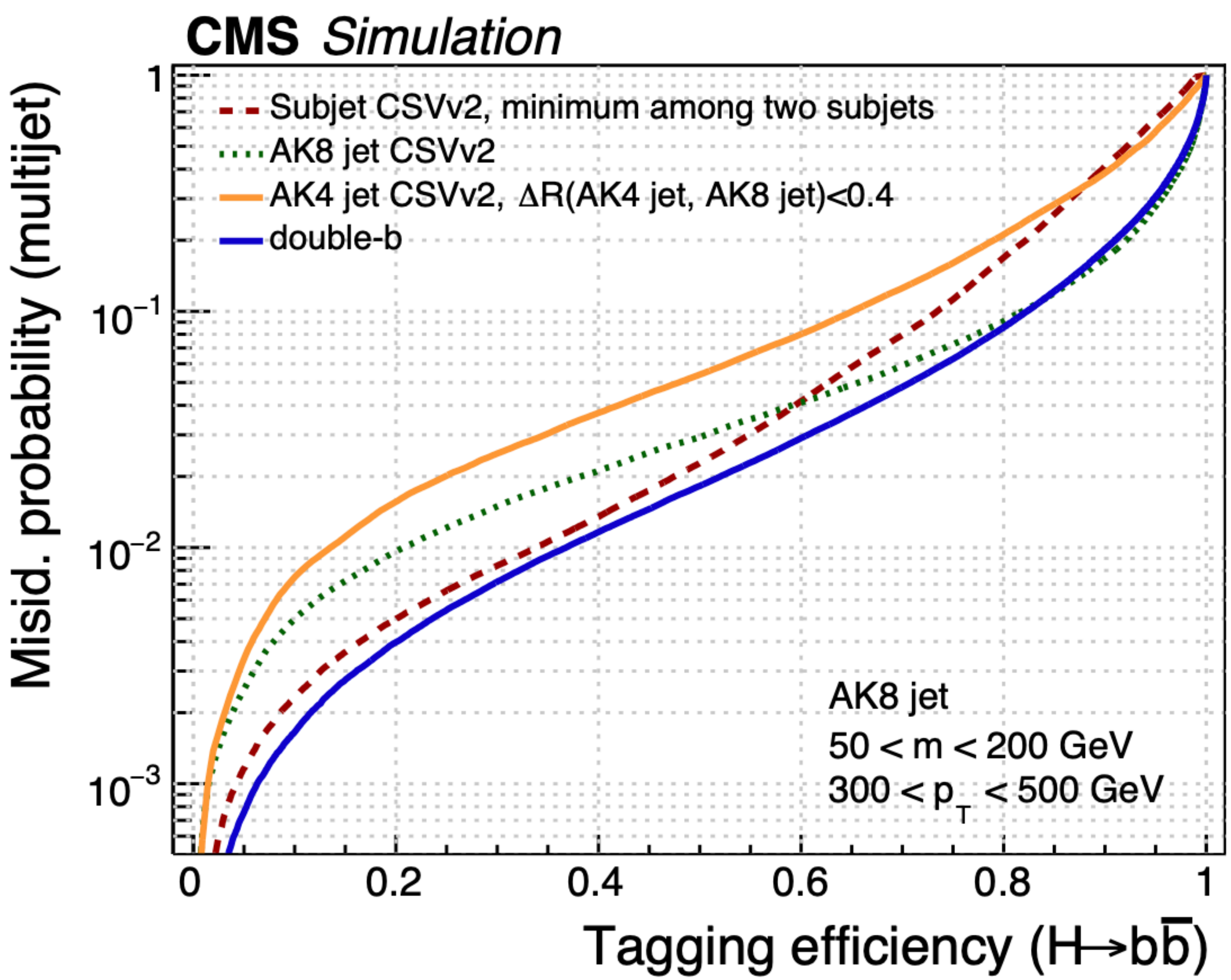
[JINST 17 (2022) P03014]

Fermilab

Double charm tagging rationale

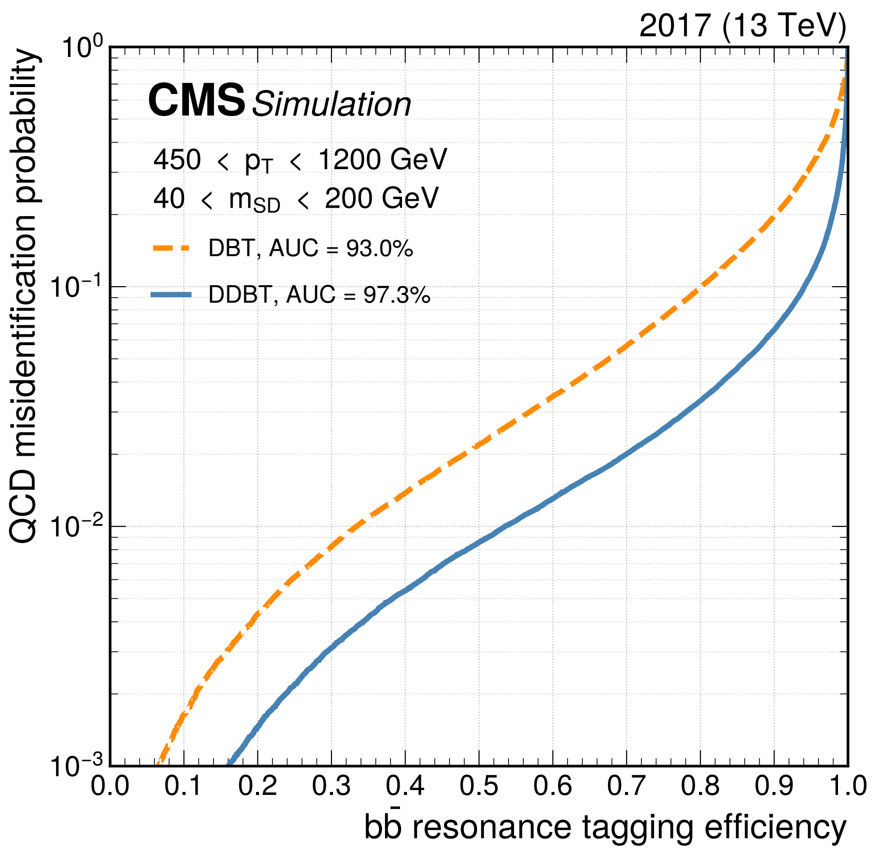
- Whole large-R jet tagger wins over sub-jet tag JINST 13 (2018) P05011
- Downside: cannot calibrate using top tag & probe
  - Instead through gluon splitting proxy jet





Double charm tagging advances

- Big gains with more complex DNN
  - SOTA graph networks



JHEP 12 (2020) 085

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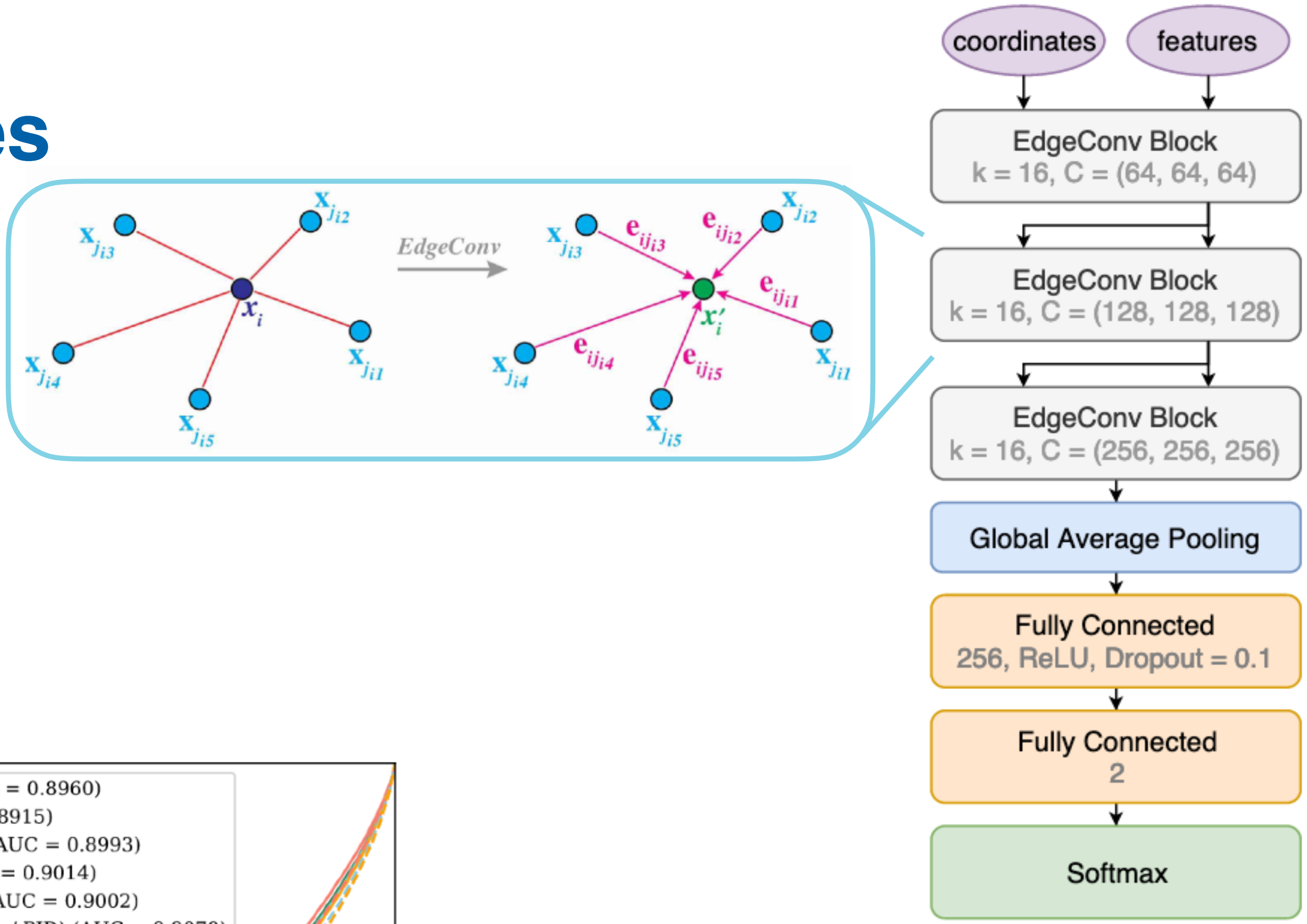
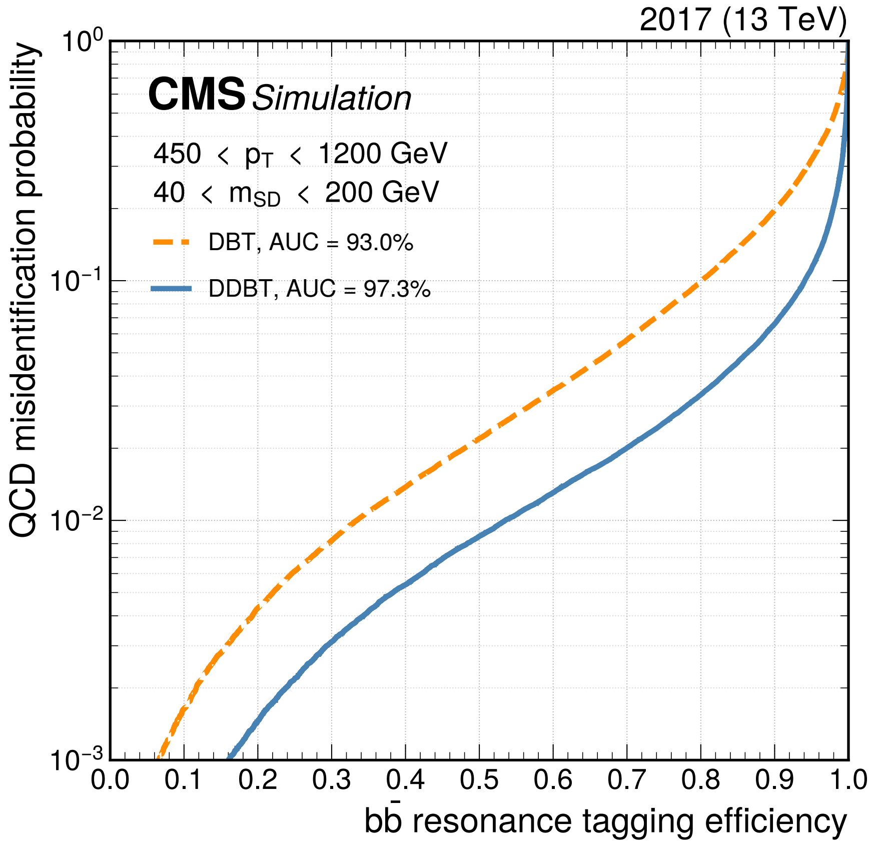
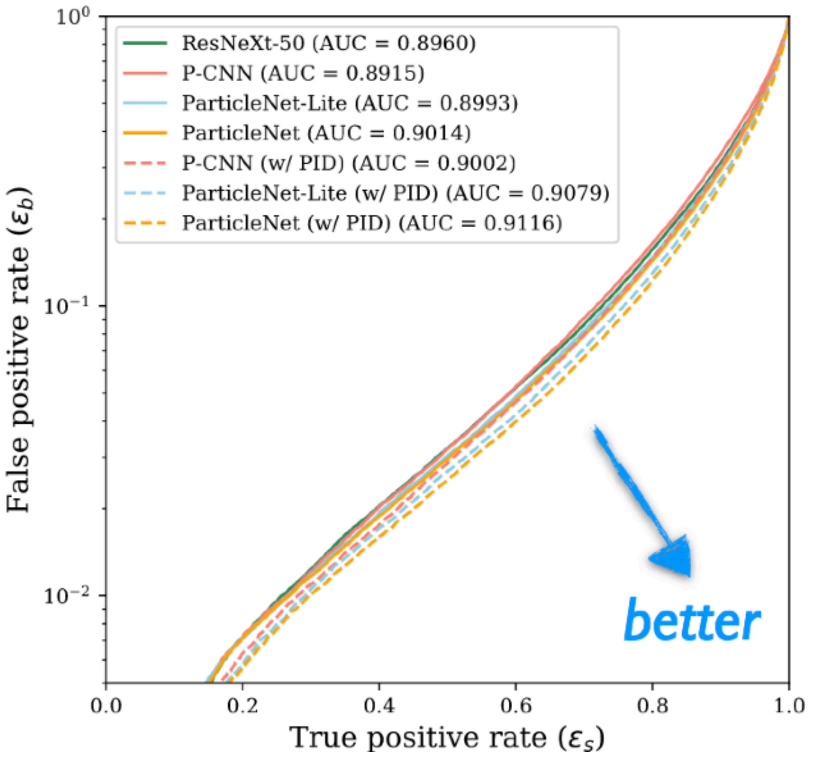




[JHEP 12 (2020) 085]



[PRD 101, 056019 (2020)]

Double charm tagging advances

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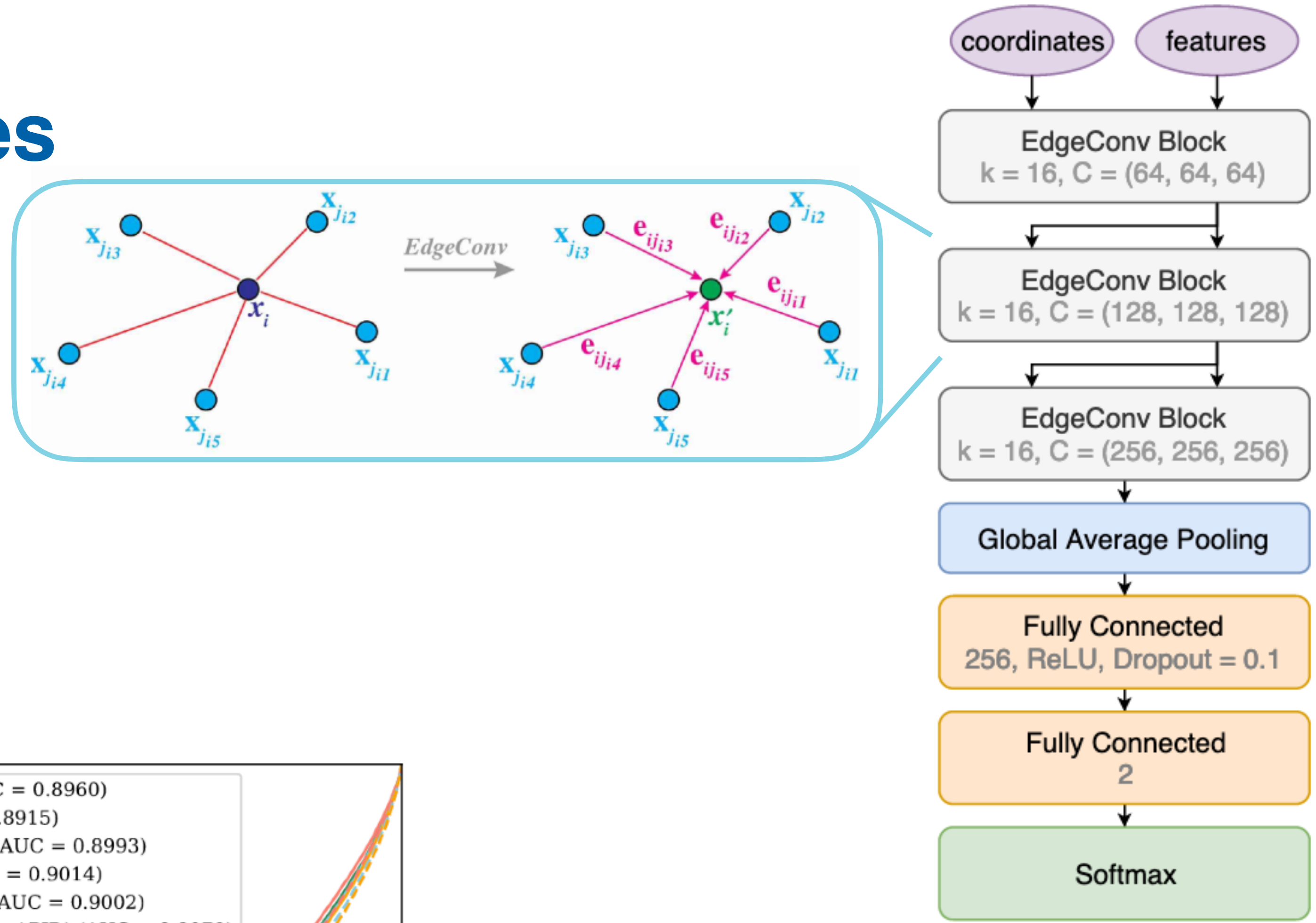
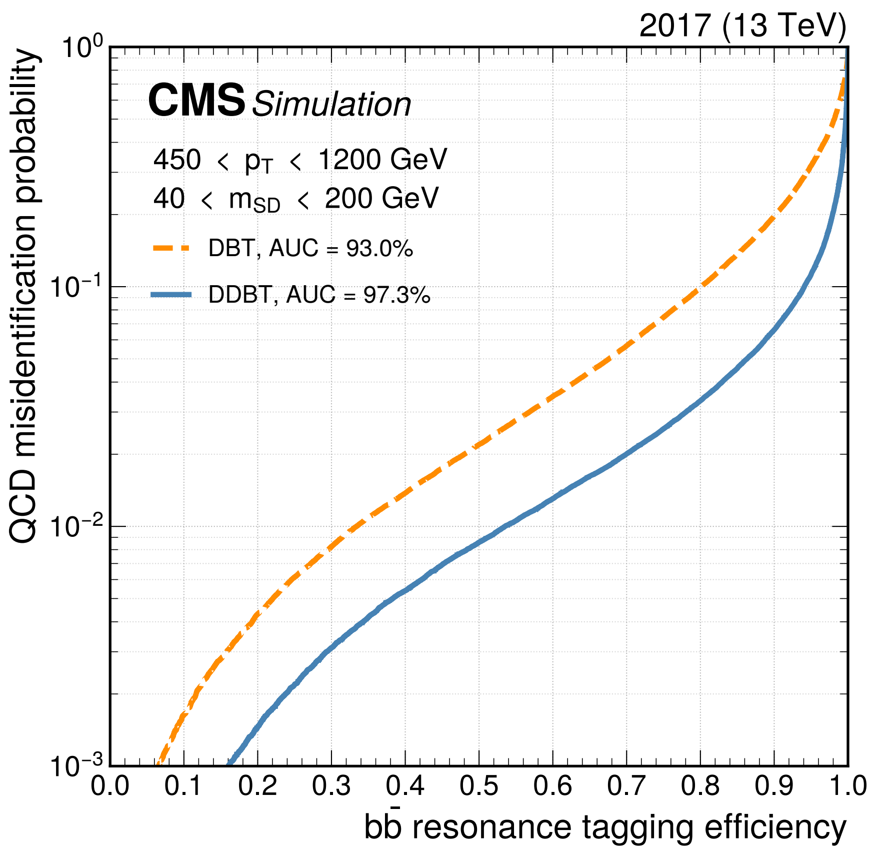
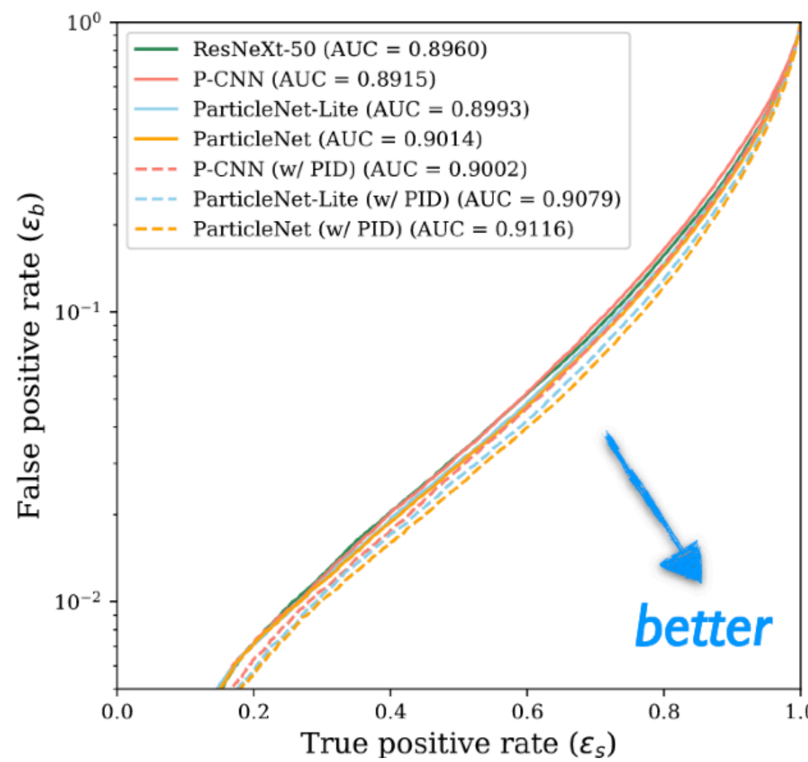
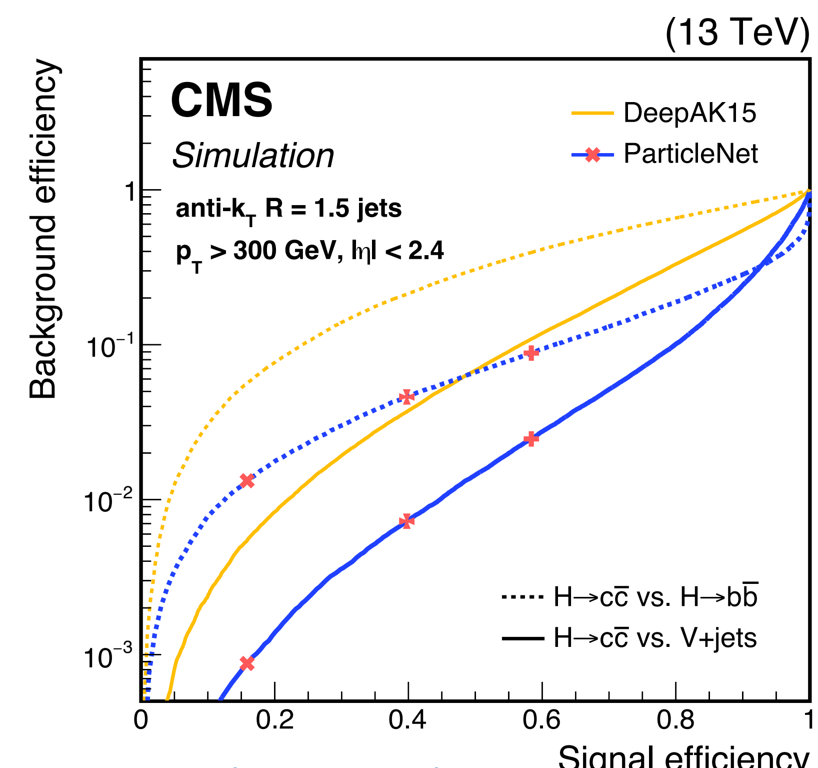




[JHEP 12 (2020) 085](#)



[PRD 101, 056019 (2020)](#)



[2205.05550 (acc. PRL)](#)

Double charm tagging advances

- Big gains with more complex DNN
  - SOTA ~~graph networks~~ transformers

PMLR 162:18281-18292, 2022

	All classes		$H \to b\bar{b}$	$H \to c\bar{c}$
	Accuracy	AUC	$\text{Rej}_{50\%}$	$\text{Rej}_{50\%}$
PFN	0.772	0.9714	2924	841
P-CNN	0.809	0.9789	4890	1276
ParticleNet	0.844	0.9849	7634	2475
ParT	**0.861**	**0.9877**	**10638**	**4149**
ParT (plain)	0.849	0.9859	9569	2911

Model complexity

	Accuracy	# params	FLOPs
PFN	0.772	86.1 k	4.62 M
P-CNN	0.809	354 k	15.5 M
ParticleNet	0.844	370 k	540 M
ParT	**0.861**	2.14 M	340 M
ParT (plain)	0.849	2.13 M	260 M

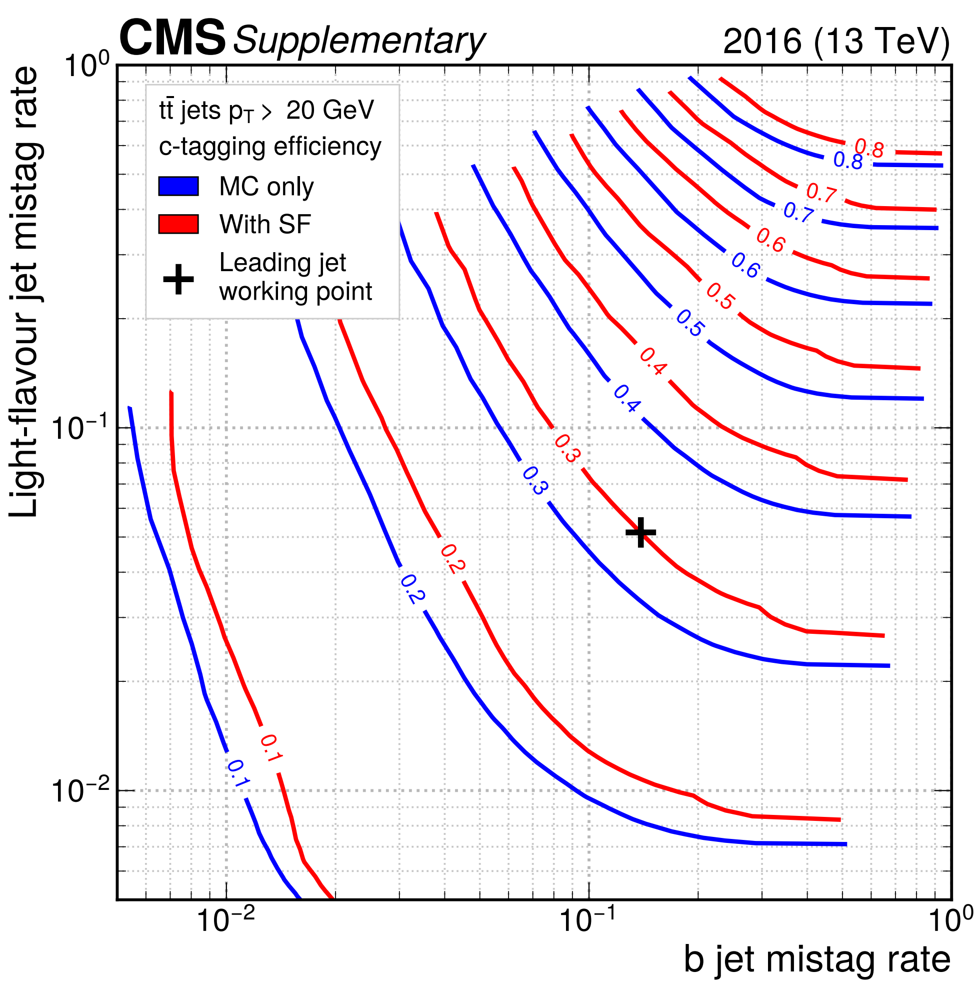
- Computation cost still under control.

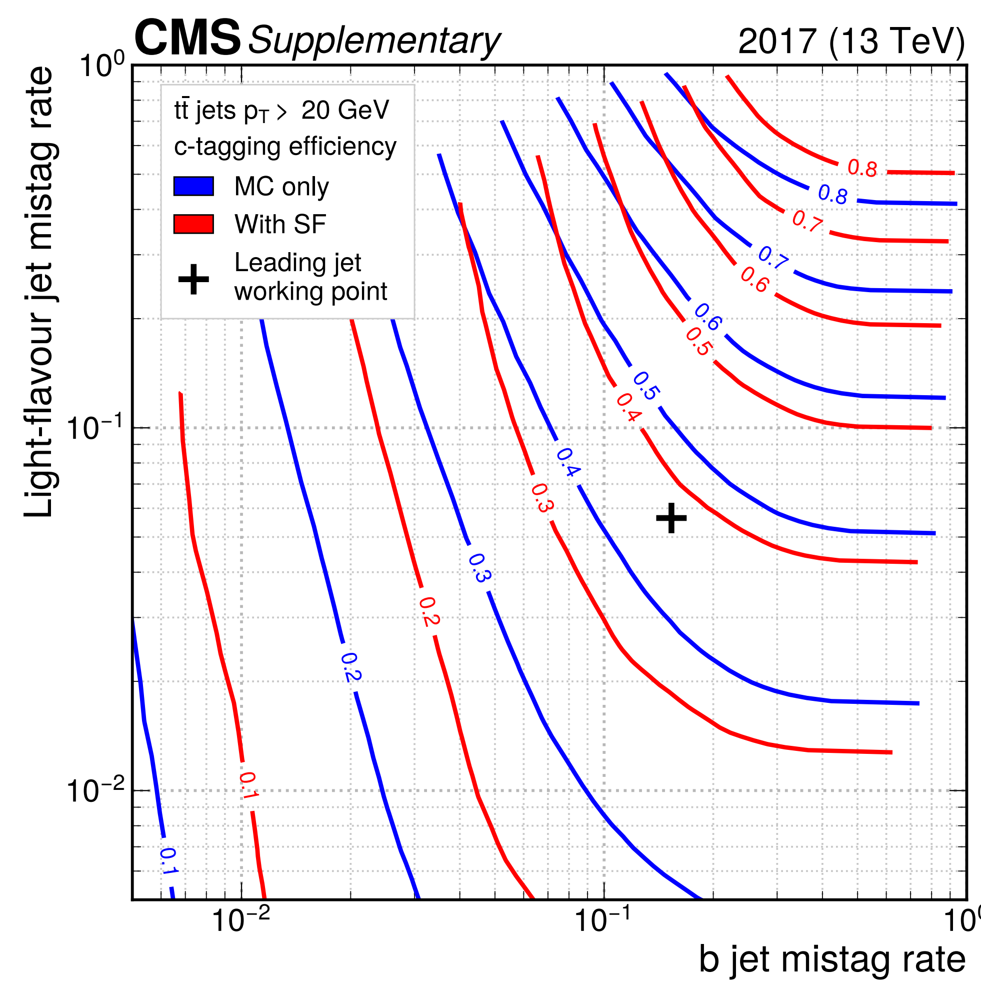
Single-charm jet calibration

Selection	Jet yield	c %	b %	udsg %
W+c	362 002	**92.9**	0.957	6.14
$t\bar{t}$	380 366	12.1	**81.0**	6.91
DY + jet	8 509 206	8.87	5.05	**86.1**

JINST 17 (2022) P03014

- CMS: calibrate via template fit to $W + c, t\bar{t}, Z + jets$ topologies
  - ATLAS: top only
- Calibrated performance degrades, SF 0.9-1 ± 2-5%
  - Aside: 2017 > 2016 due to CMS Phase-I pixel upgrade

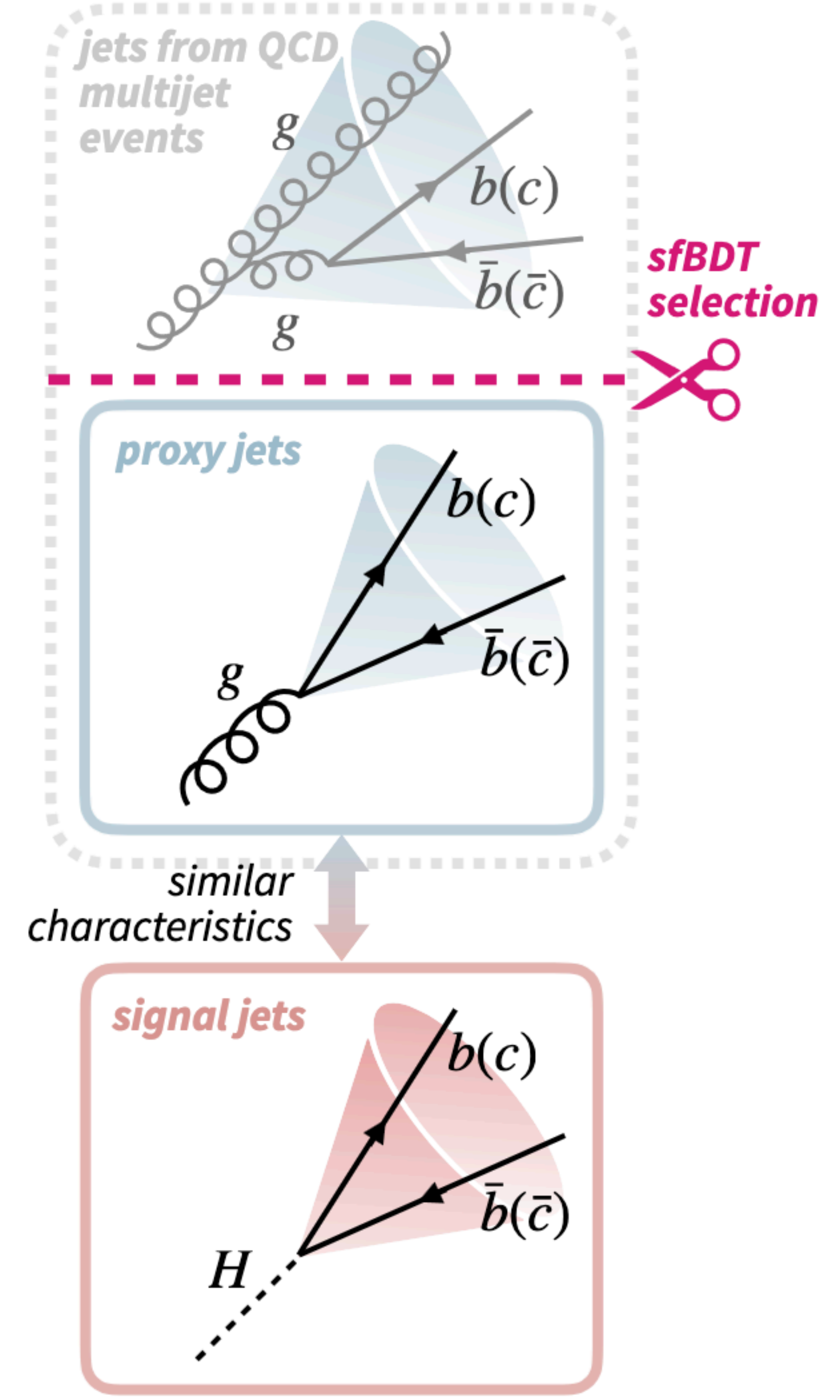


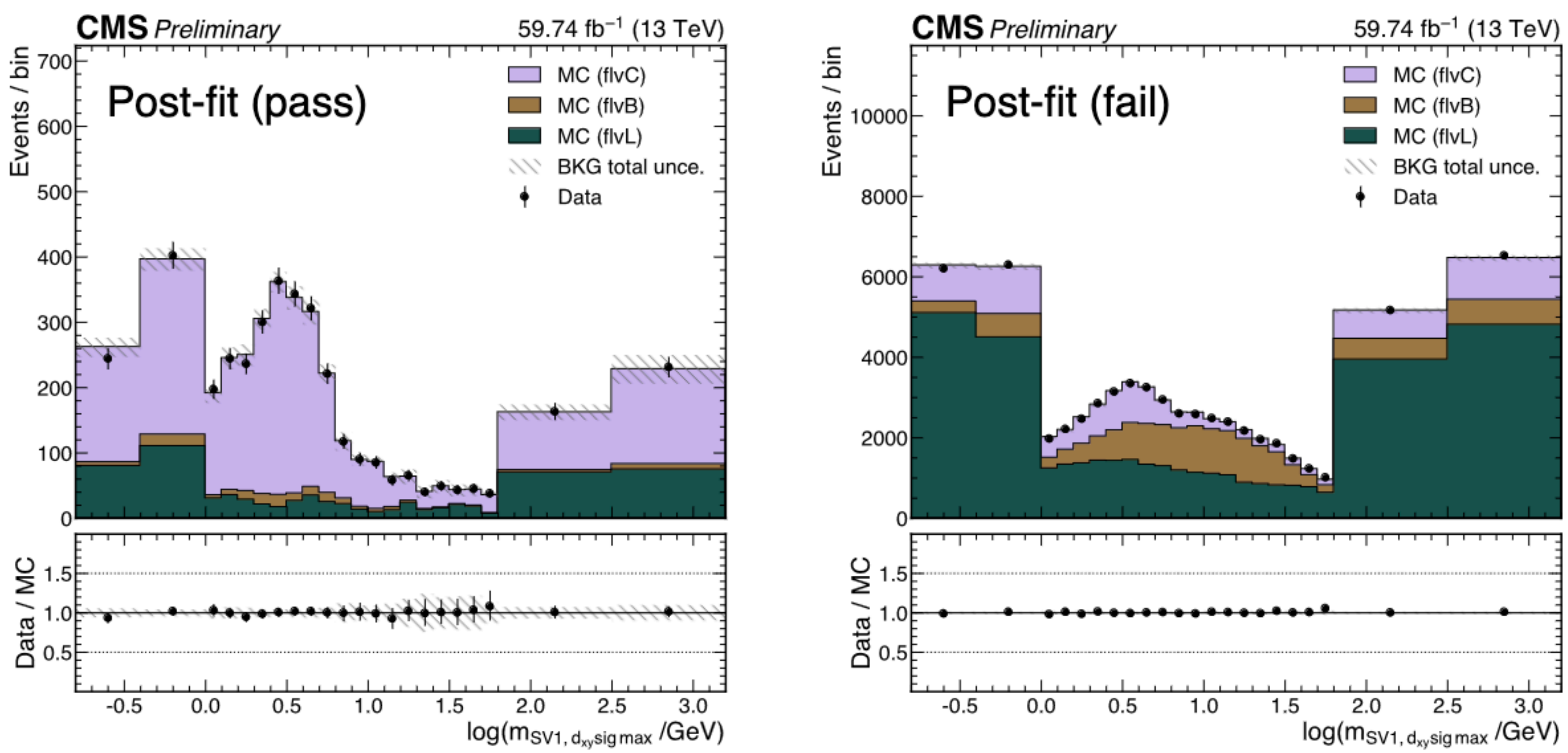


2205.05550 (acc. PRL)

Double-charm jet calibration

- Gluon-splitting proxy jet sample obtained via
  - Soft muon selection (low-p_T muon in each subjet)
  - sfBDT (trained on parton-level gluon energy fraction)
- Template fit to 3 components in leading SV mass
- Typical uncertainty ~30%
  - Dominant systematic for VH(cc), ggH(cc)

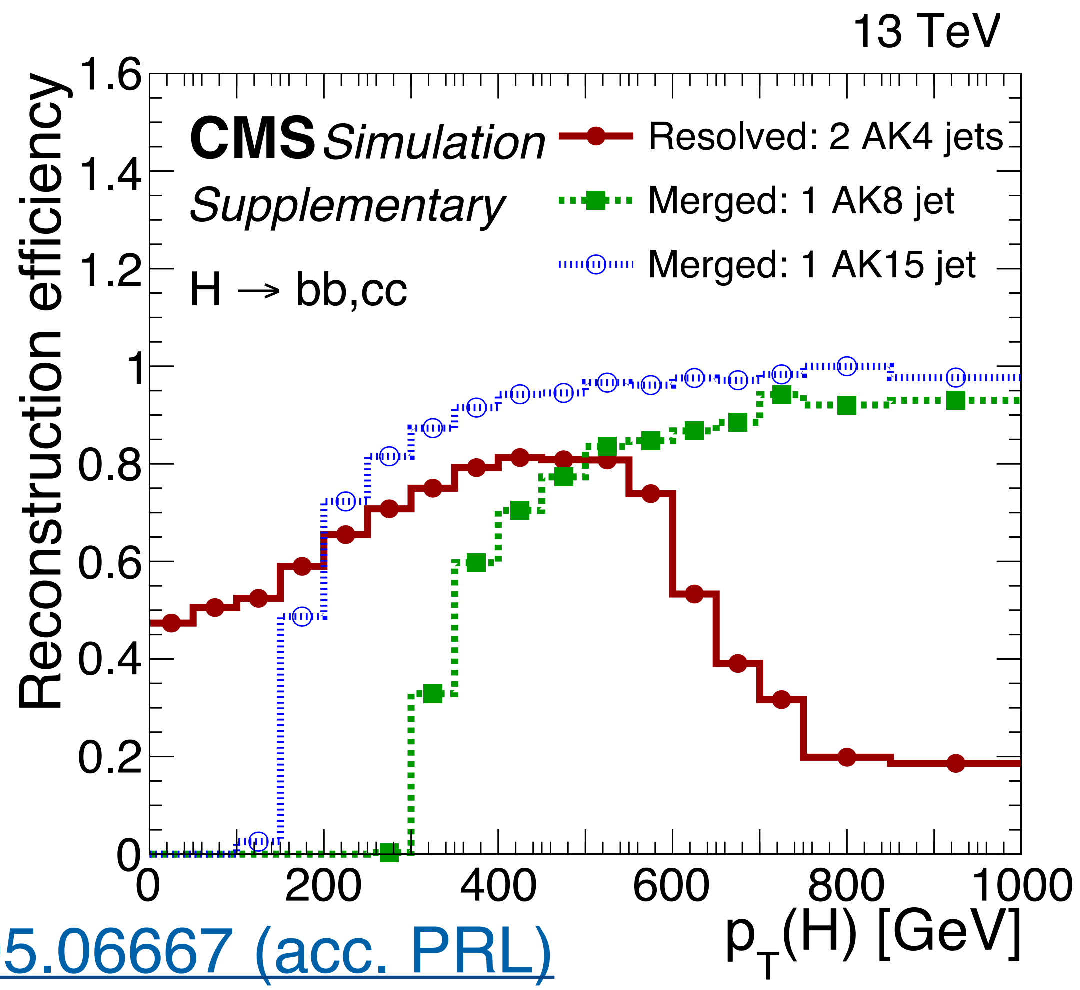




CMS-DP-2022-005

Applying charm tagging in VH topology

- Analysis strategy very much like VH(bb)
  - Tag V boson in lepton multiplicity categories
  - Use DNN to tag c jets, improve mass resolution
  - Multi-region fit to constrain V+jets background
- For CMS, split analysis into resolved + boosted
  - Boosted: anti-k_T R=1.5 jet with $p_T > 300$ GeV exists



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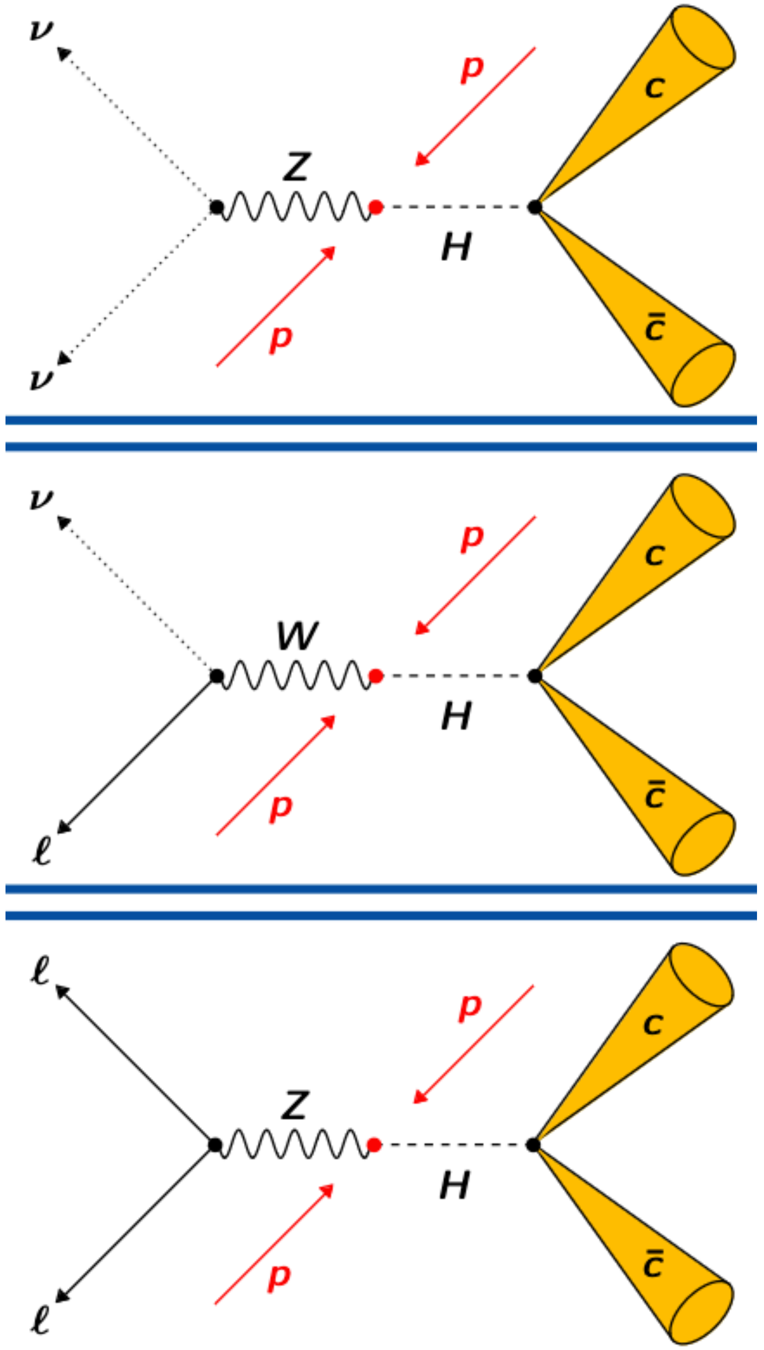
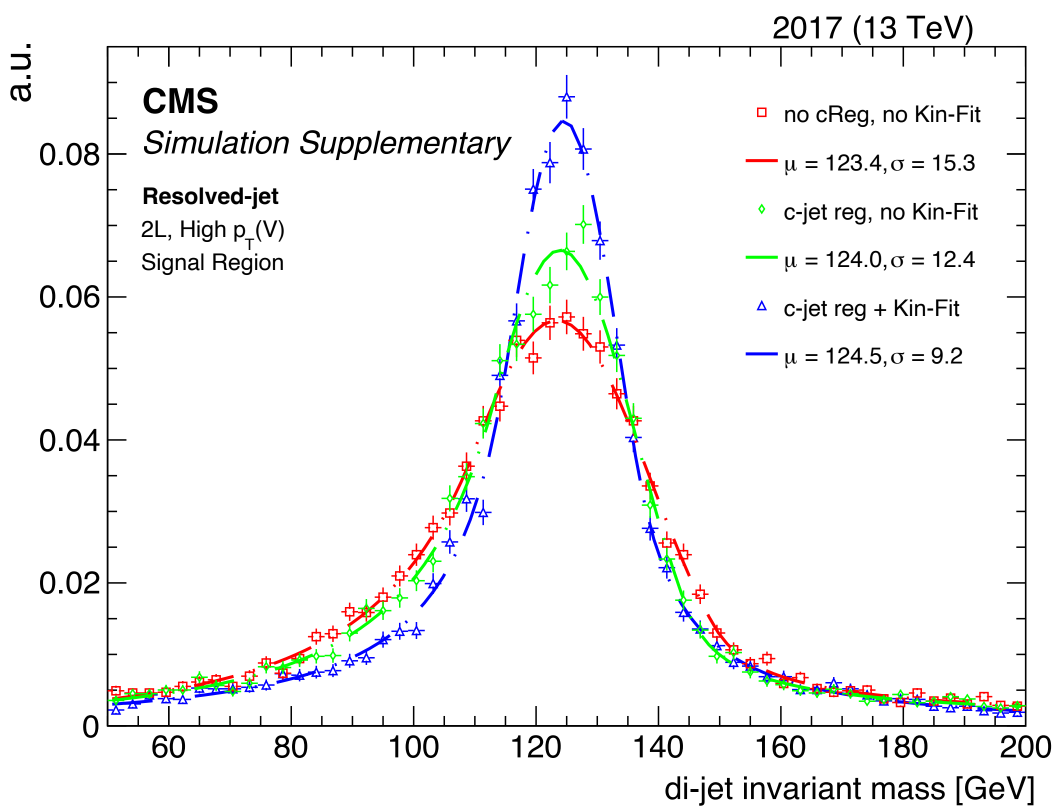


Diagram: A. Chisholm, CERN Seminar

Fermilab

Jet mass resolution

- For resolved jets, challenge is energy resolution & FSR recovery
  - ATLAS: muon recovery (topoclusters)
  - For 2ℓ channel, can use kinematic fit as well
- For boosted jets, challenge is ISR, underlying event, and pileup
  - Historically handled via soft-drop grooming
  - Soft-drop can send mass to zero; instead train ParticleNet regression on PF candidates



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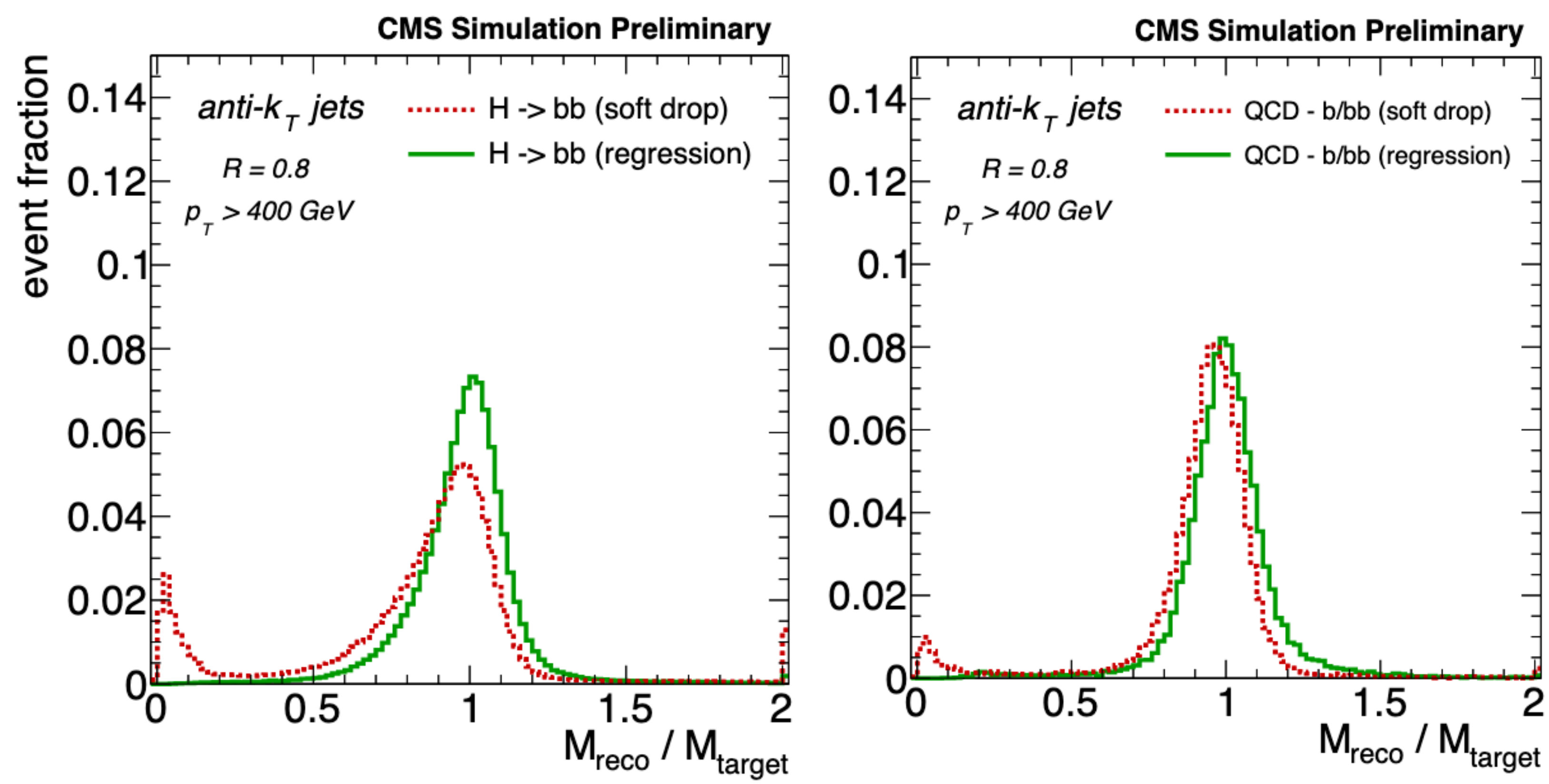


$$M_{\text{target}} = \begin{cases} M_{\text{SD}}^{\text{gen}} & \text{if jet is QCD} \\ m_{\text{H}} \in [15, 250] & \text{otherwise} \end{cases}$$

CMS-DP-2021-017

Dealing with V+jets

- For all analyses, control regions (CRs) are formed via kinematic sidebands
  - Resolved: sideband in $\Delta R(j,j)$ or m_{jj}
  - Boosted: kinematic BDT (only jet + leptons)
- CRs further split by flavor tagger inversions
  - Independent normalization+shape uncertainties for light, c, and b flavor, varied definitions ATLAS/CMS
- Common theme: free parameters in fit necessary, even when using NLO QCD V+jets samples
  - ATLAS: 2-point Sherpa/FxFx modeling uncertainty
  - MC statistics also challenging

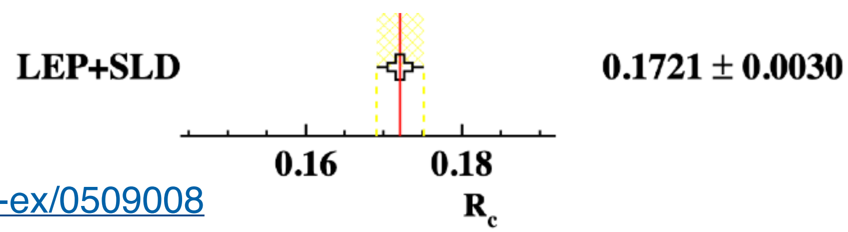
Excerpt from ATLAS VH(cc) uncertainty model

$Z+$jets	
$Z+hf$ normalisation	Floating
$Z+mf$ normalisation	Floating
$Z+lf$ normalisation	Floating
$Z+bb$ to $Z+cc$ ratio	20%
$Z+bl$ to $Z+cl$ ratio	18%
$Z+bc$ to $Z+cl$ ratio	6%
p_T^V acceptance	1%–8%
N_{jet} acceptance	10%–37%
High-ΔR CR to SR	12%–37%
0- to 2-lepton ratio	4%–5%
$W+$jets	
$W+hf$ normalisation	Floating
$W+mf$ normalisation	Floating
$W+lf$ normalisation	Floating
$W+bb$ to $W+cc$ ratio	4%–10%
$W+bl$ to $W+cl$ ratio	31%–32%
$W+bc$ to $W+cl$ ratio	31%–33%
$W\to\tau\nu(+c)$ to $W+cl$ ratio	11%
$W\to\tau\nu(+b)$ to $W+cl$ ratio	27%
$W\to\tau\nu(+l)$ to $W+l$ ratio	8%
N_{jet} acceptance	8%–14%
High-ΔR CR to SR	15%–29%
$W\to\tau\nu$ SR to high-ΔR CR ratio	5%–18%
0- to 1-lepton ratio	1%– 6%

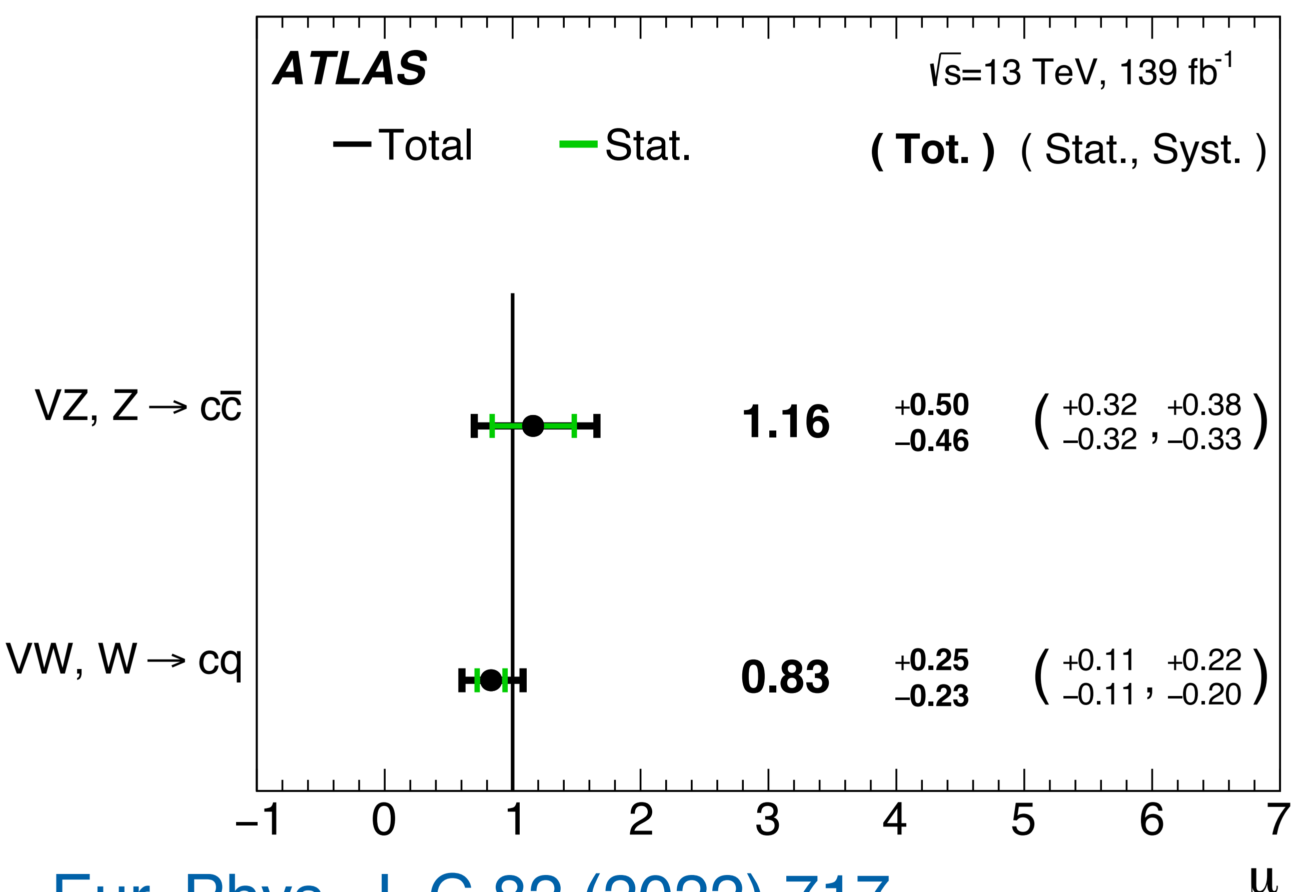
Fermilab

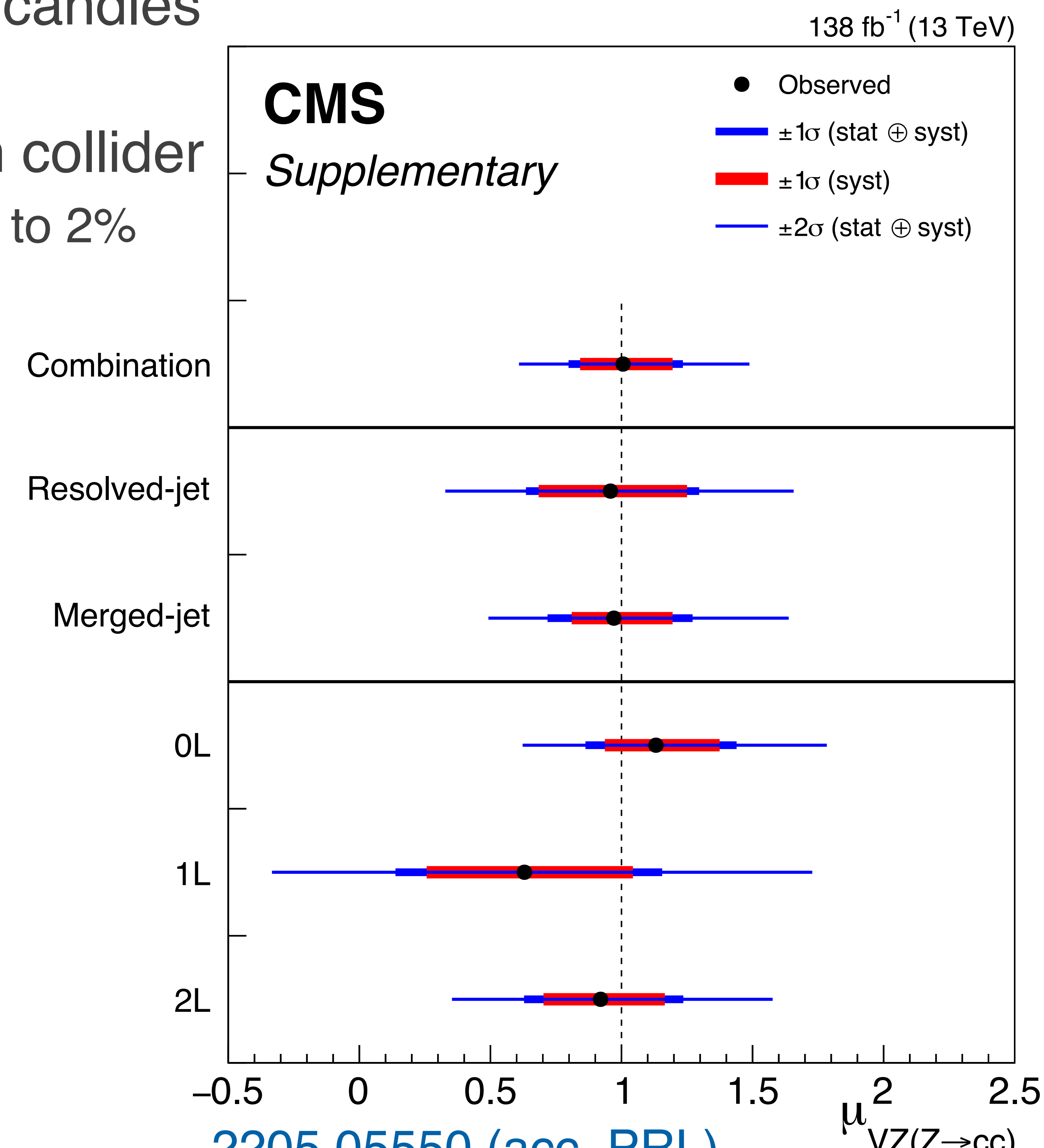
Standard candles

- VW, VZ production serve as standard candles
  - In all analyses, compatible with SM
- CMS: first Z(cc) observation at hadron collider
  - LEP: R_c ratio of cc to hadronic Z decay BR to 2%



arxiv:hep-ex/0509008

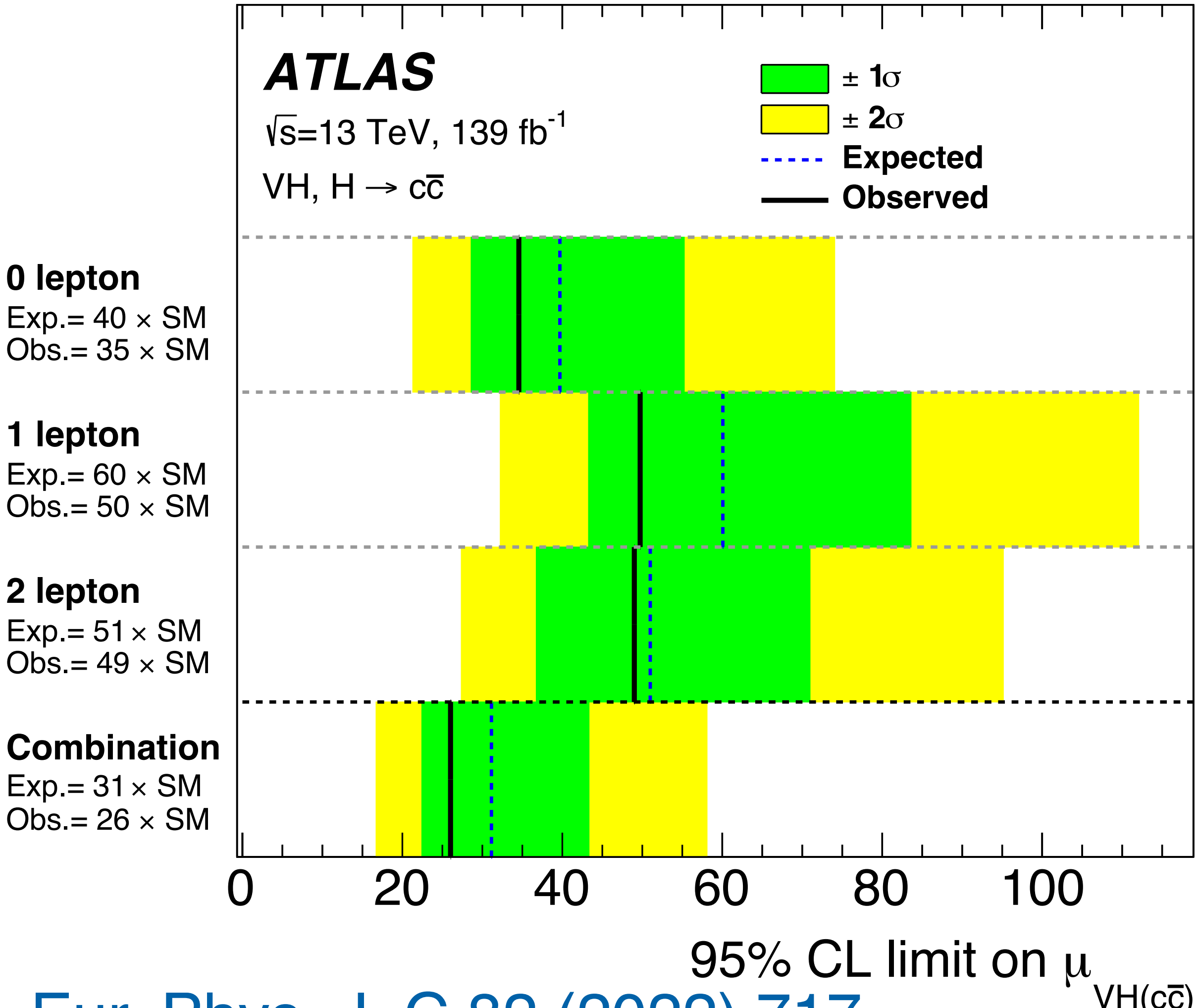




Eur. Phys. J. C 82 (2022) 717 [2205.05550](2205.05550) (acc. PRL)

VH(cc) results

- CMS/ATLAS comparison in resolved result is difficult
  - Competition with merged jet for phase space
- Uncertainty budget: statistical ~ systematic
  - Leading systematic: Z+jets modeling (ATLAS); MC stat (CMS resolved); c-tag efficiency (CMS boosted)



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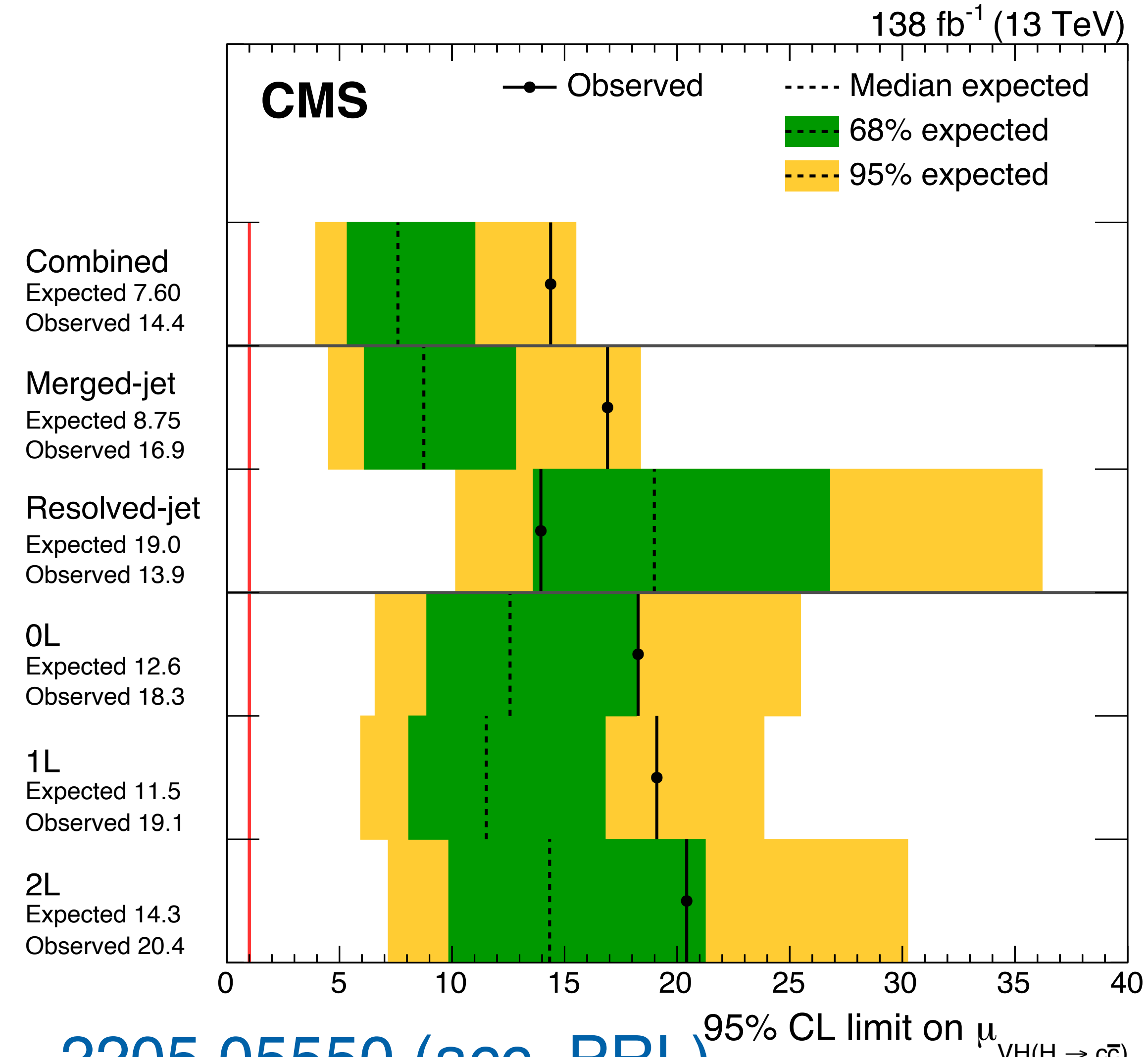
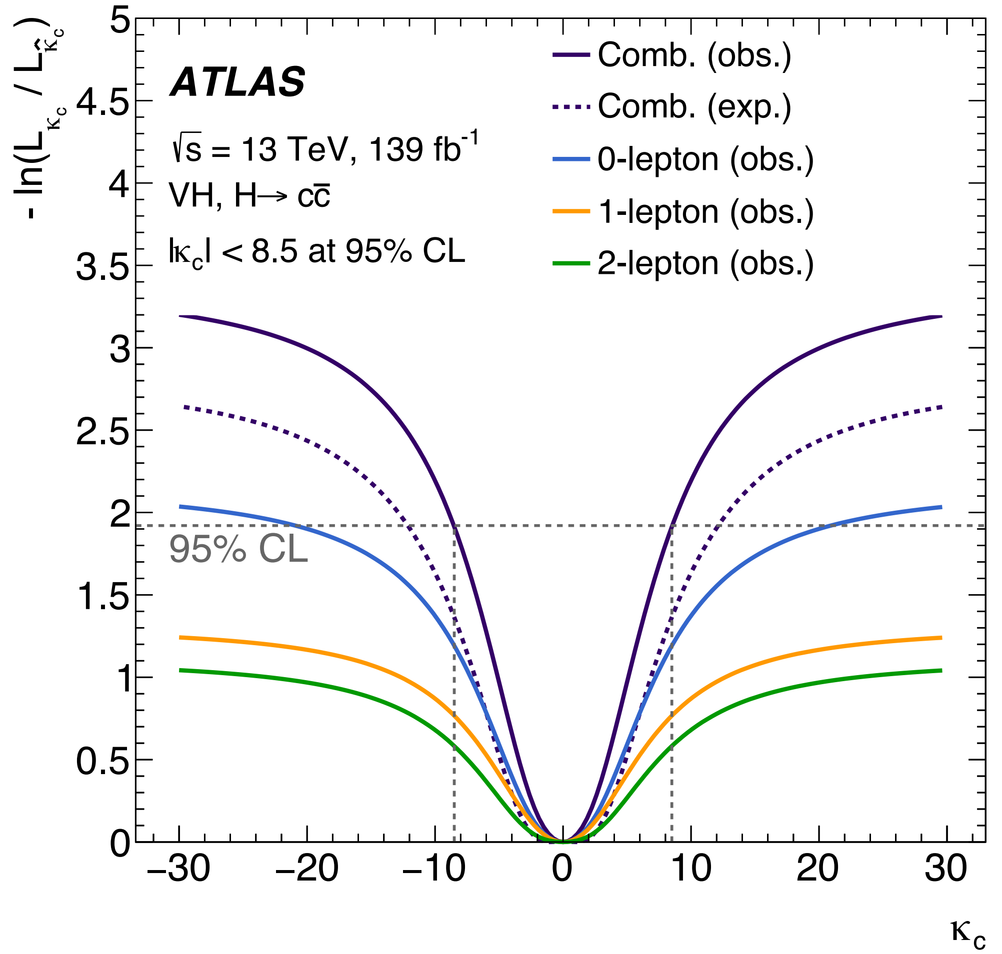
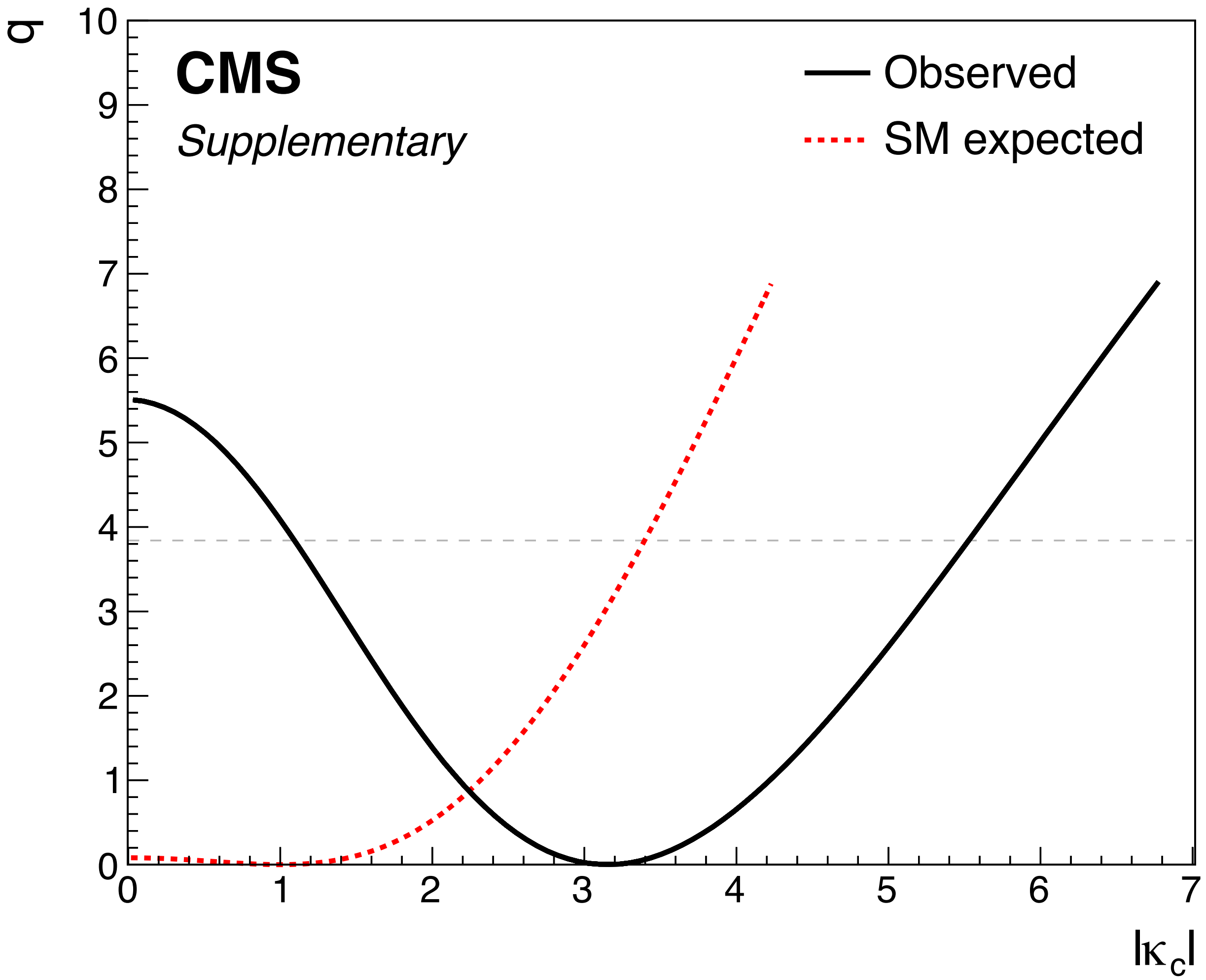


2205.05550 (acc. PRL)

VH(cc) results

- Translation to κ_c constraint assuming other $\kappa = 1$
  - $\mu_{VH(cc)} = \dfrac{\kappa_c^2}{1 + B_{cc}^{SM}(\kappa_c^2 - 1)}$





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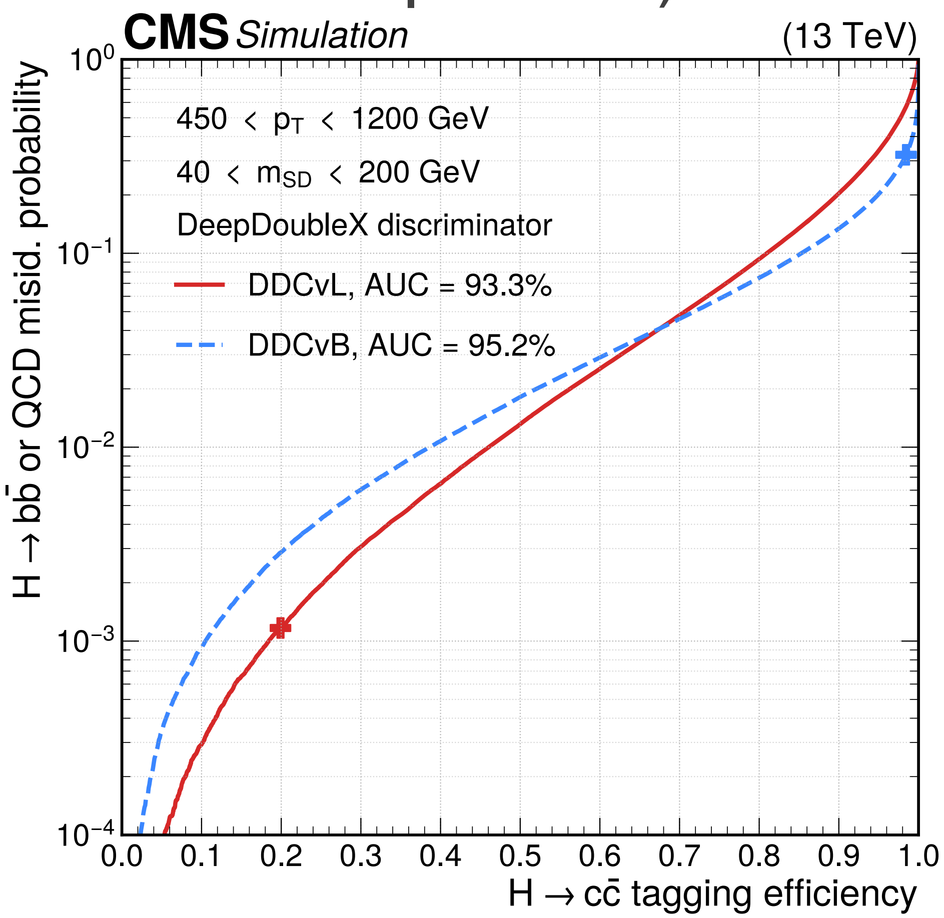
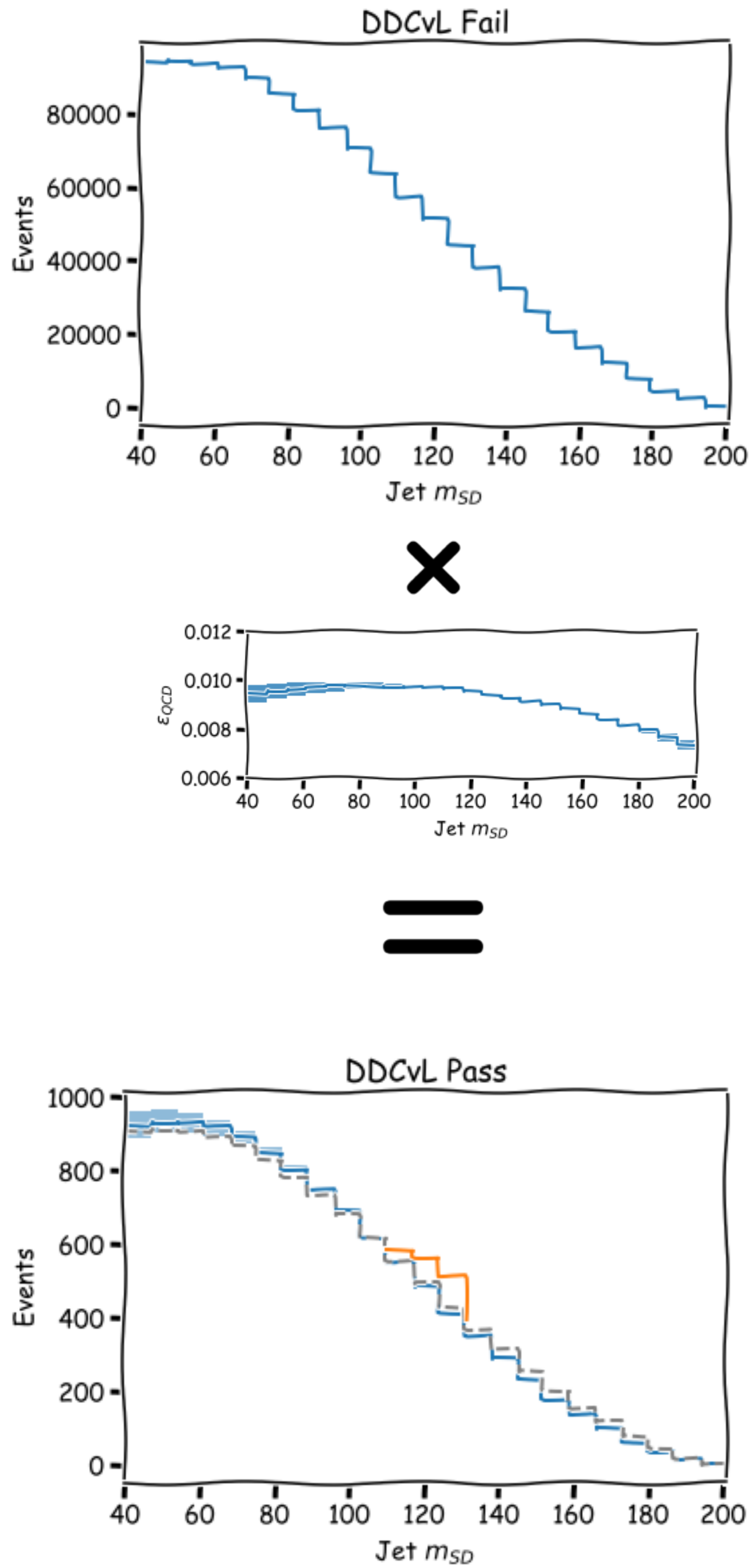
2205.05550 (acc. PRL)

Boosted ggH(cc)

- CMS has probed ggH(cc) with full Run II data
- Event selection:
  - One AK8 *DeepDoubleX* cc-tagged jet
  - No leptons, b-tag veto
- Large QCD background suppressed by 10^{-3}, accurately modeled via CR + sideband constraint ("differential alphabet")



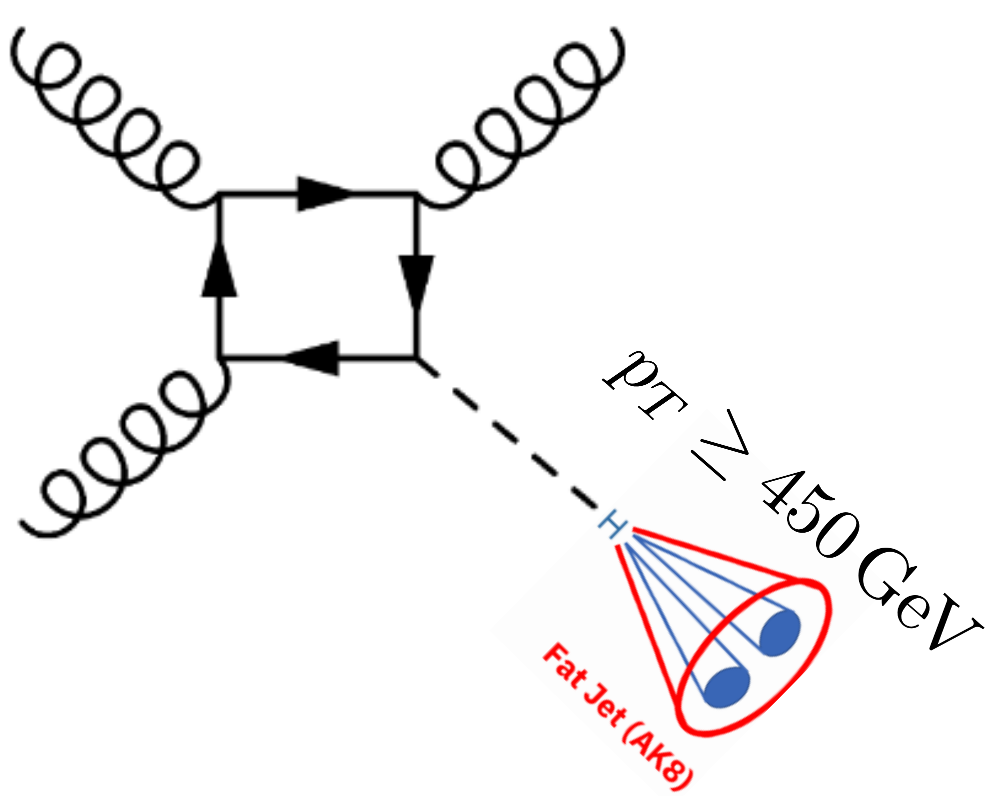


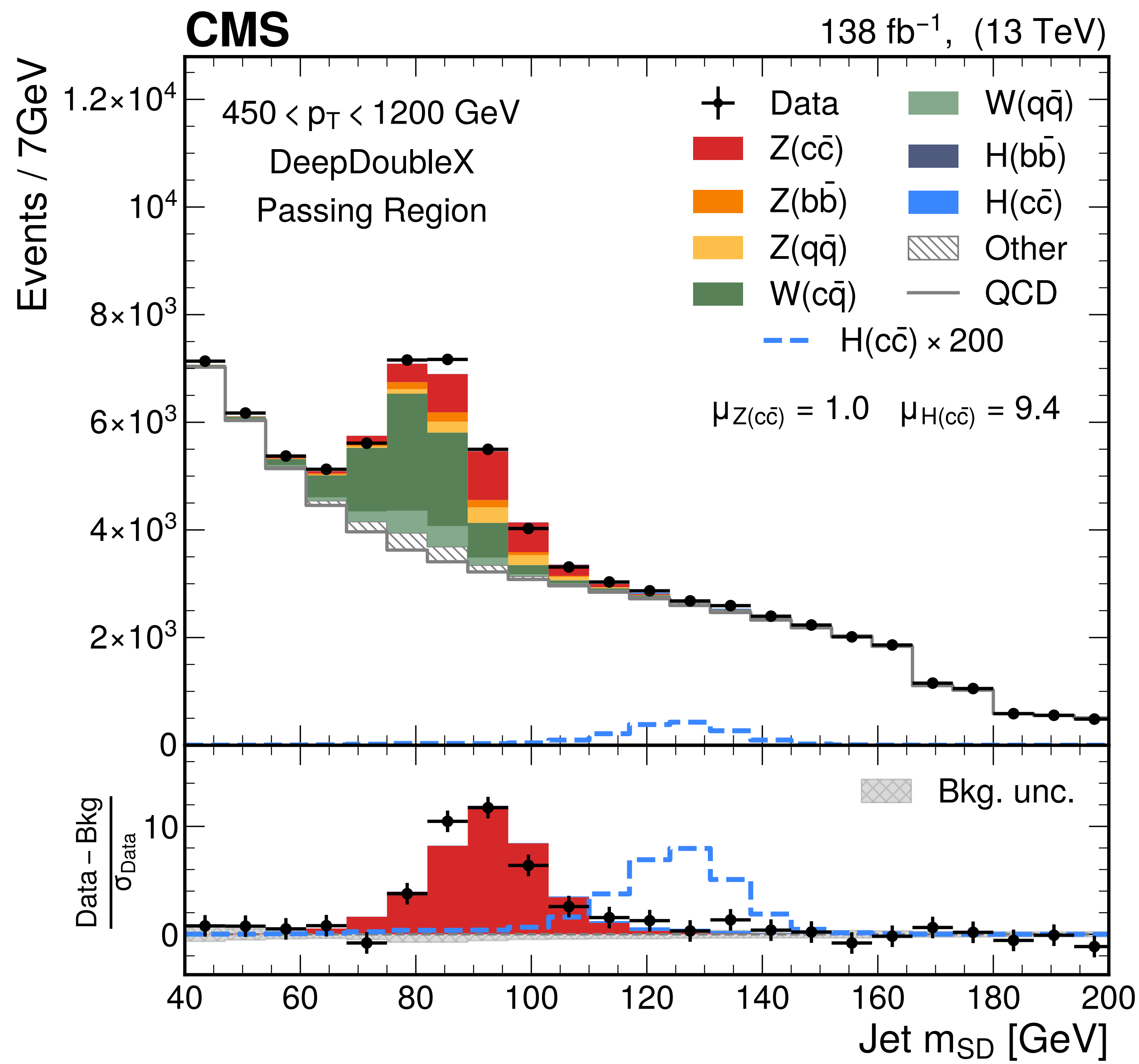
2211.14181 (acc. PRL)

Fermilab

Boosted ggH(cc)

- Double charm tagger calibration validated using Z(cc)
  - Observation of Z(cc)+jets!
- ggH(cc) upper limit: 47 (39) x SM
  - Leading uncertainty is statistical

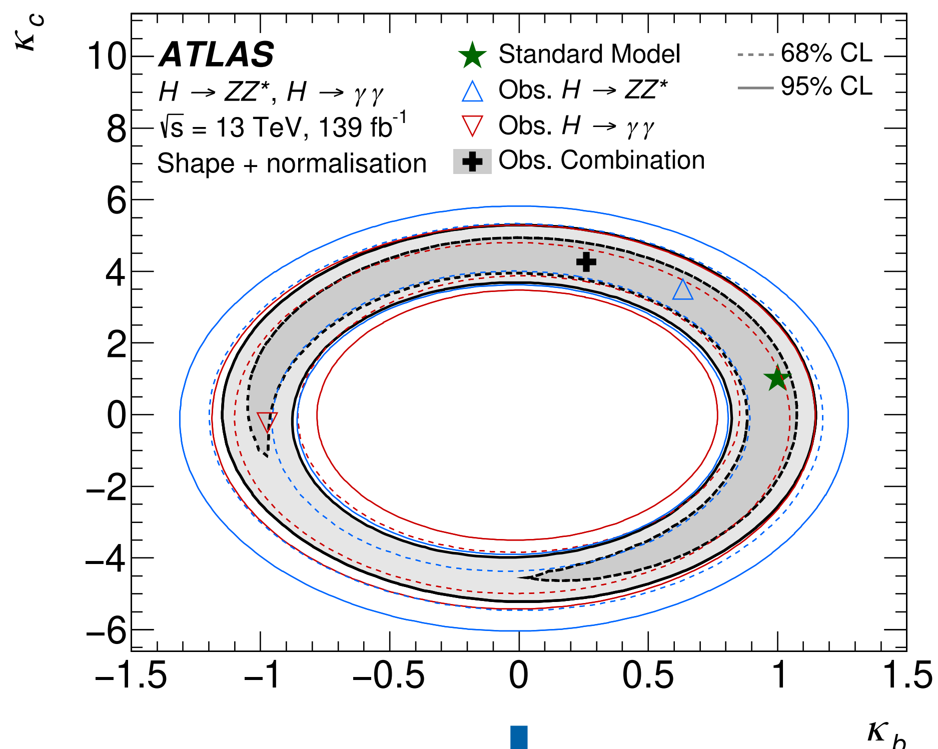


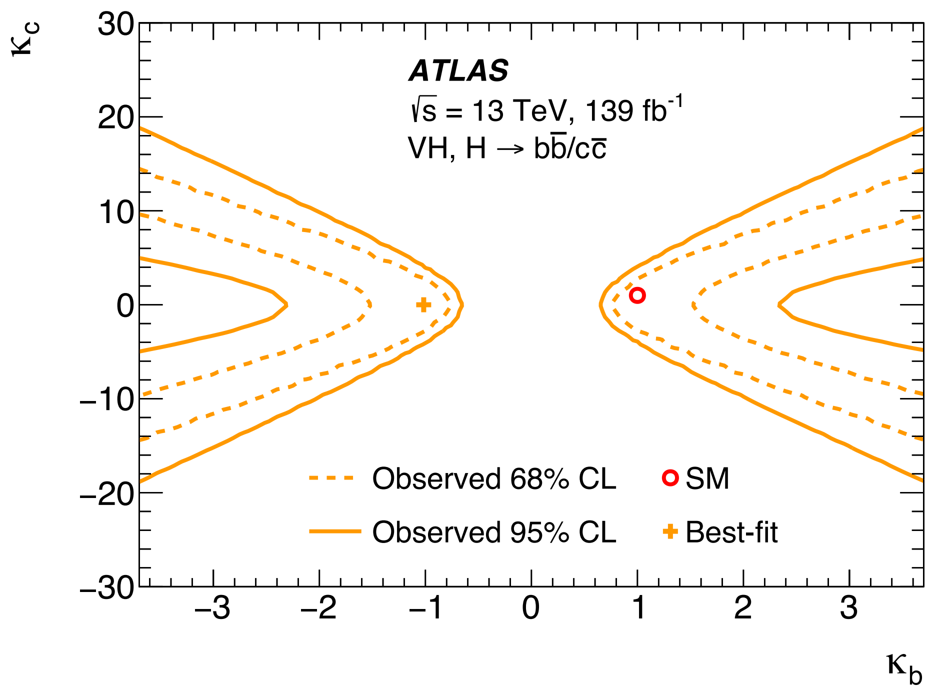


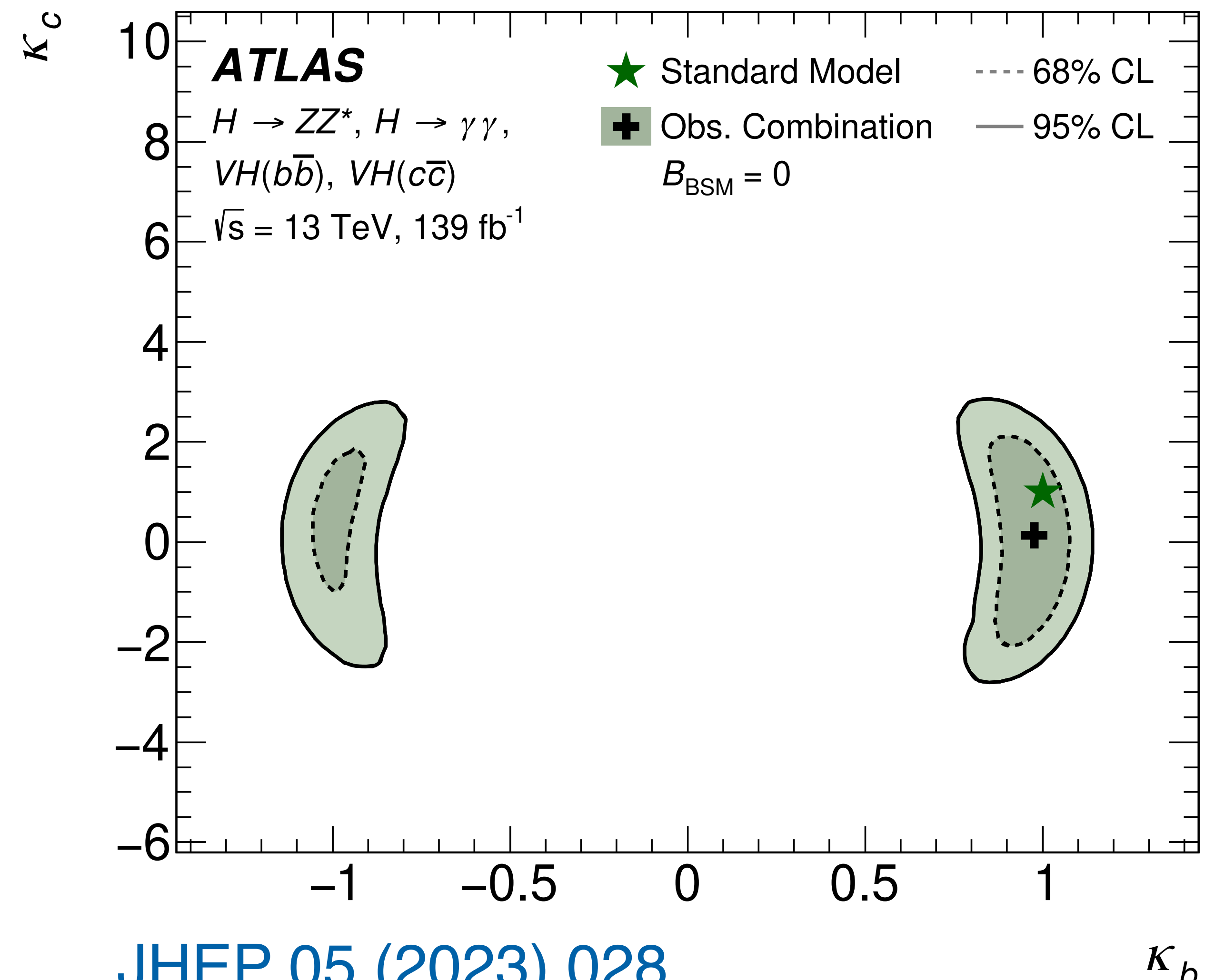
[2211.14181](2211.14181) (acc. PRL)

Combinations

- ATLAS VH(bb)+VH(cc) combination provides complementary constraints to Higgs p_T differential measurement: combine them!
  - Removing VH(cc) degrades κ_c constraint 10% for $B_{BSM} = 0$ (2x for floating BSM)







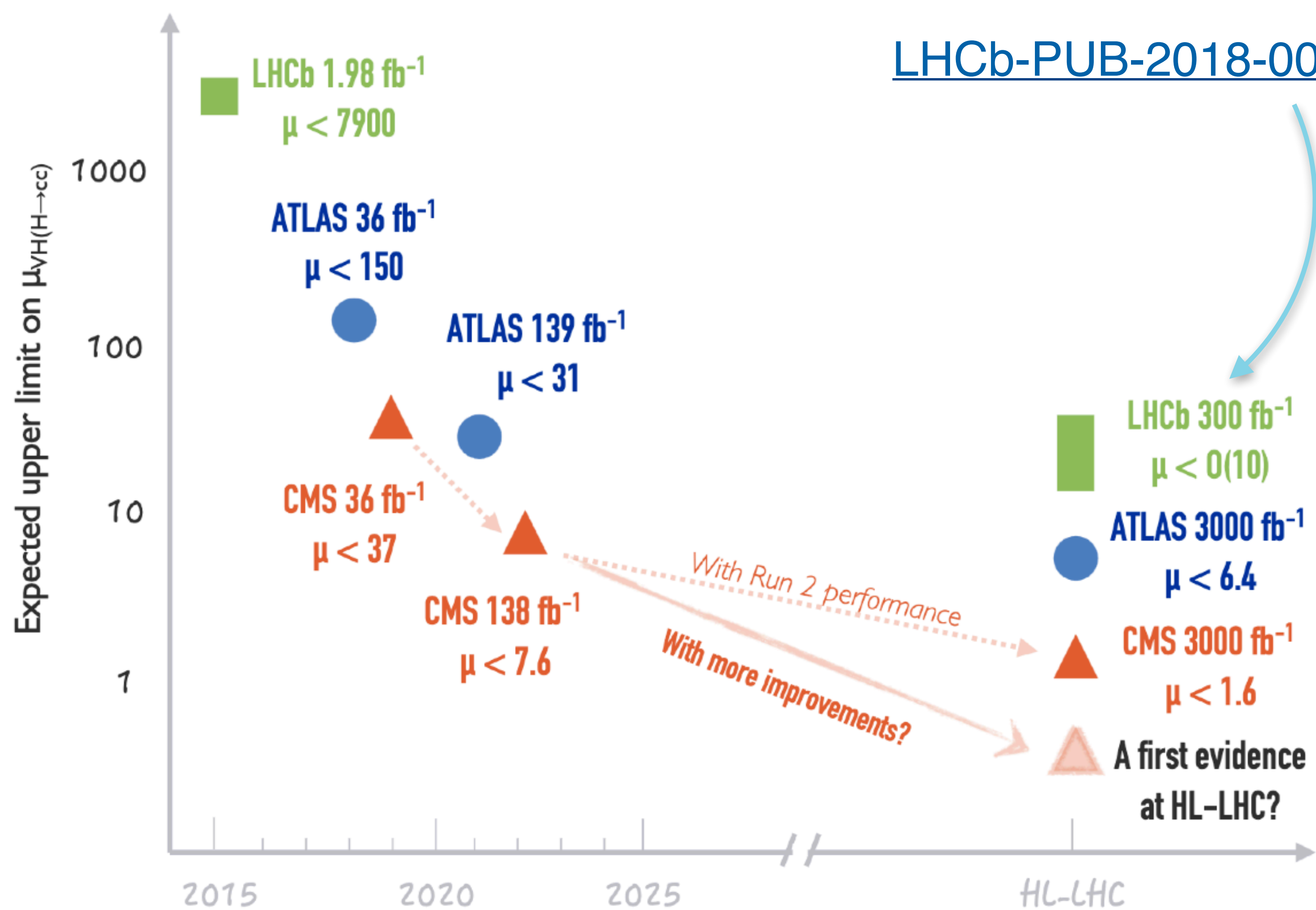
[JHEP 05 (2023) 028]

Summary & Outlook

- A large amount of progress towards κ_c in the last few years
- Indirect searches become more precise w/$\sqrt{L}$
- Direct searches see large gains with novel experimental techniques
  - cc-tagging as good now as bb-tagging was 3 years ago!
- Statistical uncertainty still significant in all searches—we will gain much from HL-LHC

Thanks for your attention!

LHCb-PUB-2018-009

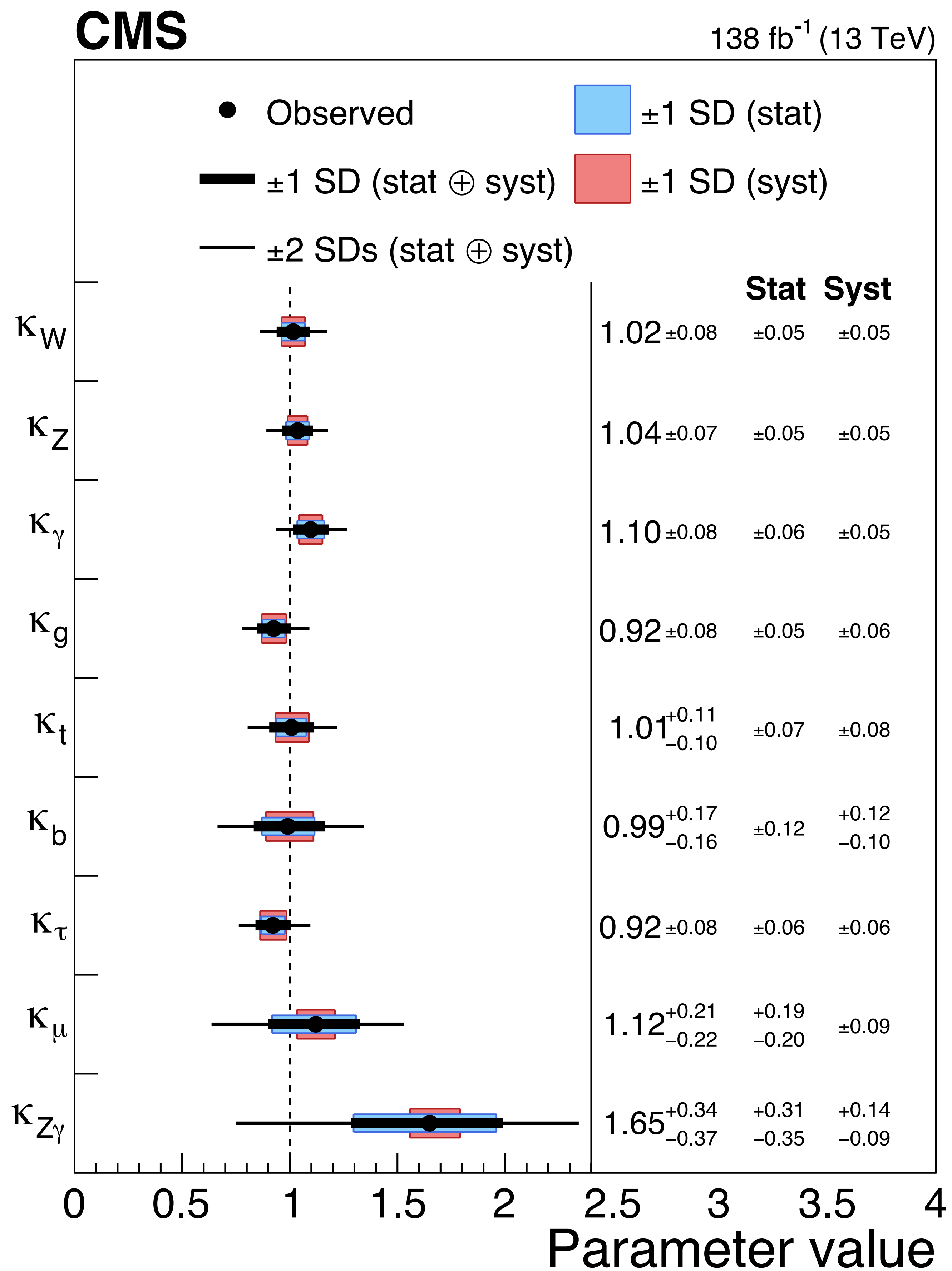


From H. Qu & L. Mastrolorenzo, CERN seminar

Backup

CMS kappa fit

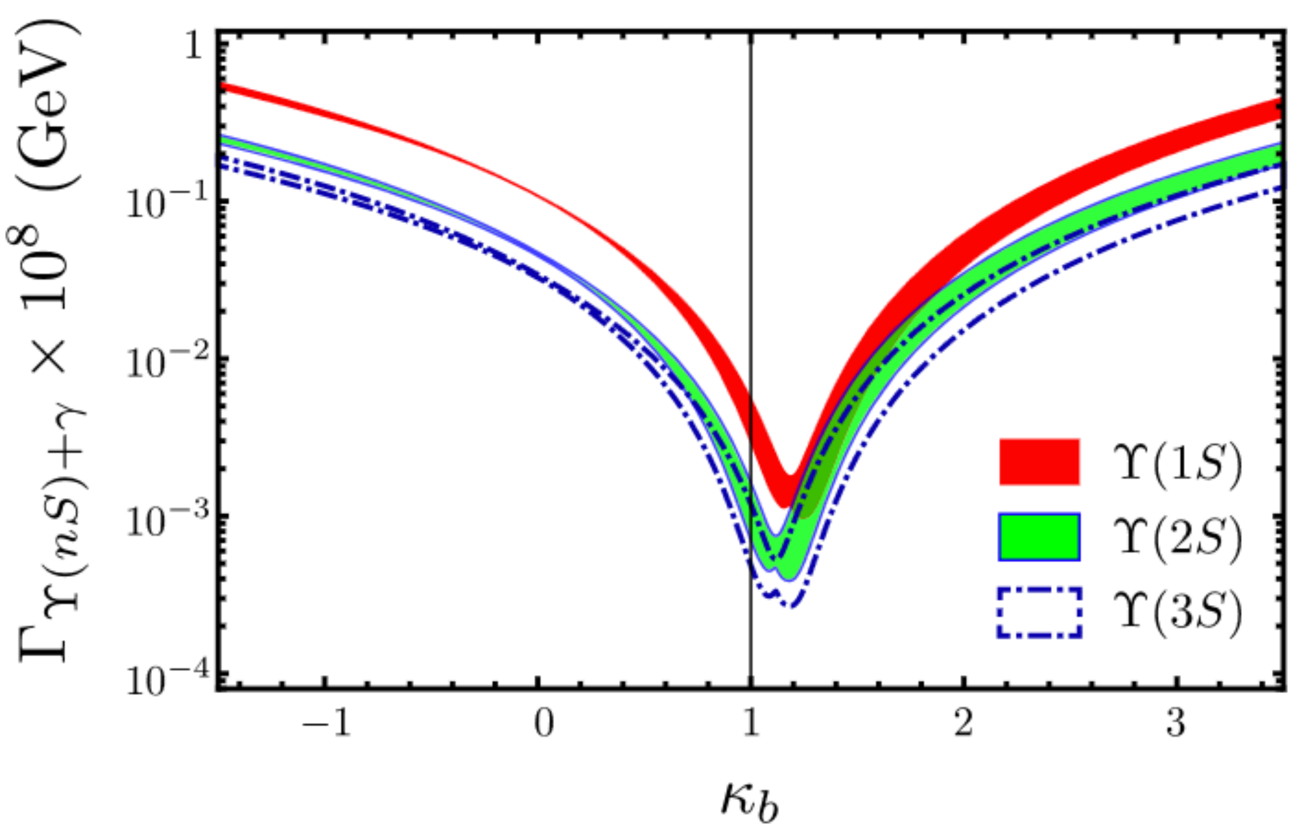
- Without invisible/undetected component



Other γ + meson decays

- Υ may be more interesting

[PRD 100, 054038](#)

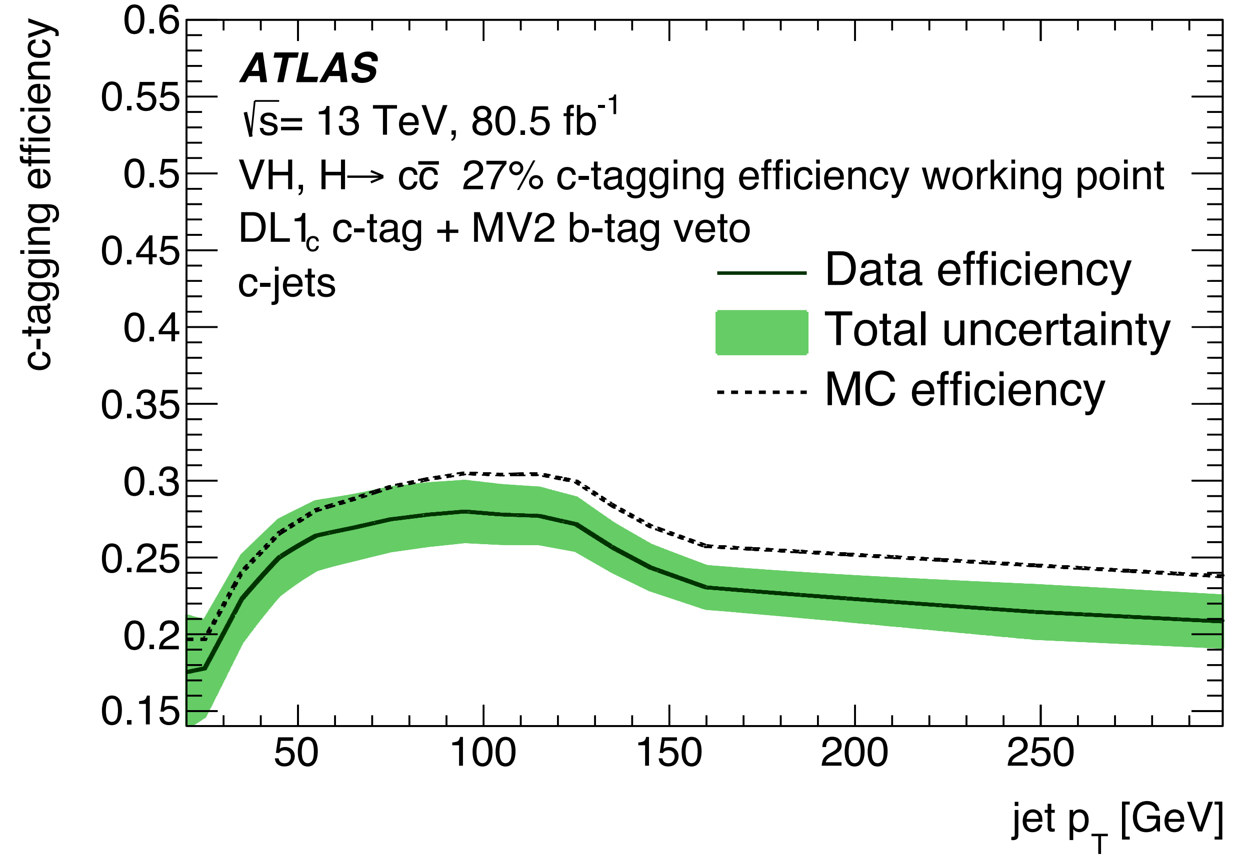


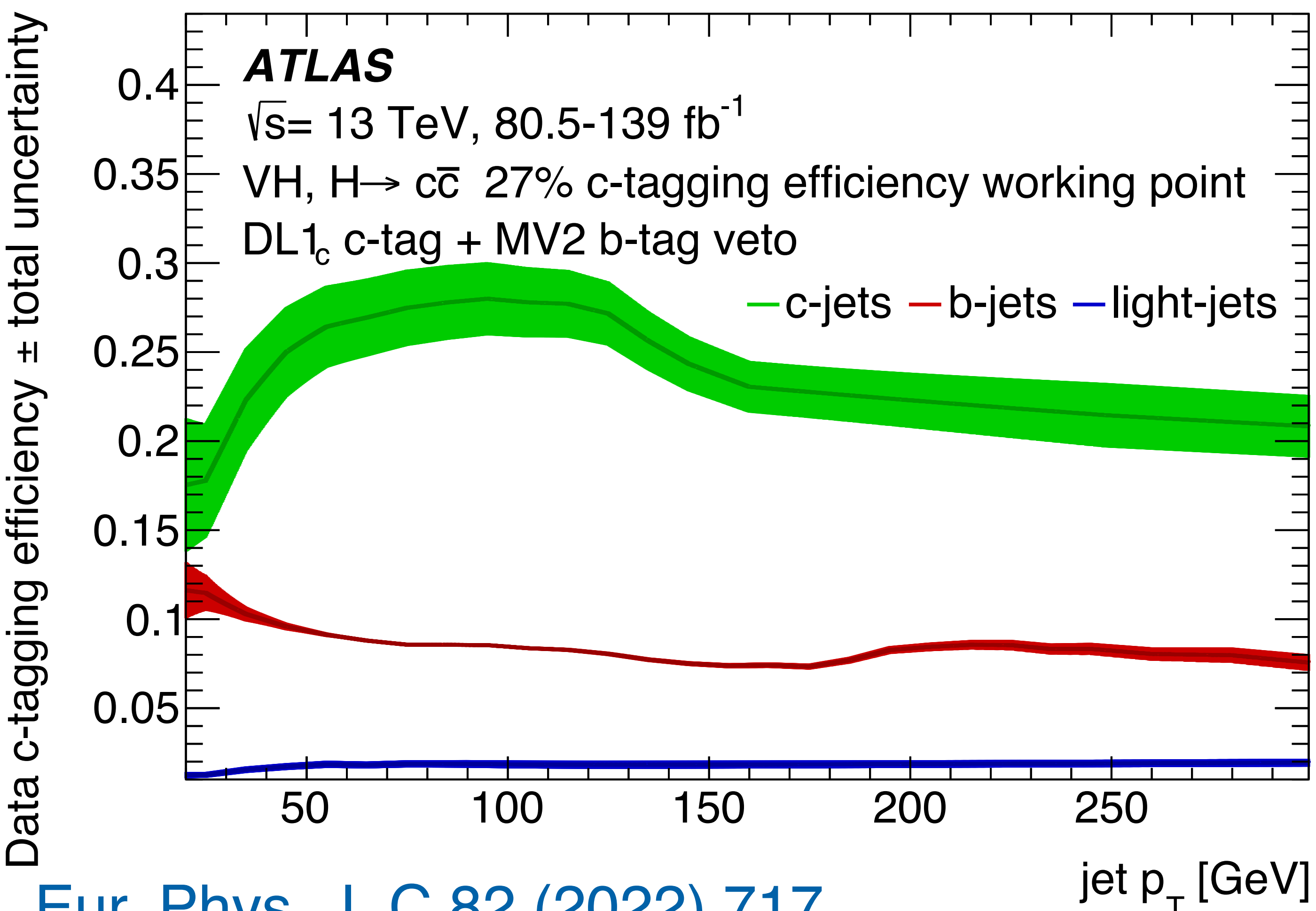
- [Phys. Lett. B 786 (2018) 134](#)

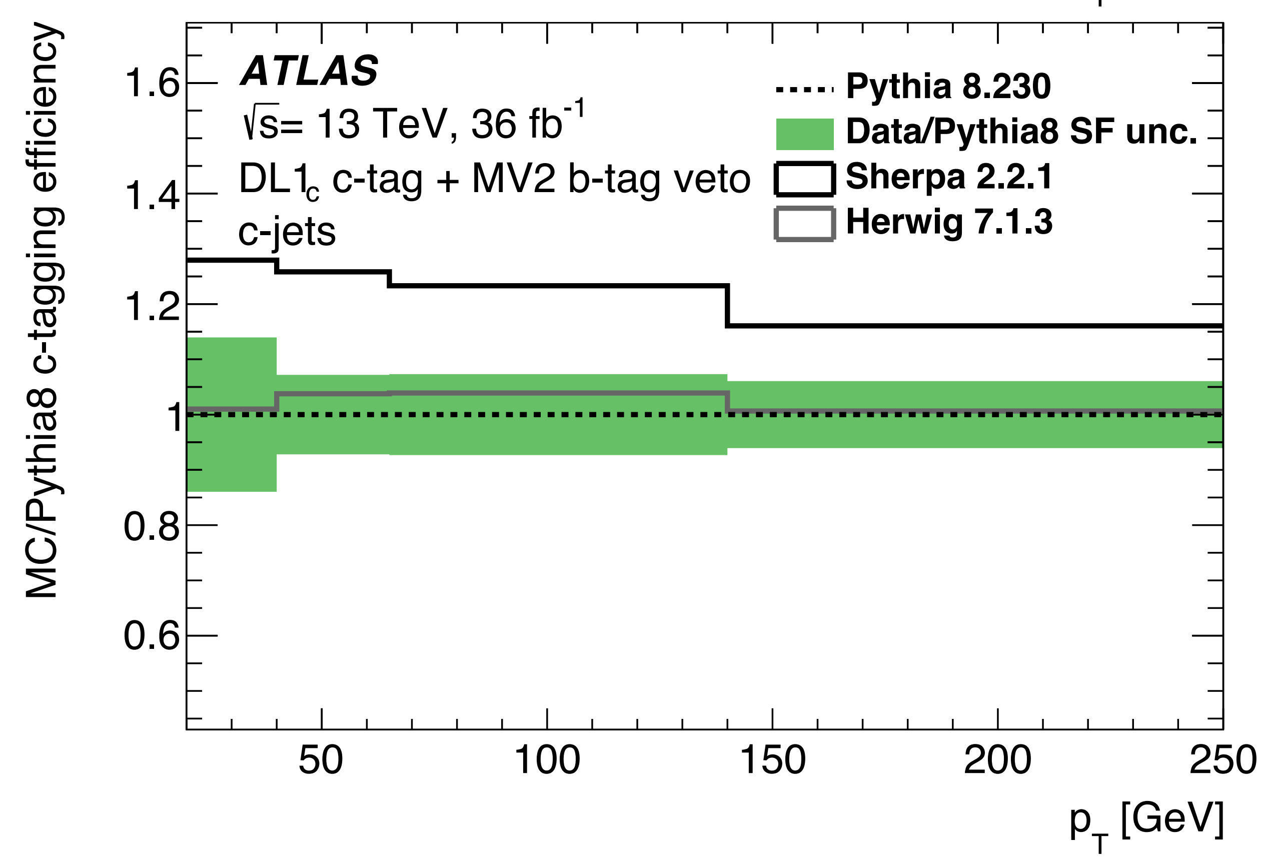
Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi(2S)\,\gamma)\,[\,10^{-4}\,]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(Z \to J/\psi\,\gamma)\,[\,10^{-6}\,]$	$1.1^{+0.5}_{-0.3}$	2.3
$\mathcal{B}(Z \to \psi(2S)\,\gamma)\,[\,10^{-6}\,]$	$6.0^{+2.7}_{-1.7}$	4.5
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.5}_{-1.4}$	5.7
$\mathcal{B}(Z \to \Upsilon(1S)\,\gamma)\,[\,10^{-6}\,]$	$2.8^{+1.2}_{-0.8}$	2.8
$\mathcal{B}(Z \to \Upsilon(2S)\,\gamma)\,[\,10^{-6}\,]$	$3.8^{+1.6}_{-1.1}$	1.7
$\mathcal{B}(Z \to \Upsilon(3S)\,\gamma)\,[\,10^{-6}\,]$	$3.0^{+1.3}_{-0.8}$	4.8

ATLAS single-charm tagging

- Charm calibration gives mild reduction in efficiency
- At 27% c-tag, 1% b-mistag:
  - light-mistag 0.2% ≈ CMS







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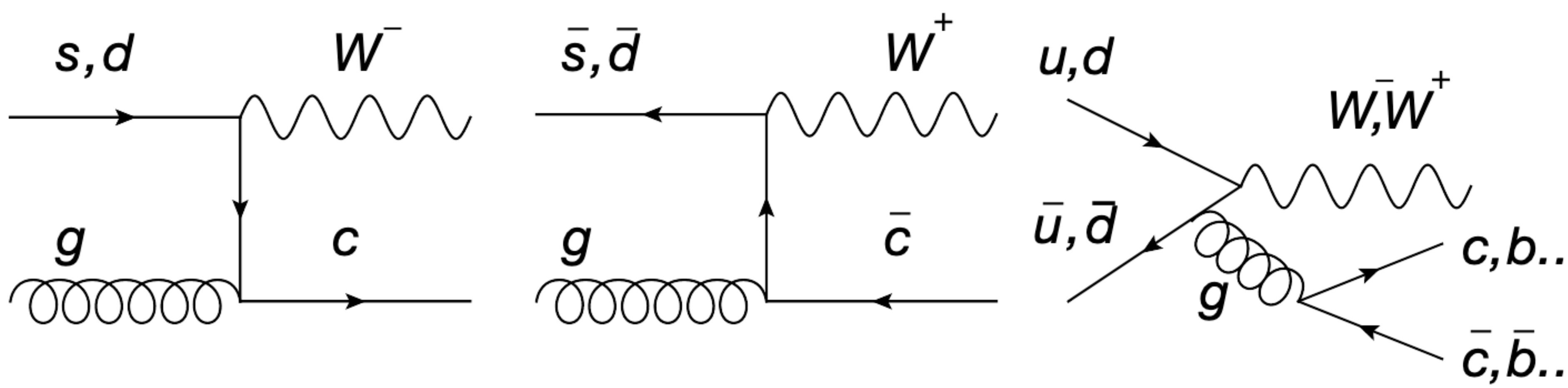
Single-charm calibration region definitions

- W+c
  - Leptonic W decay, tag charm jet with soft muon
- Top
  - B jet from top decay with soft muon; semi-leptonic and dilepton decays; >4 jets
- DY+jet
  - Dilepton (ee/mm); no soft muon in jet requirement

JINST 17 (2022) P03014

Selection	Jet yield	c %	b %	udsg %
W+c	362 002	**92.9**	0.957	6.14
$t\bar{t}$	380 366	12.1	**81.0**	6.91
DY + jet	8 509 206	8.87	5.05	**86.1**

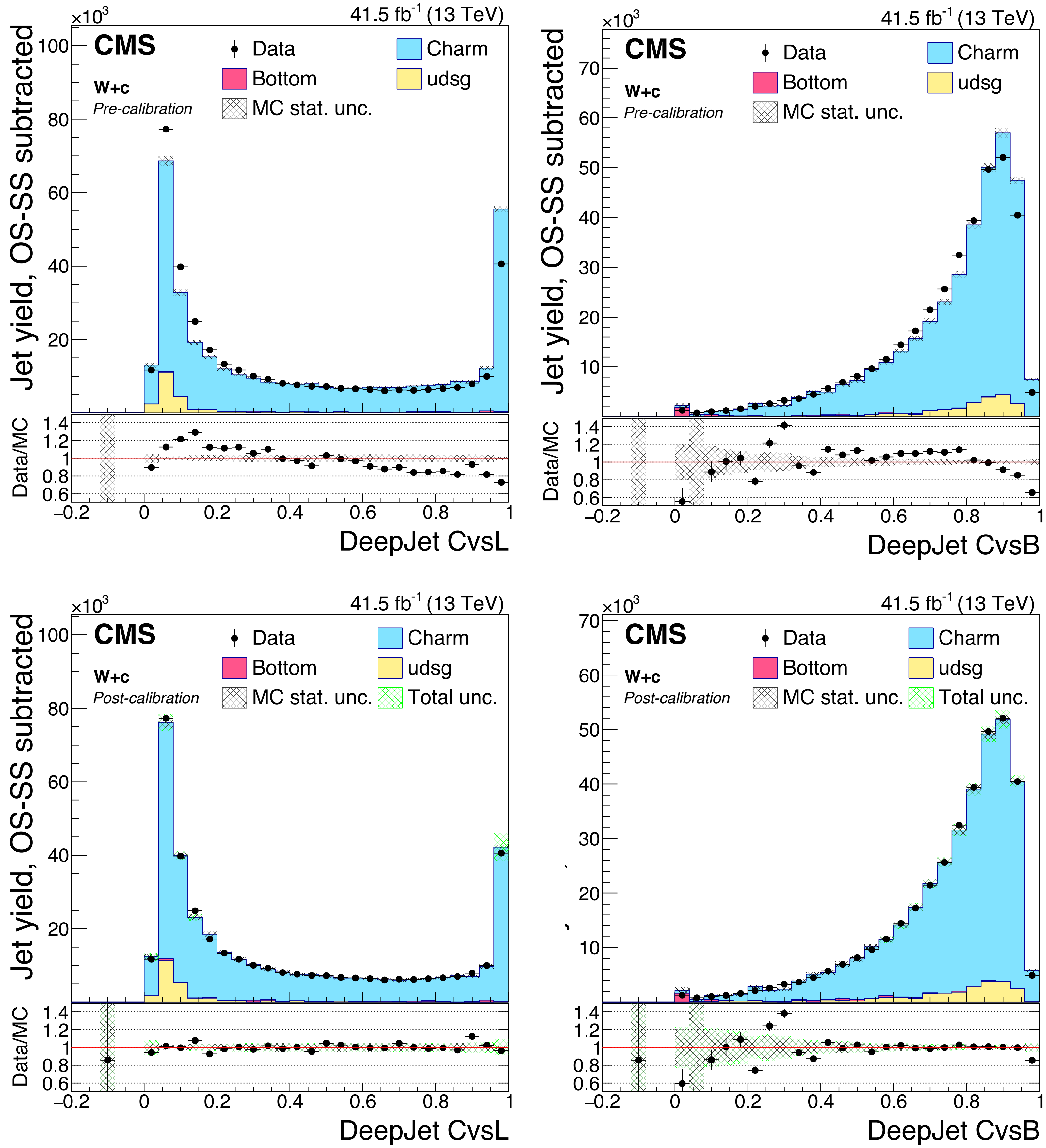


Sig: OS event *Sig: OS event* *Bkg: 50% OS, 50% SS*

Fermilab

Single-charm calibration

- Significant improvement in tagger response modeling



JINST 17 (2022) P03014

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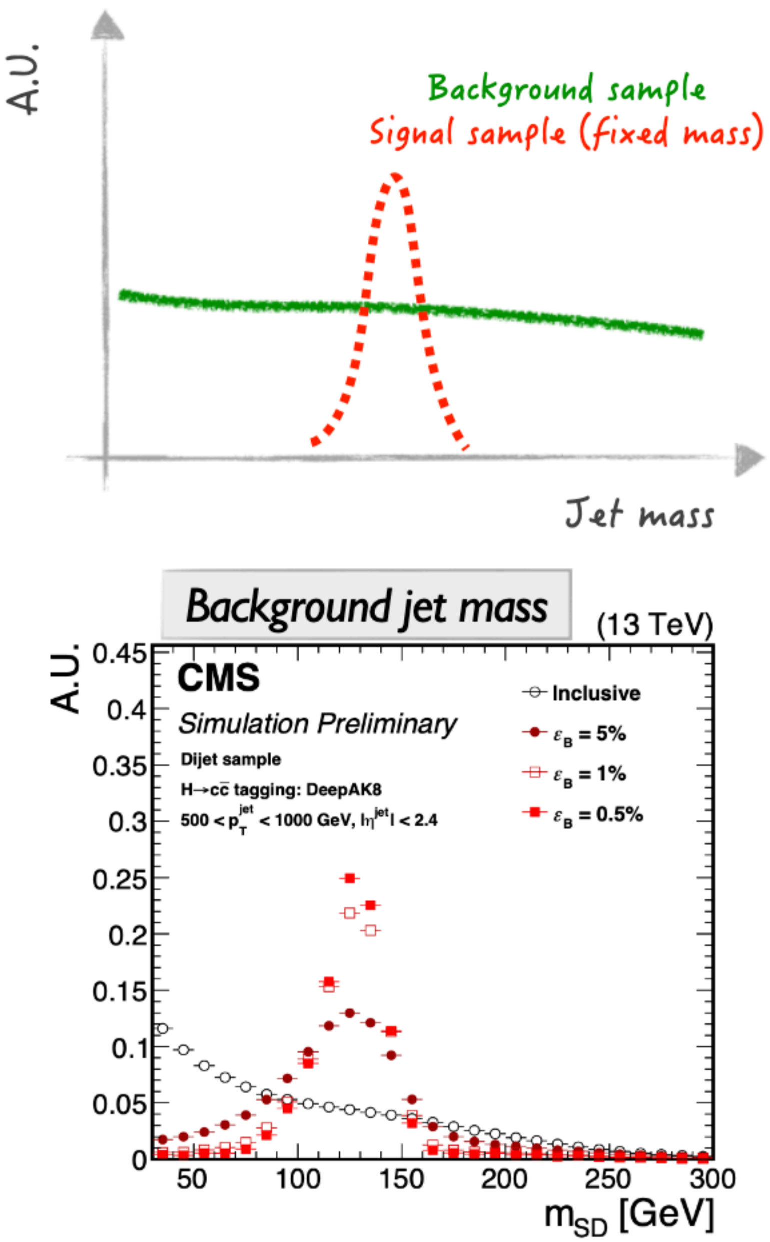
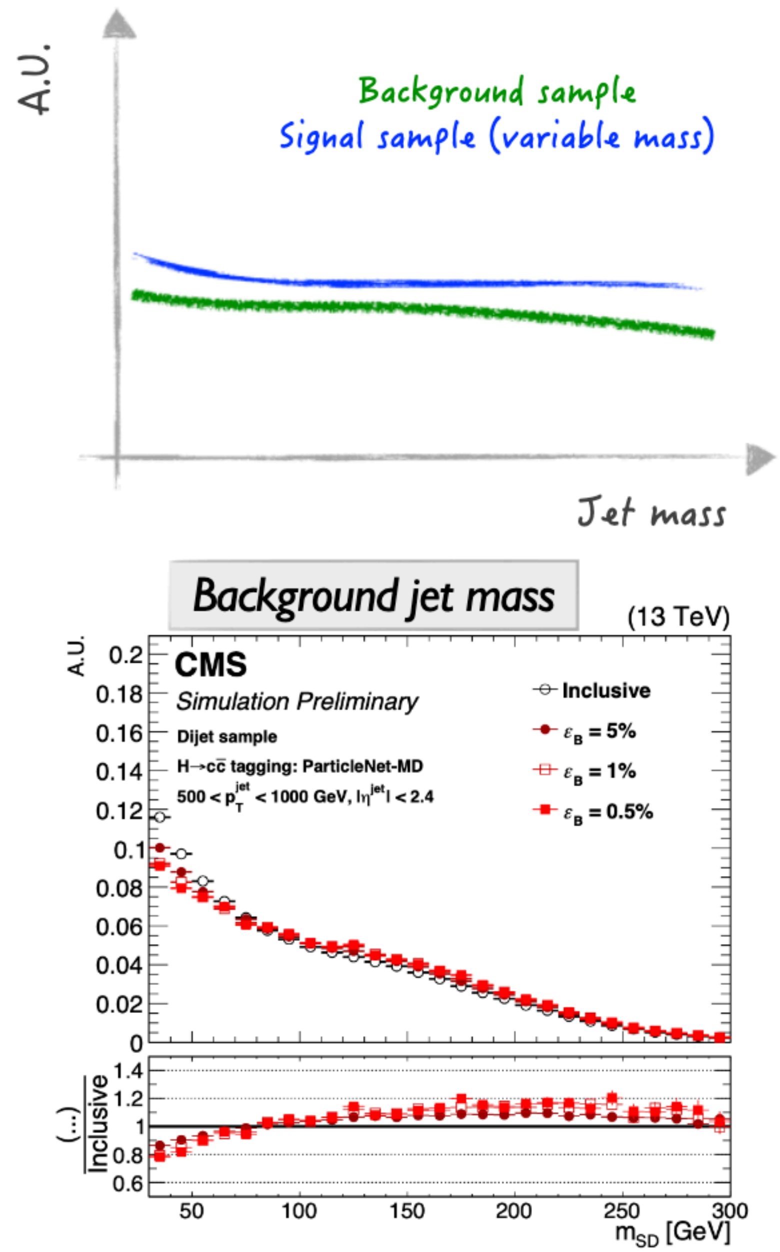
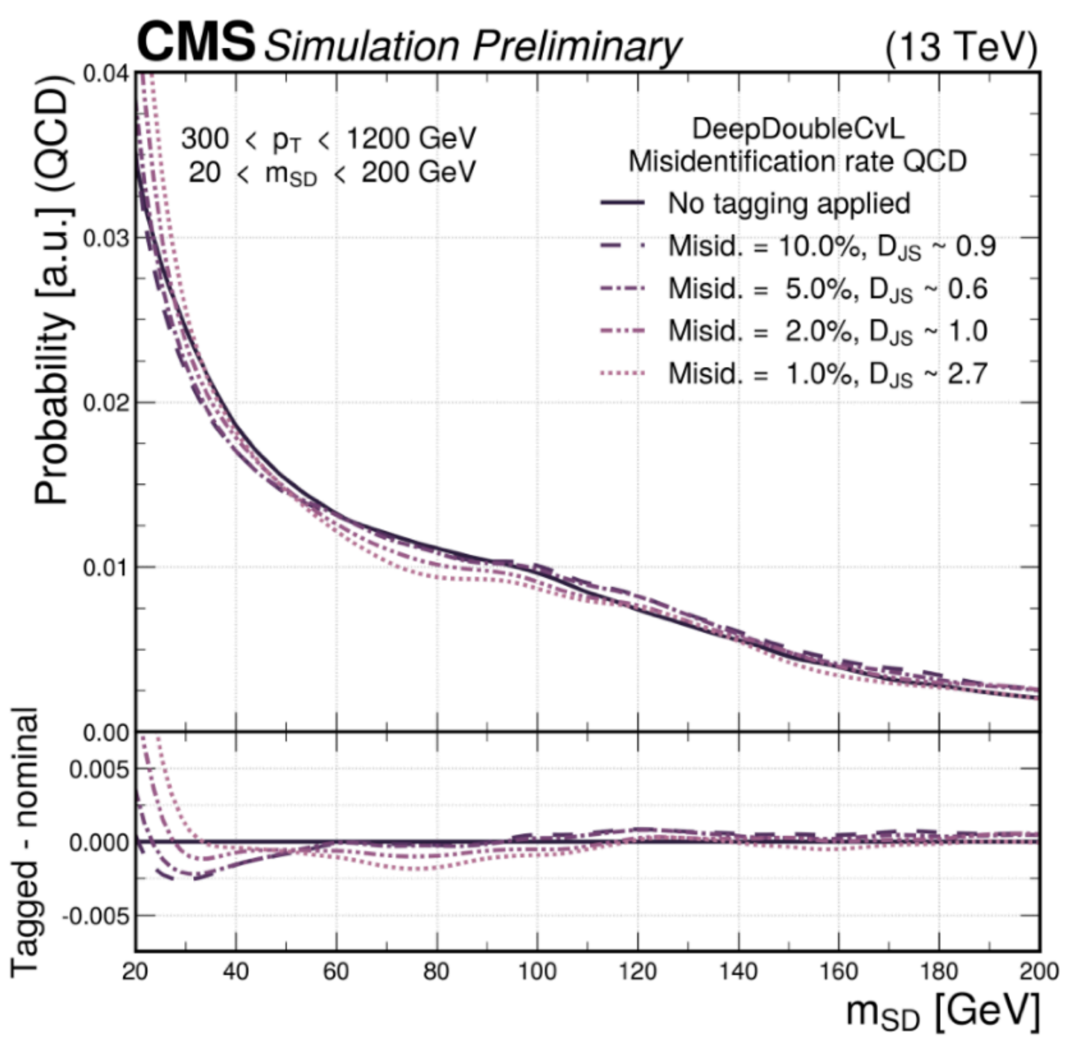
Double-charm jet mass decorrelation

CMS-DP-2020-002

Plain training: no mass decorrelation	Mass-decorrelated training







CMS-DP-2022-041

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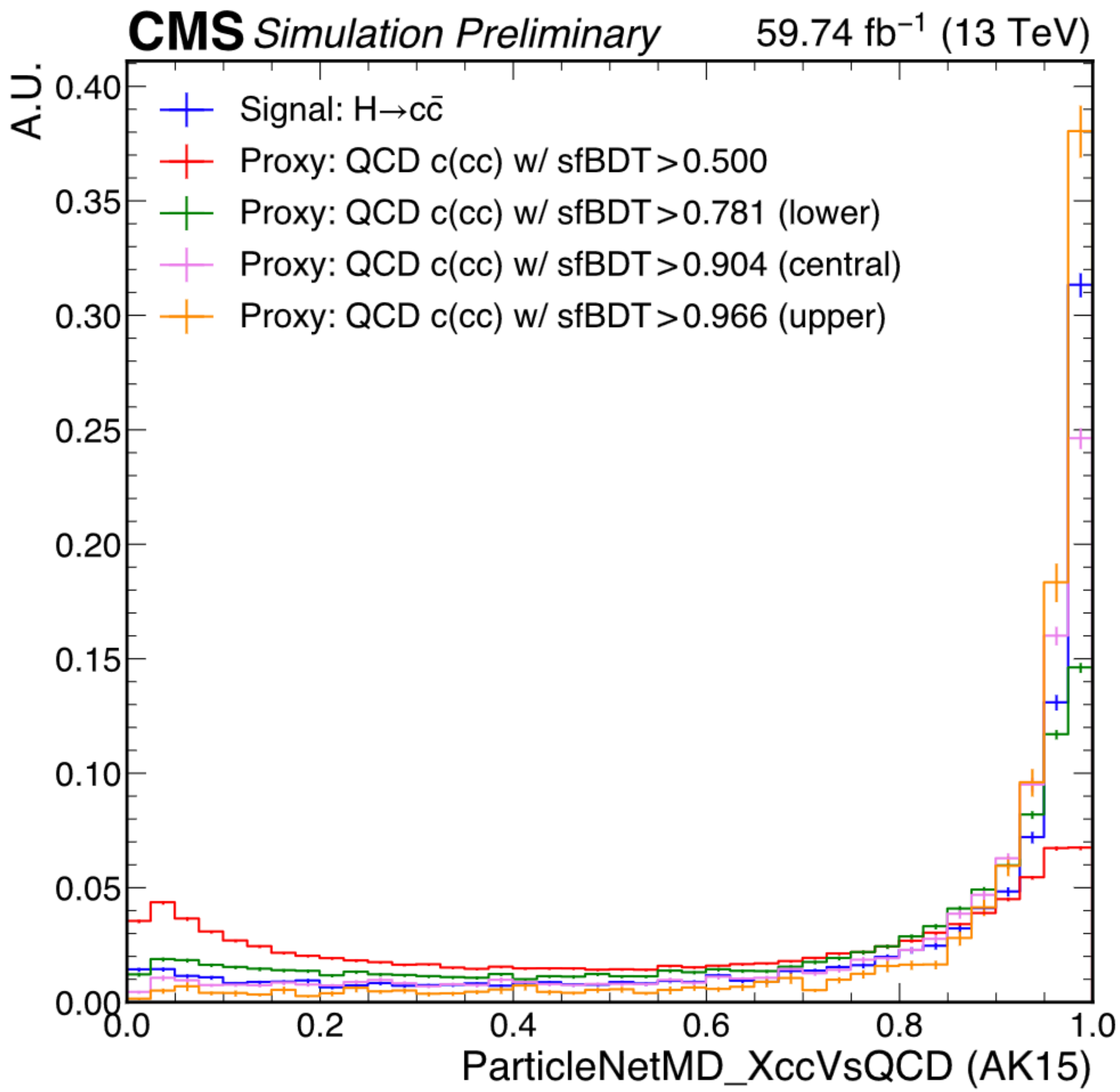
Double-charm proxy jets with sfBDT



CMS-DP-2022-005

Fermilab