

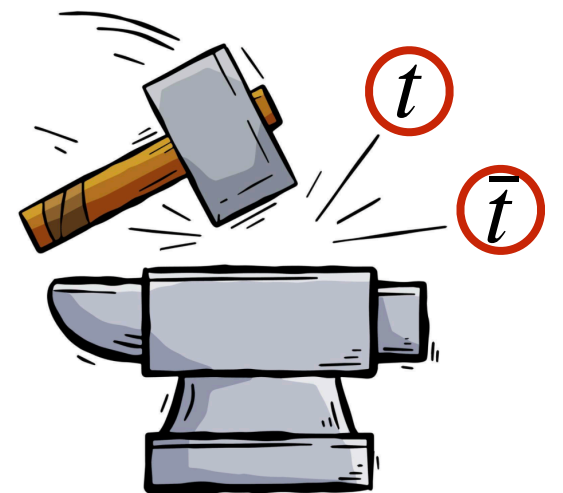
Forging top quarks

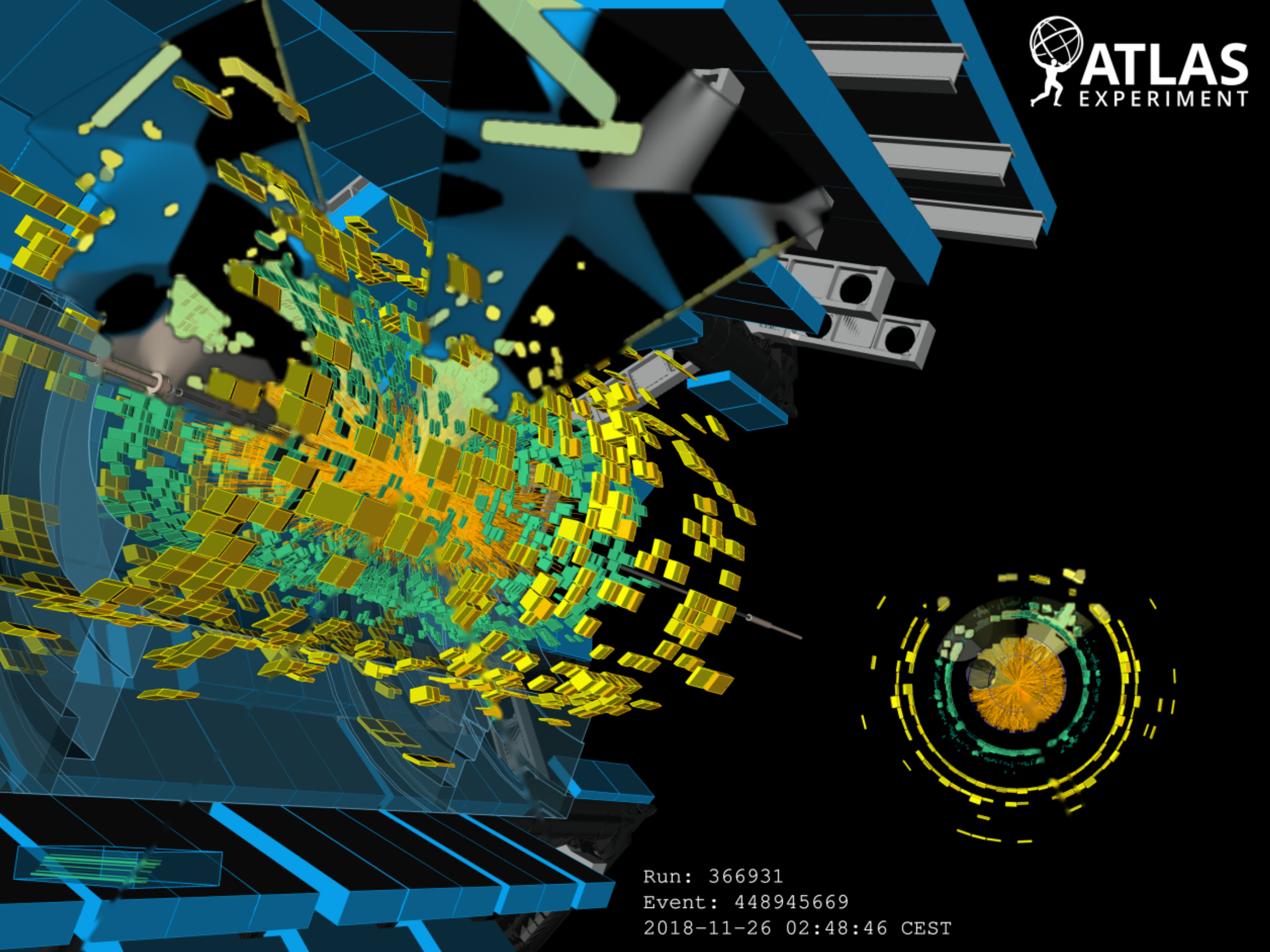
Kirill Skovpen



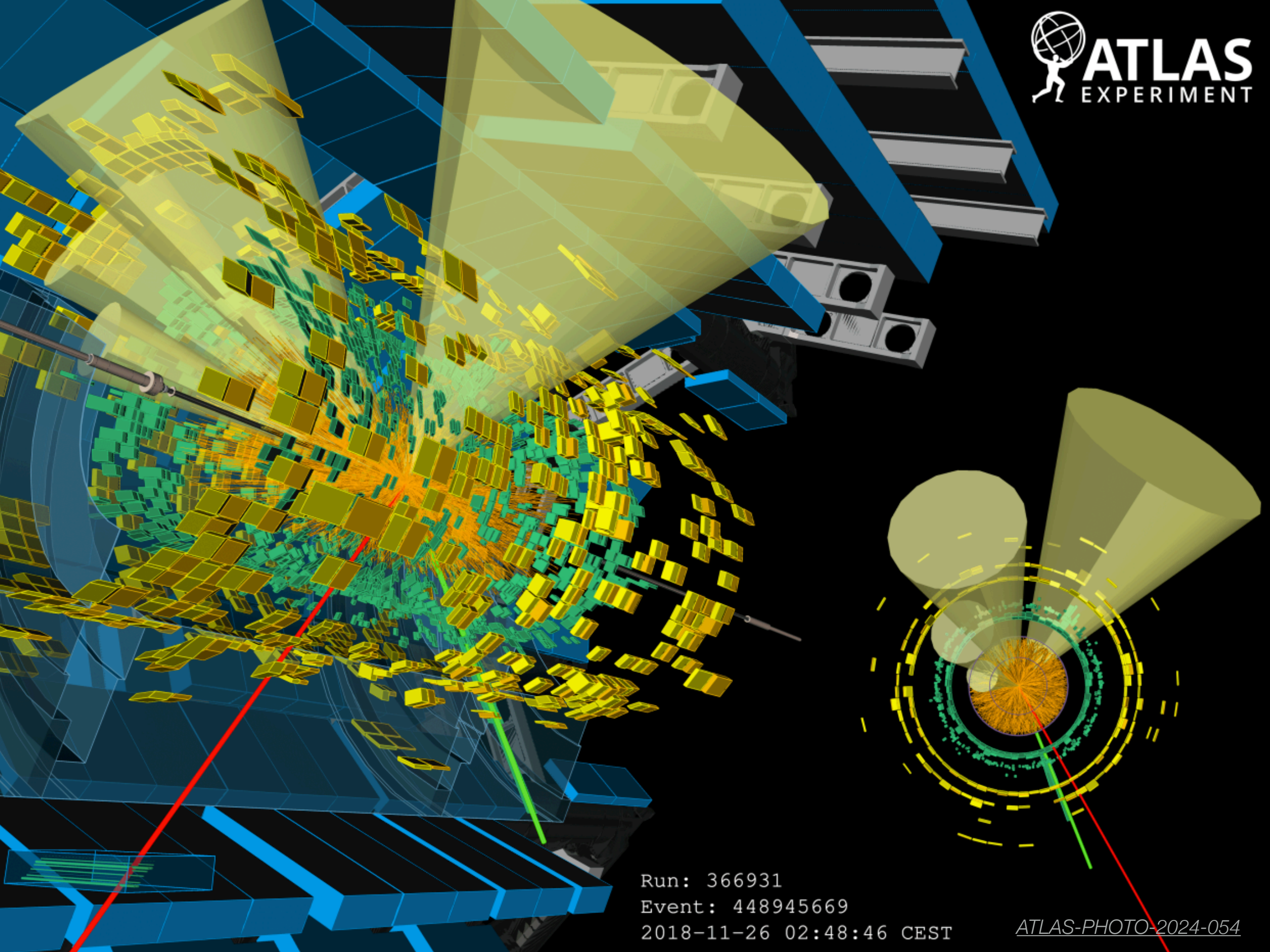
BND Graduate School

September 7-18, 2026



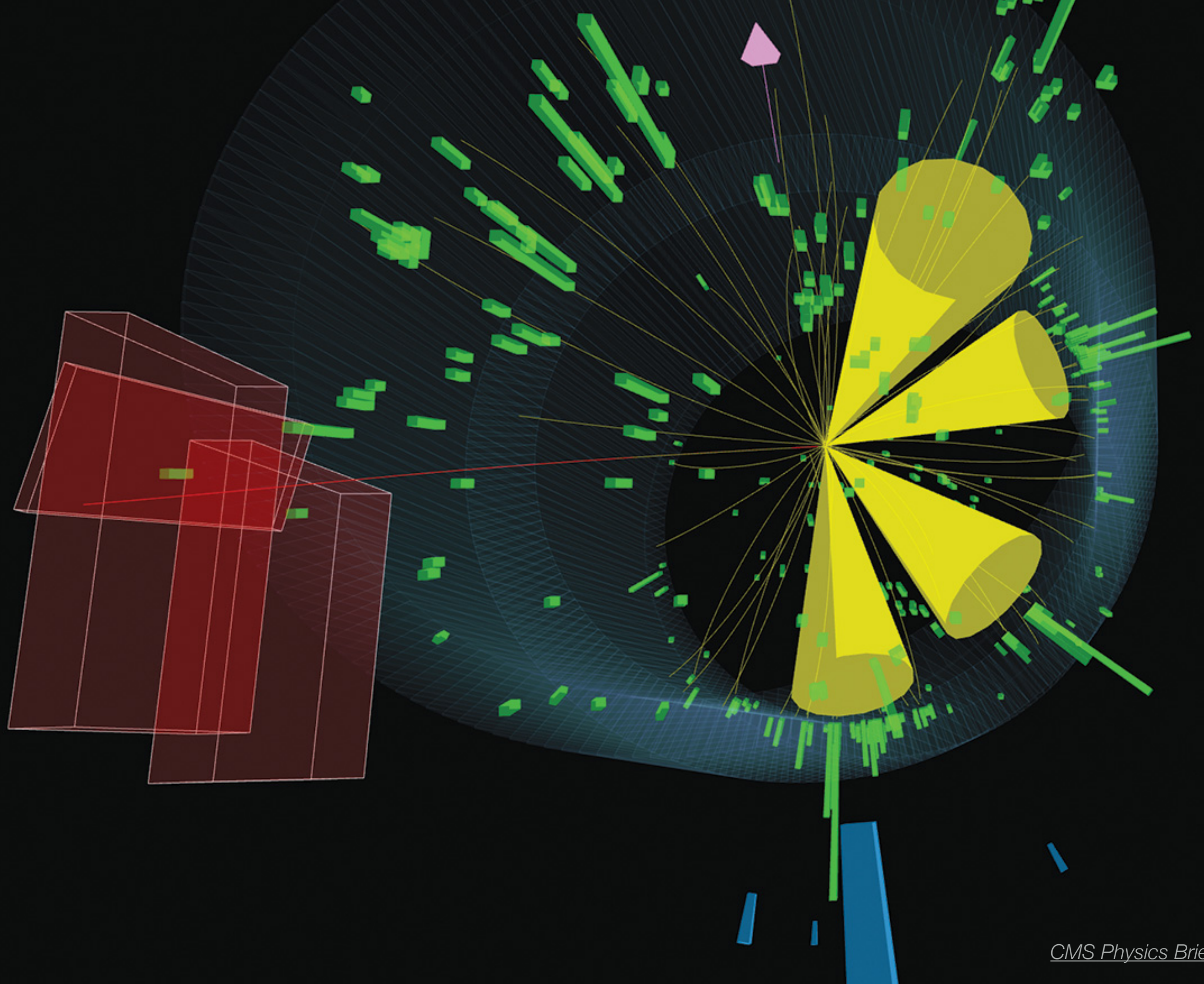


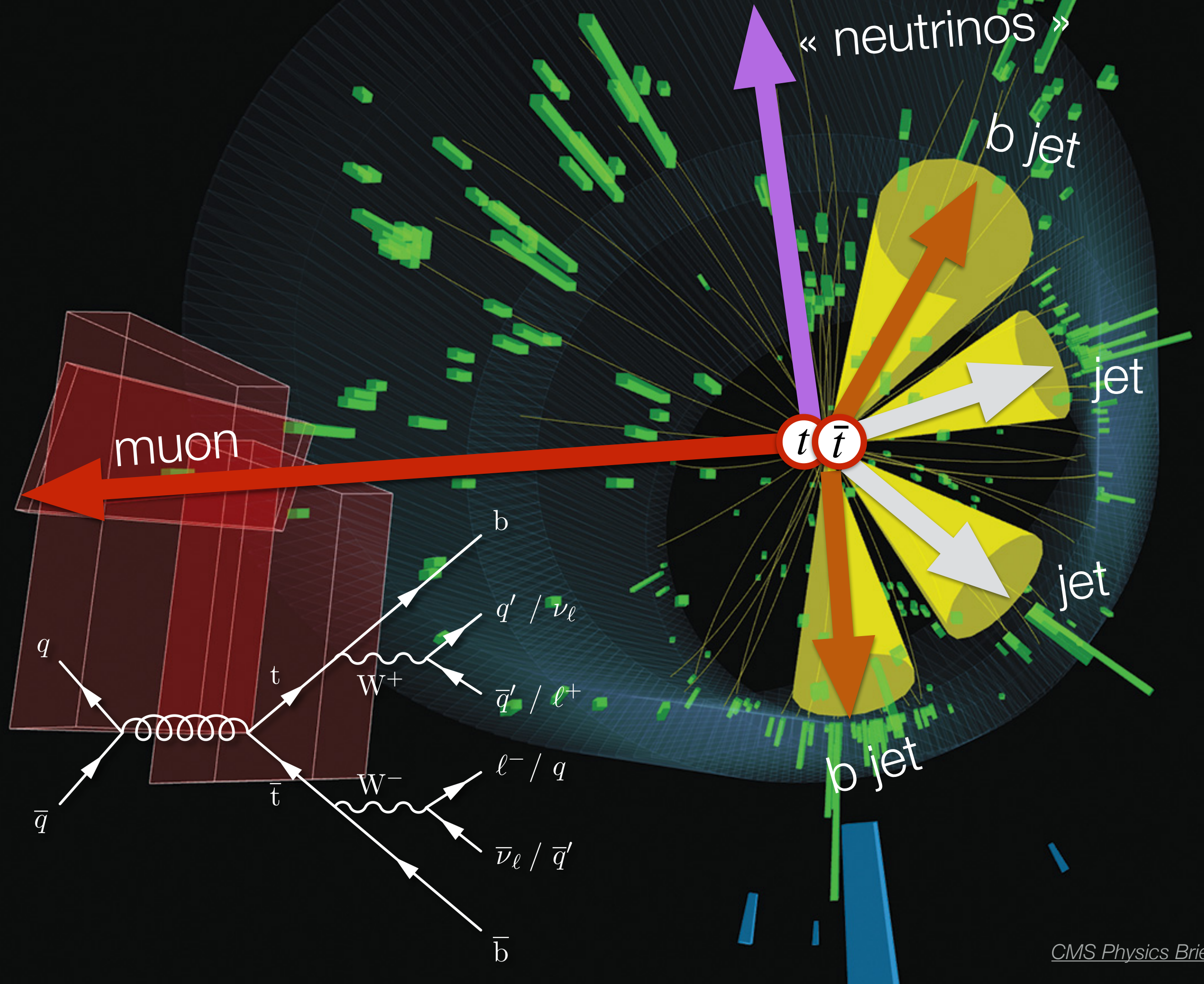
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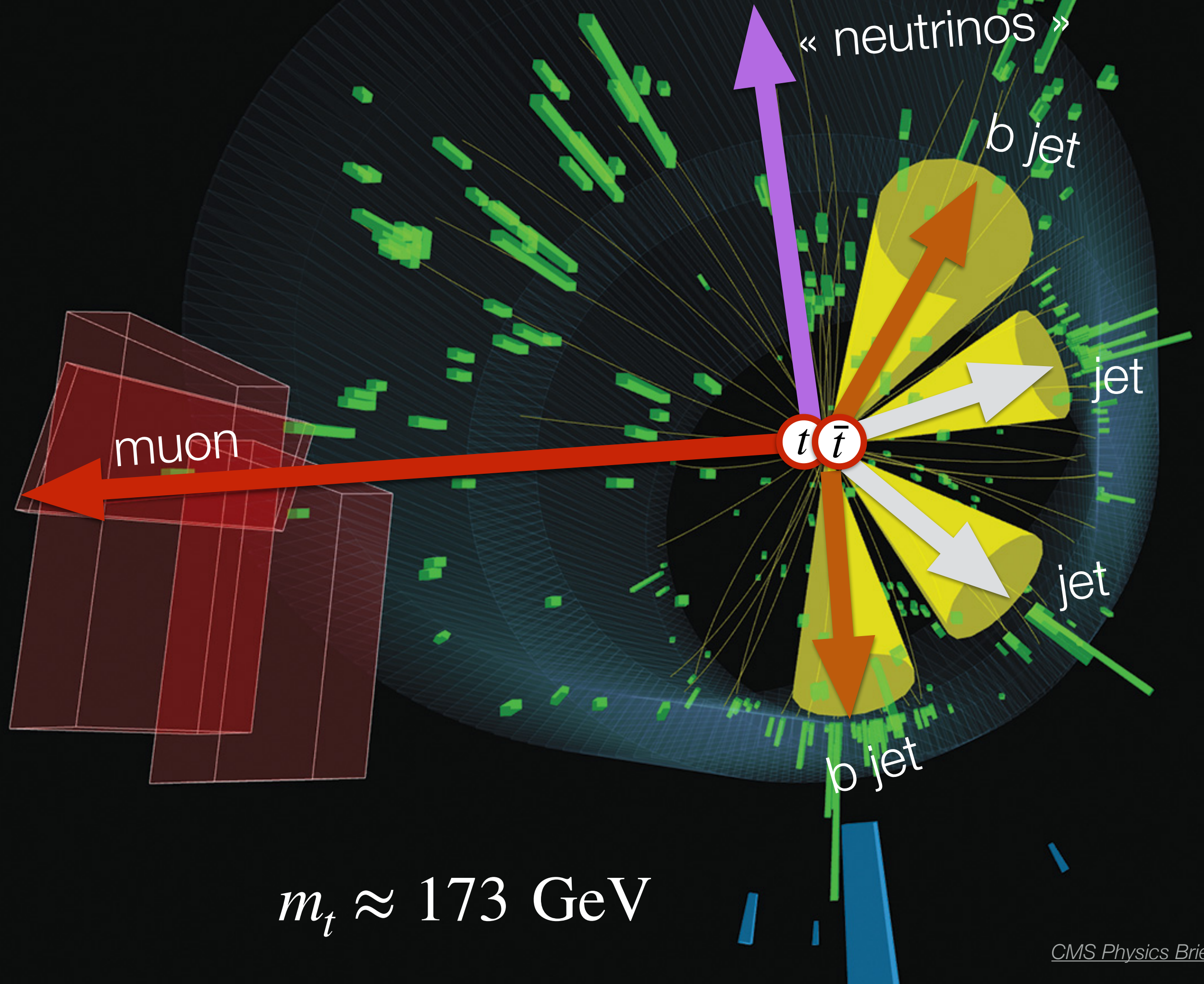


Run: 366931
Event: 448945669
2018-11-26 02:48:46 CEST

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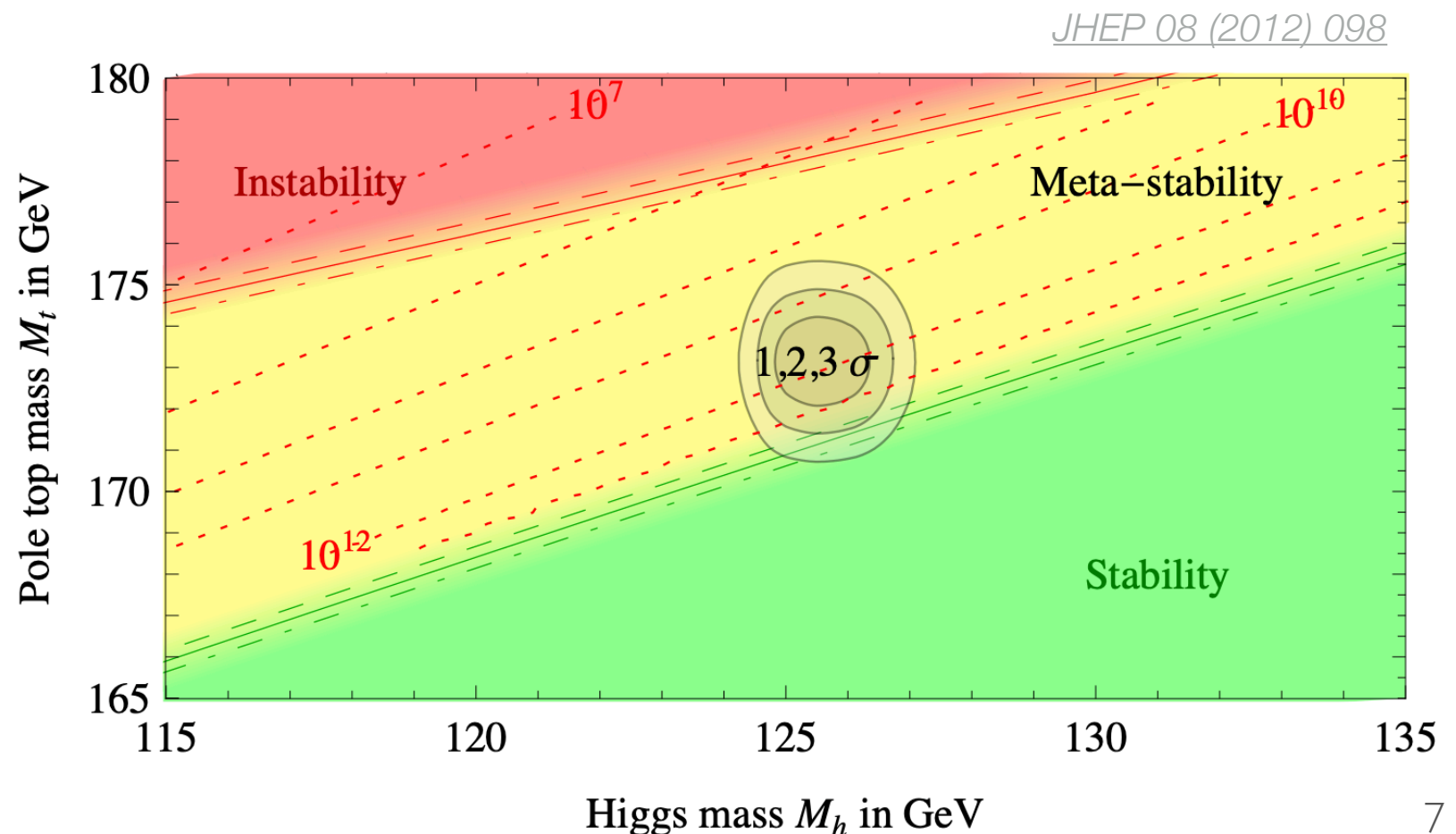
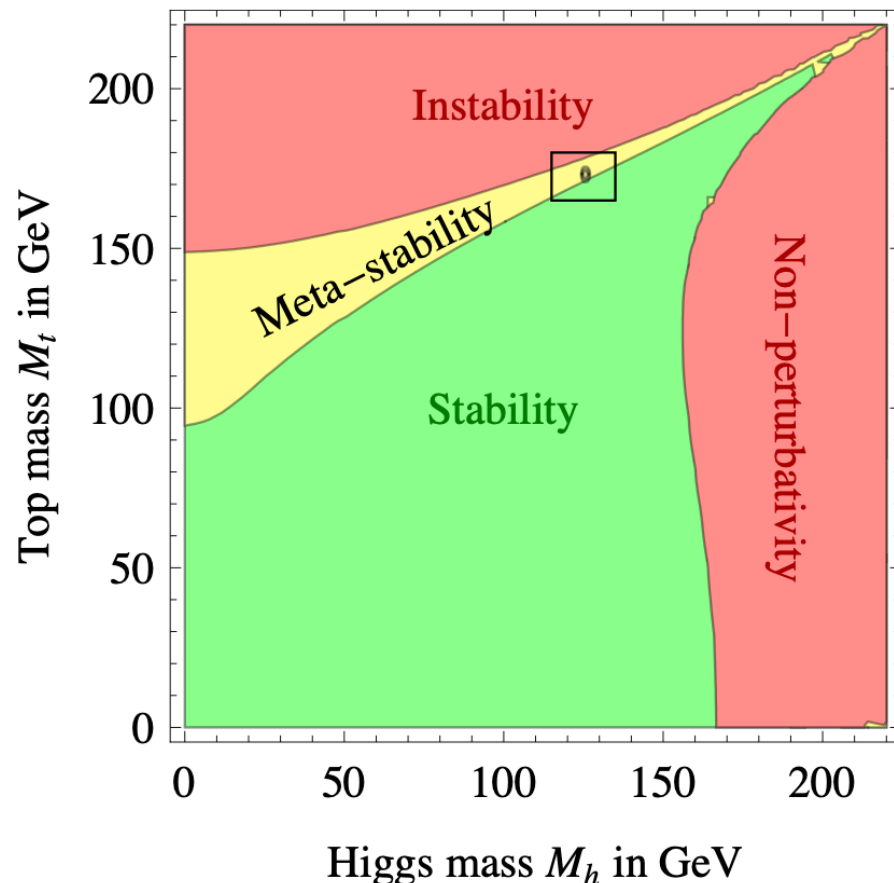






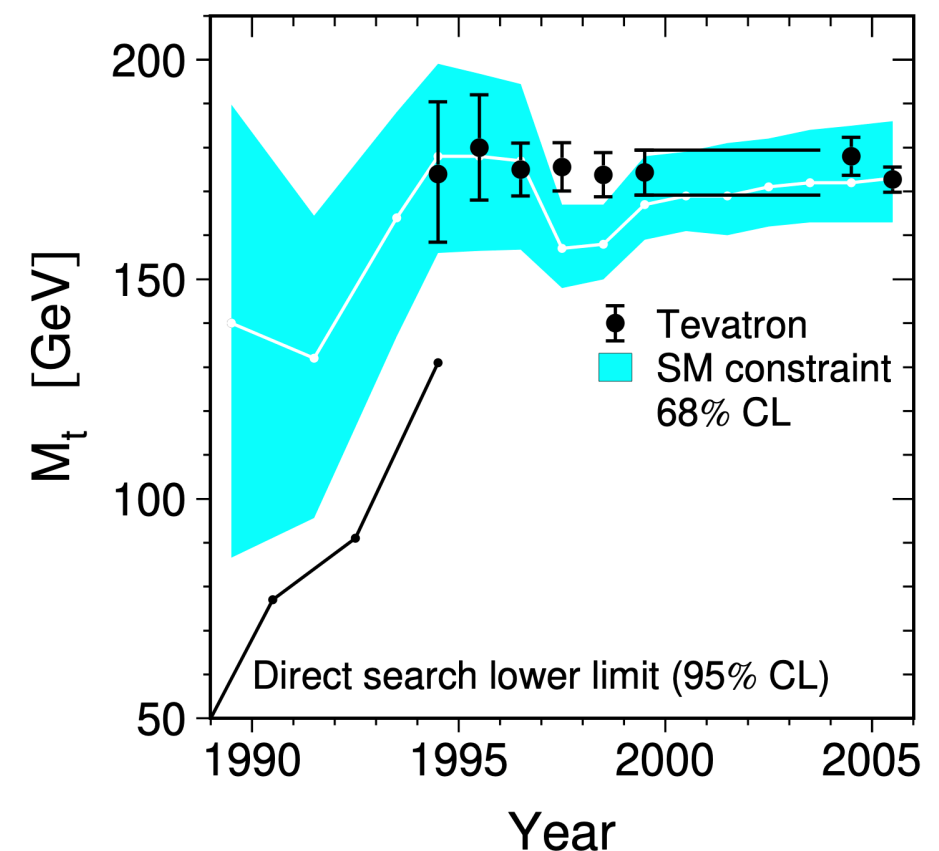
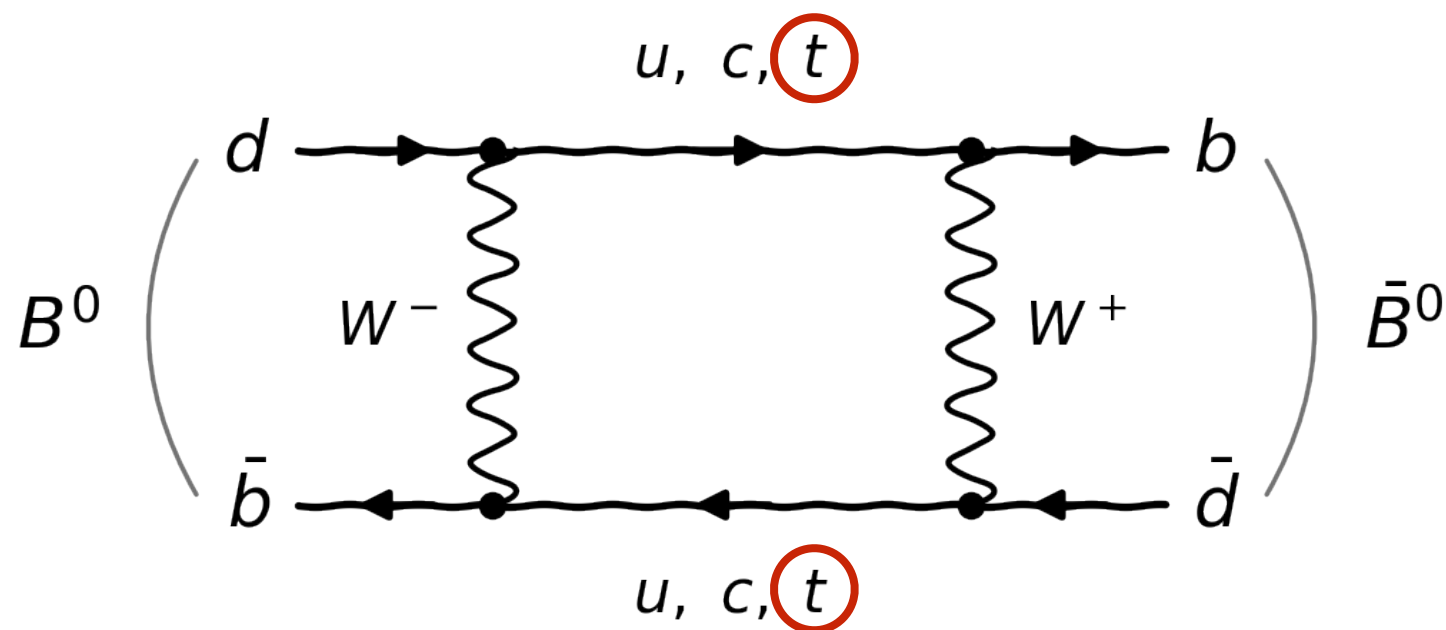
Why so heavy?

- **We don't know!**
- The fermion masses are free parameters in the SM
- Very large mass ($\approx$ tungsten atom!) $\rightarrow$ very short lifetime $\rightarrow$ top quark (almost) never hadronizes
- Important connection to the Higgs sector: $y_t = \sqrt{2}m_t/v \simeq 1$
- Direct input to EW precision fits, the Higgs sector, vacuum stability, etc.



Why a sixth quark?

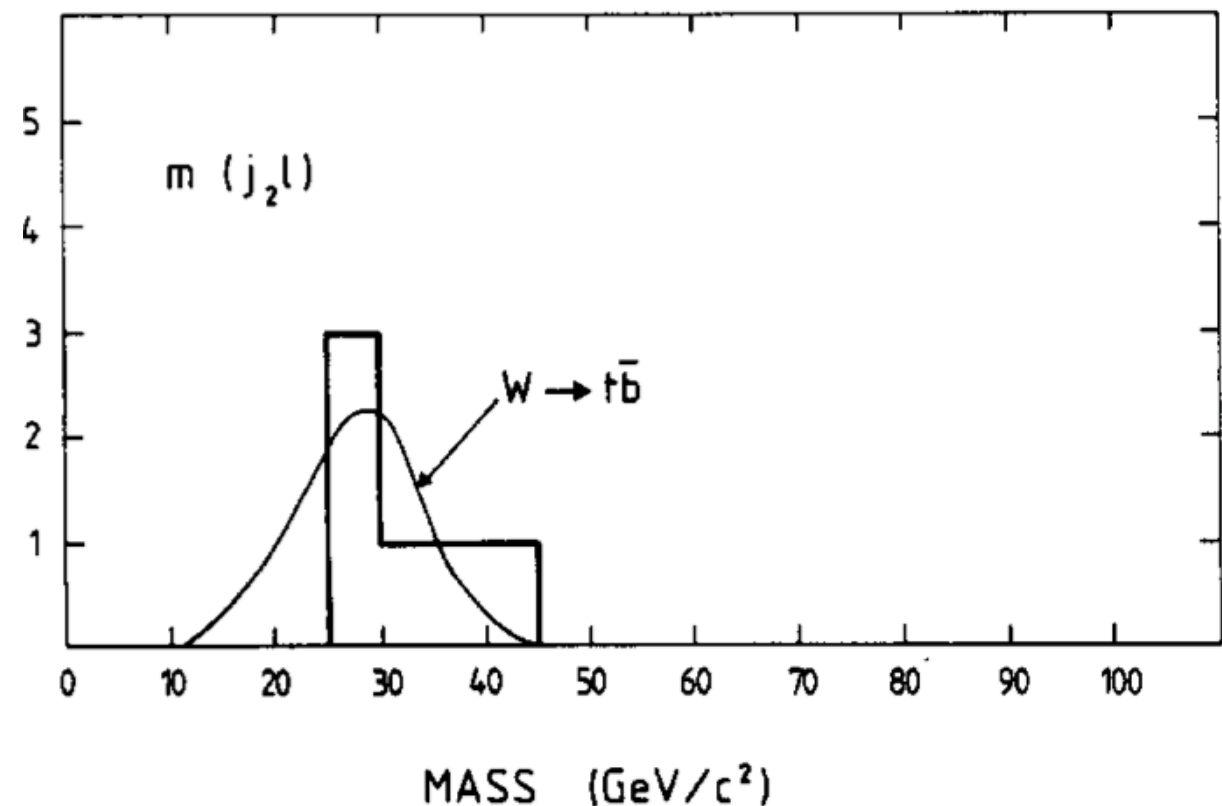
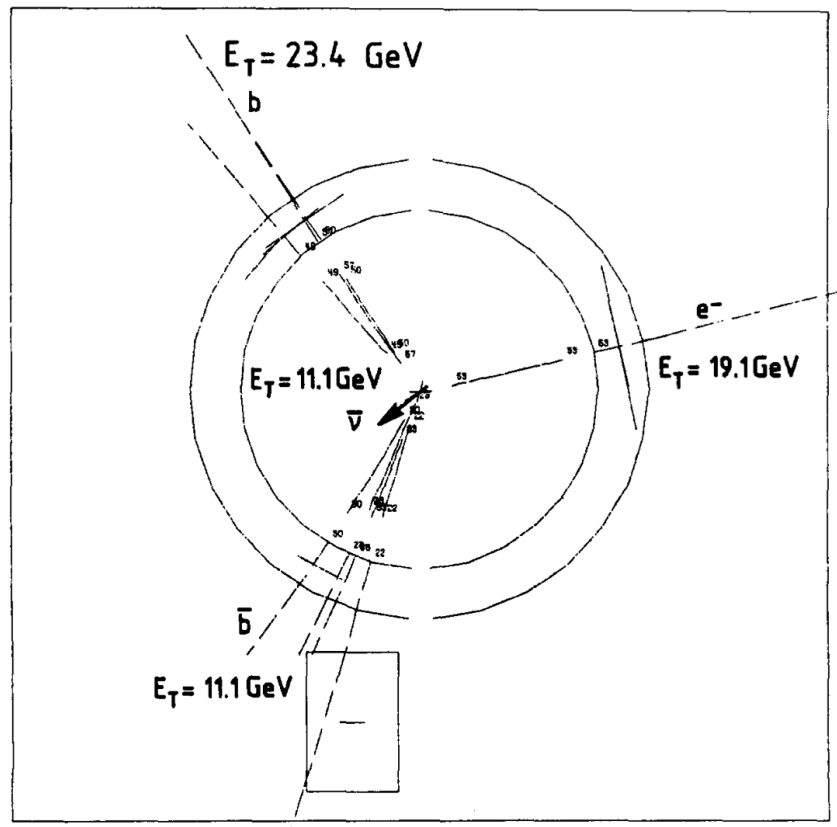
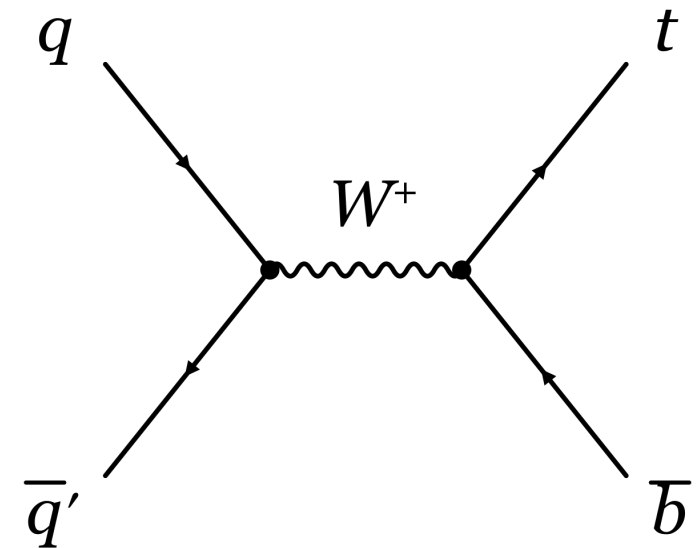
- Need to extend the two-quark model to explain CP violation in the kaon sector (1964)
- Bottom quark discovery (1977) in $\Upsilon(1S) \rightarrow \mu^+ \mu^-$ events $\rightarrow$ **a third quark generation** confirmed
- No FCNC b decays $\rightarrow$ third generation is also an isospin doublet
- A sixth quark must exist!
- Already **seen virtually**: large $B^0 - \bar{B}^0$ mixing (1987) and 1994's EW fit (178 ± 11 GeV)



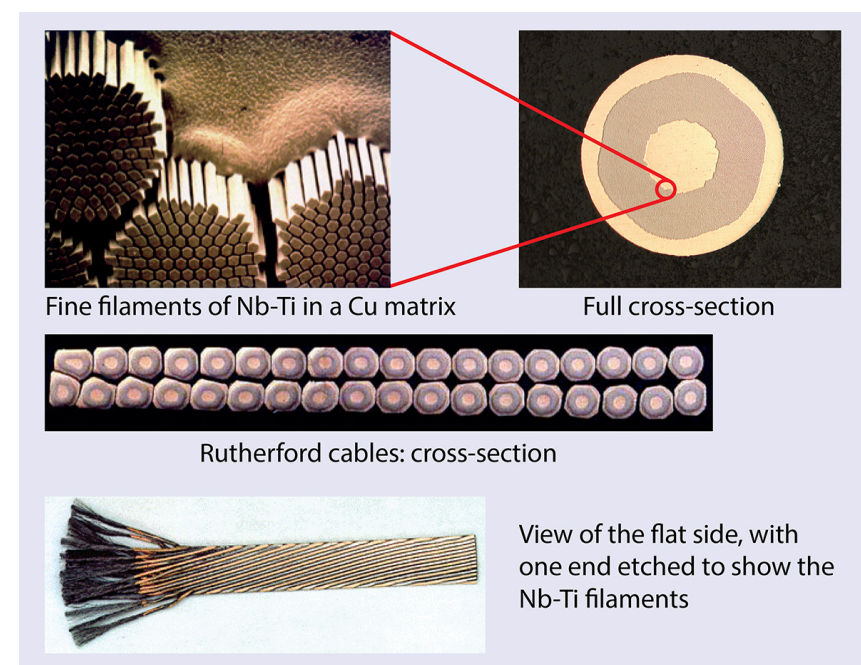
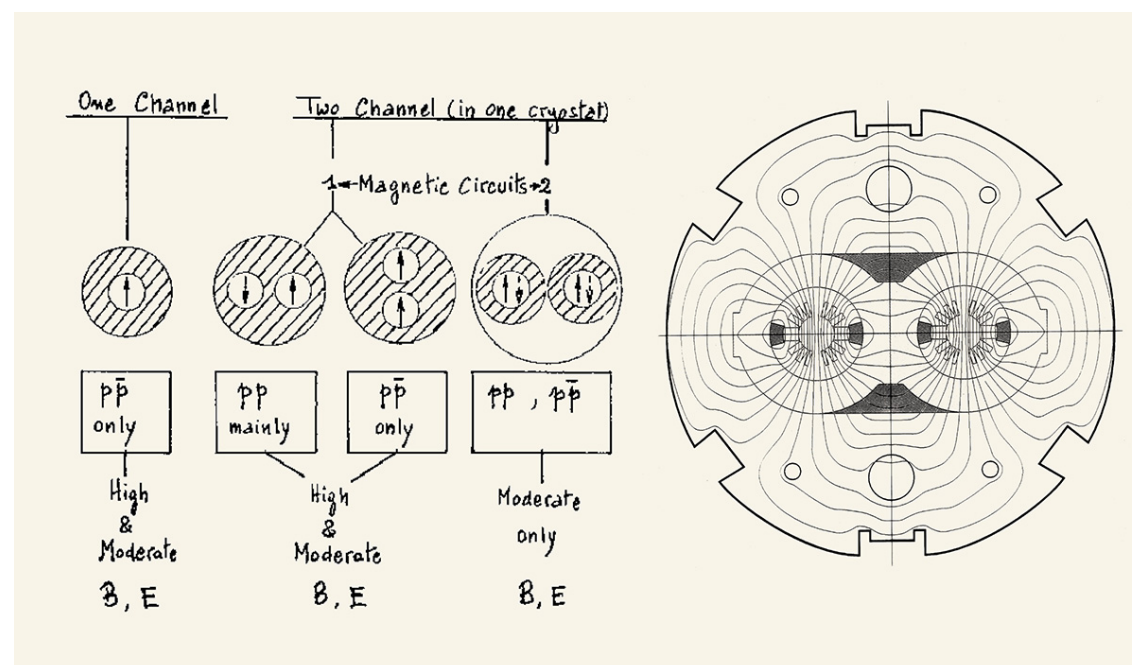
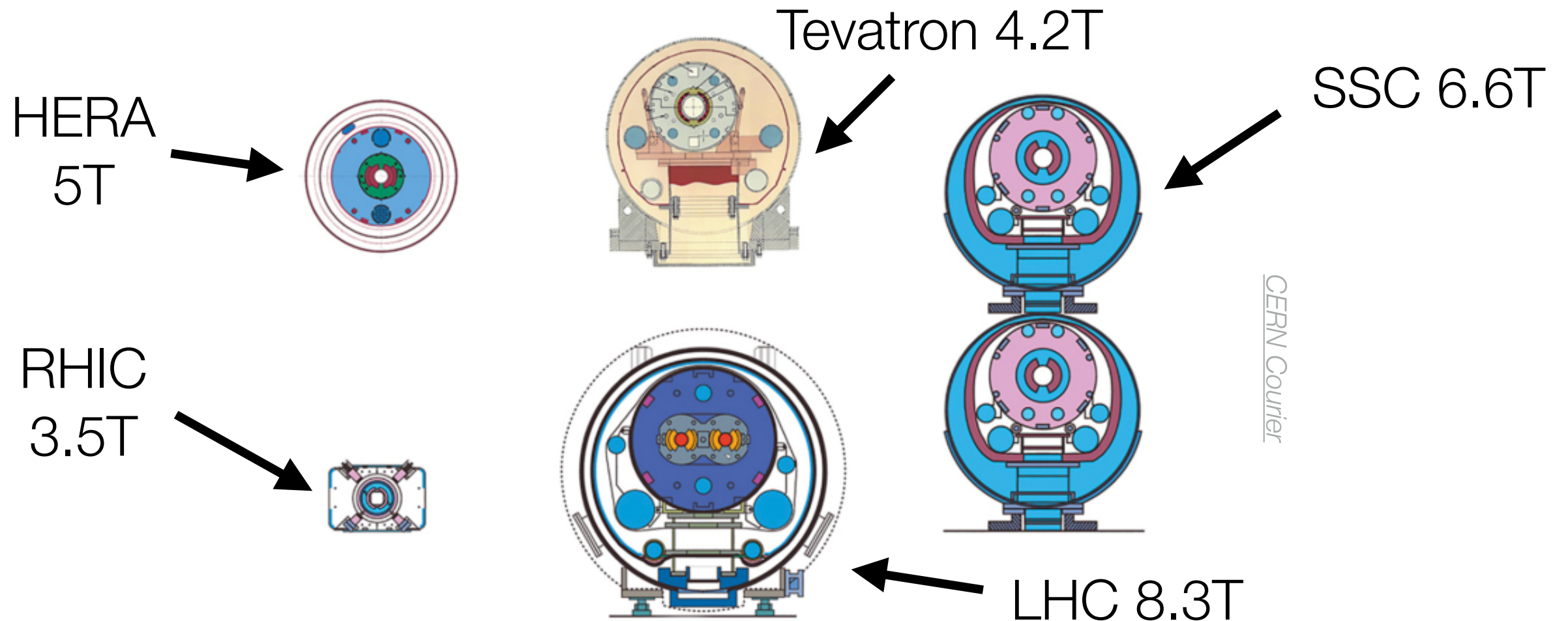
PR 427 (2006) 257

$Spp\bar{p}S$

- If $m_t < 80$ GeV, it can be produced in W boson decays: $W \rightarrow t\bar{b}$
- $Spp\bar{p}S$ is a W boson factory!
- $\sqrt{s} = 546 \rightarrow 630$ GeV
- First « evidence » of a light top at $m_t \approx 40$ GeV
- Eventually, set a lower limit $m_t > 60$ GeV



Going superconductive

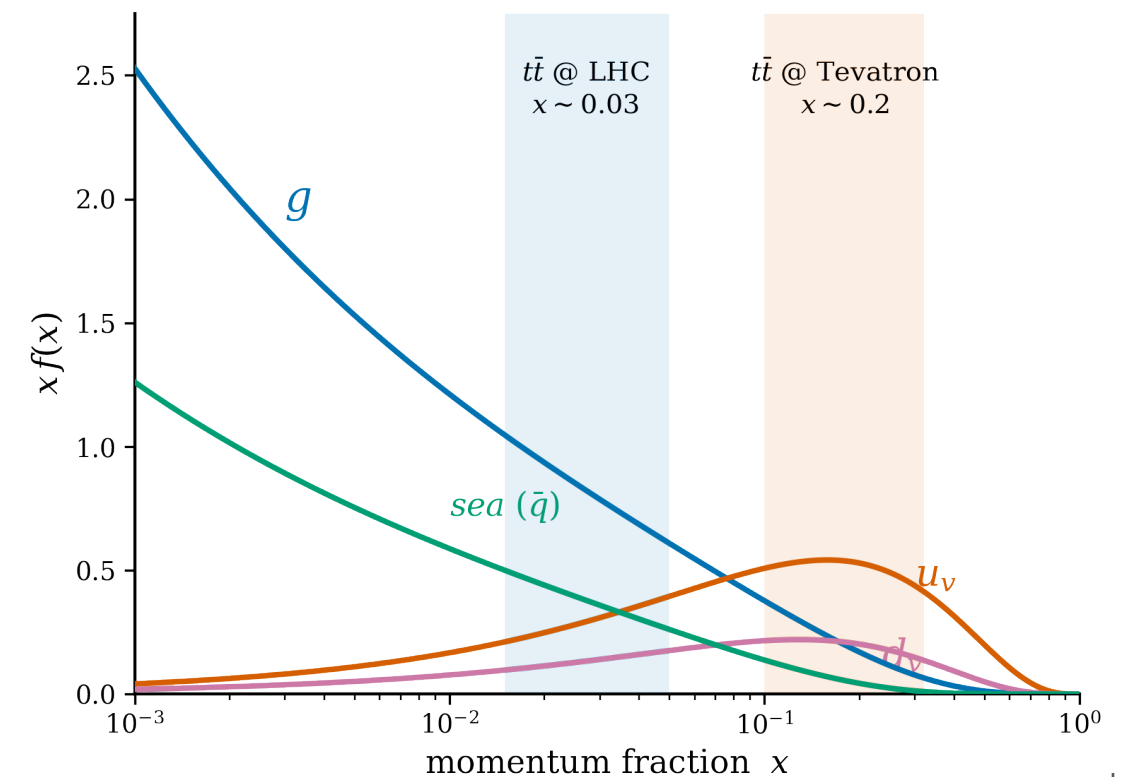
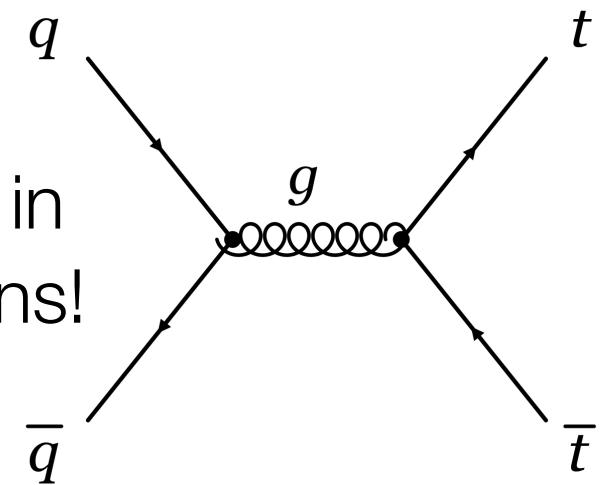


The discovery machine

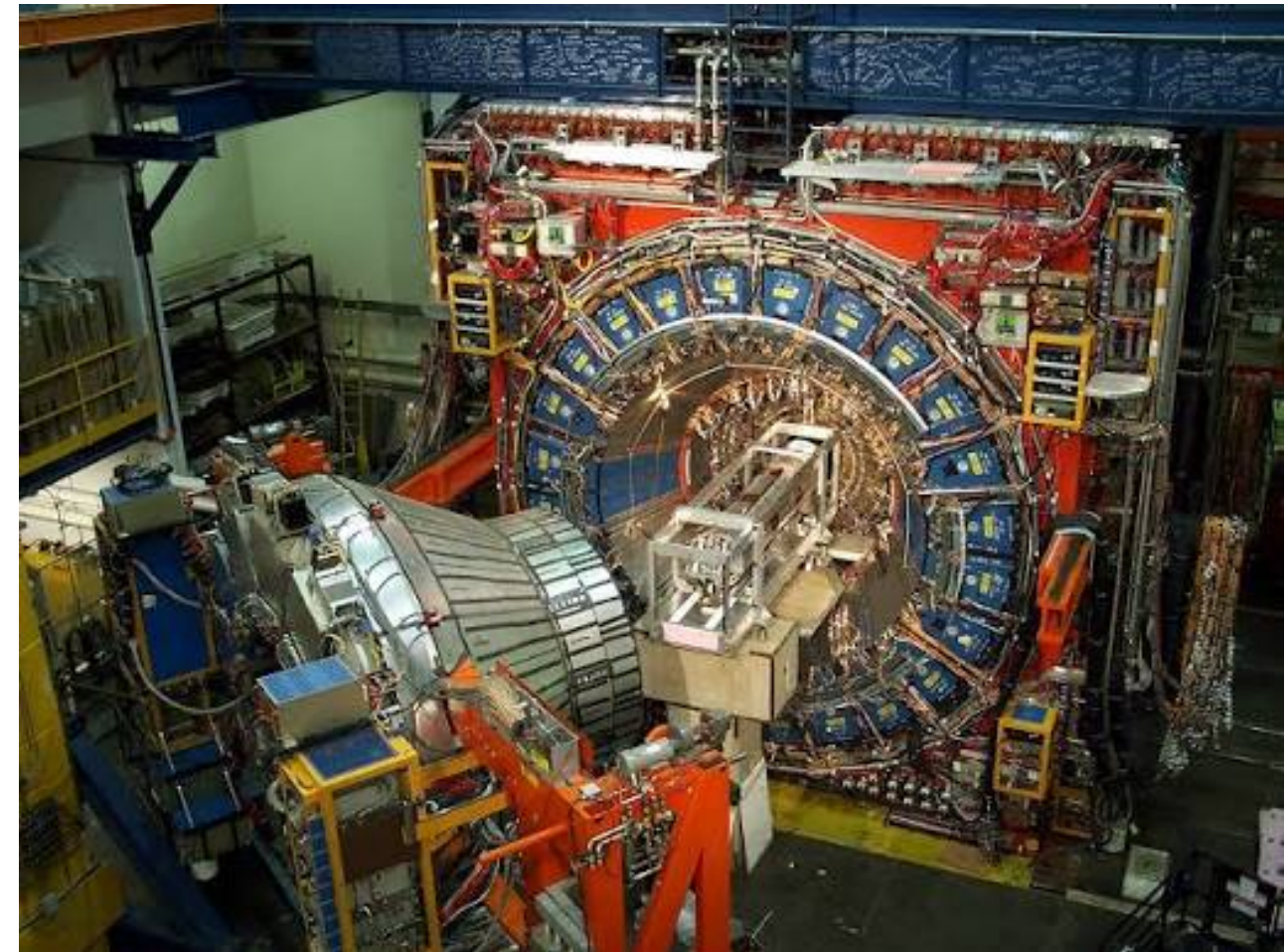
- The **Tevatron**: a $p\bar{p}$ collider, $\sqrt{s} = 1.8 \text{ TeV} > 2m_t \approx 350 \text{ GeV}$
- First large-scale ($\approx 6 \text{ km}$ ring) superconducting magnet accelerator
- Top quark production dominated by $q\bar{q} \rightarrow t\bar{t}$ ($\approx 5 \text{ pb}$)
- Two independent experiments: CDF and D0



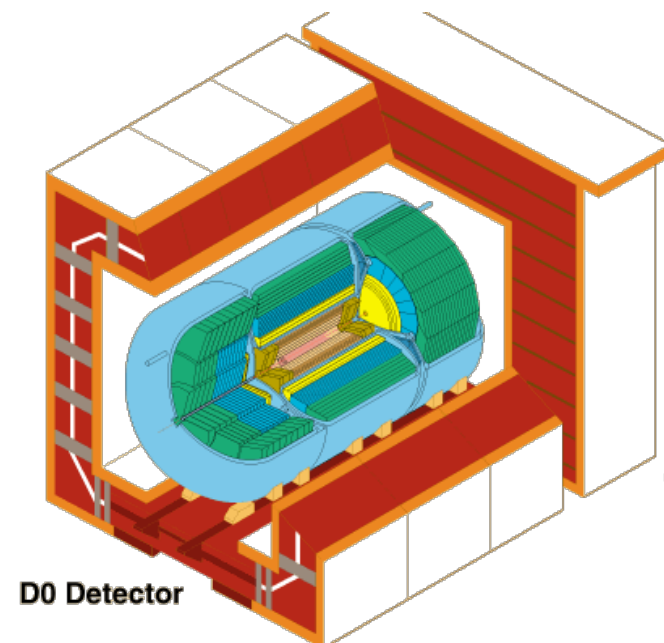
One $t\bar{t}$ pair in
 10^{10} collisions!



Eyes on top

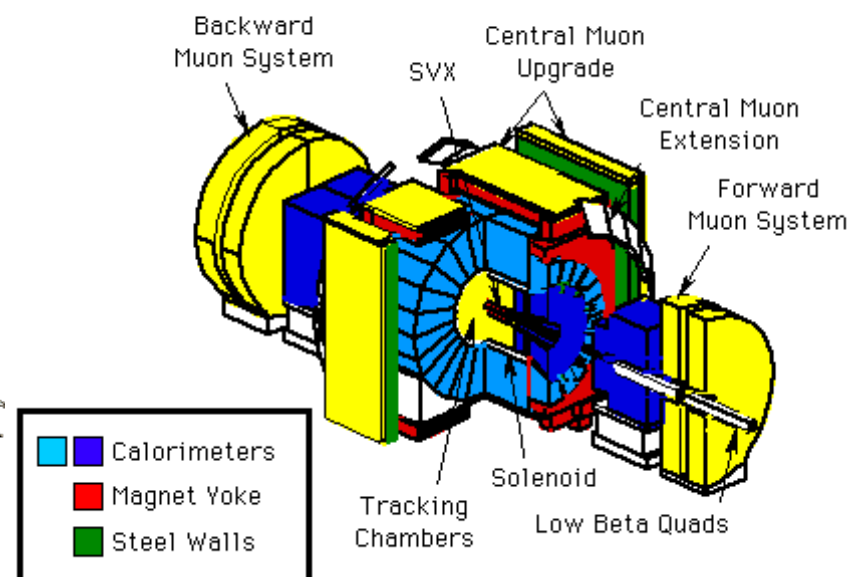


B e t t e r
h e r m e t i c &
u n i f o r m
c a l o r i m e t r y



D0 Detector

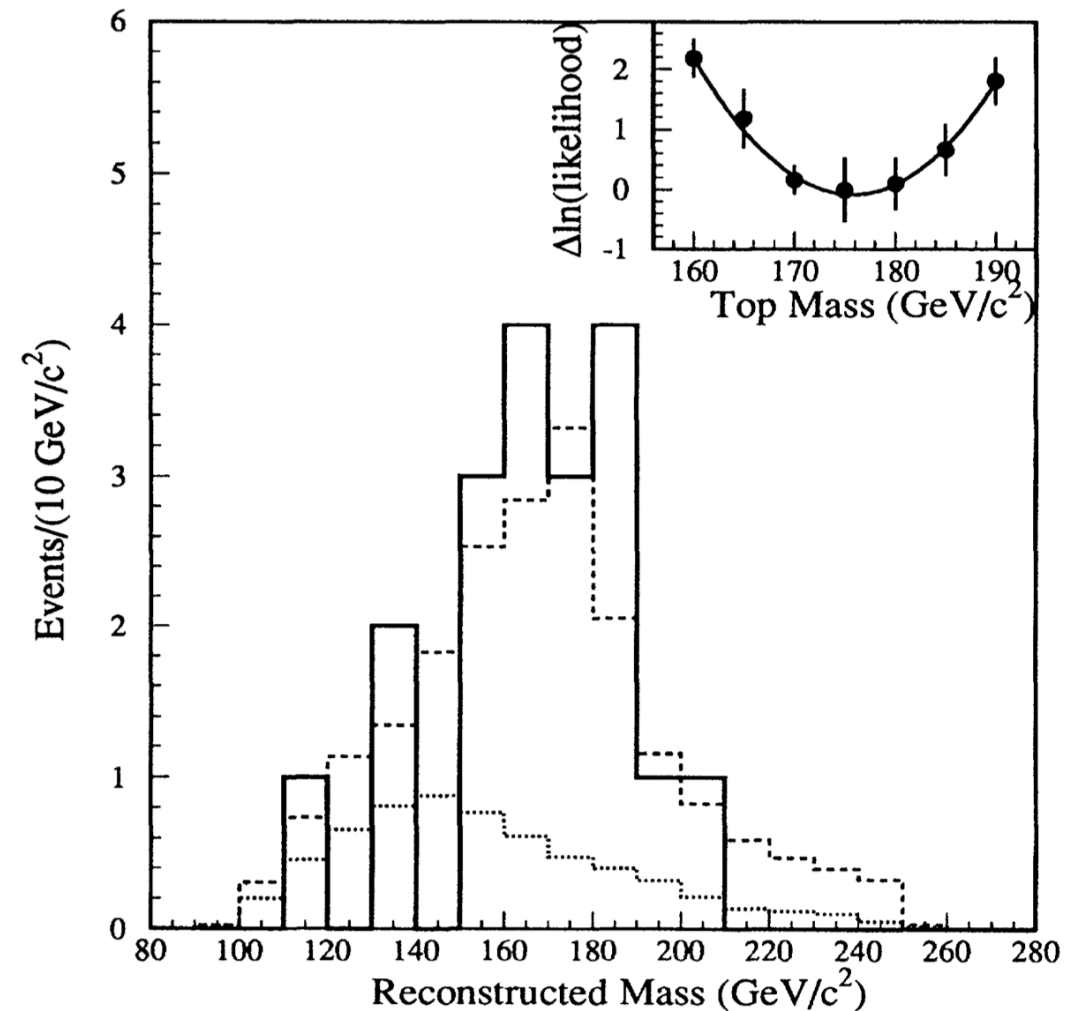
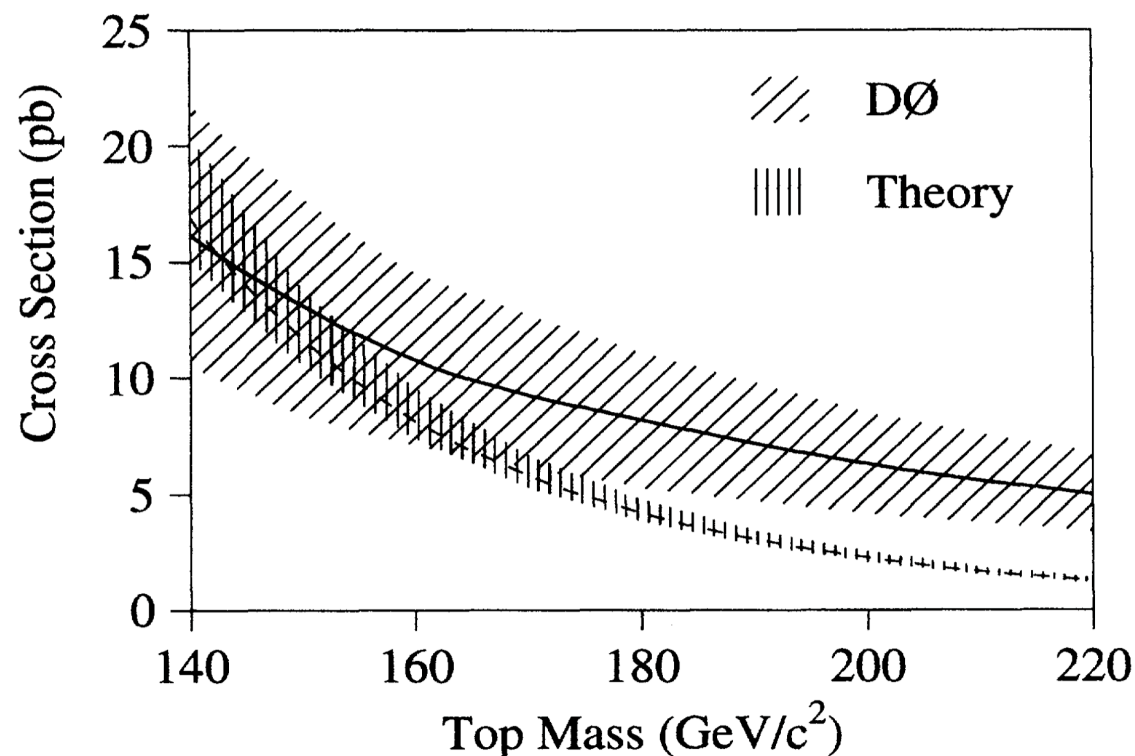
CDF Detector



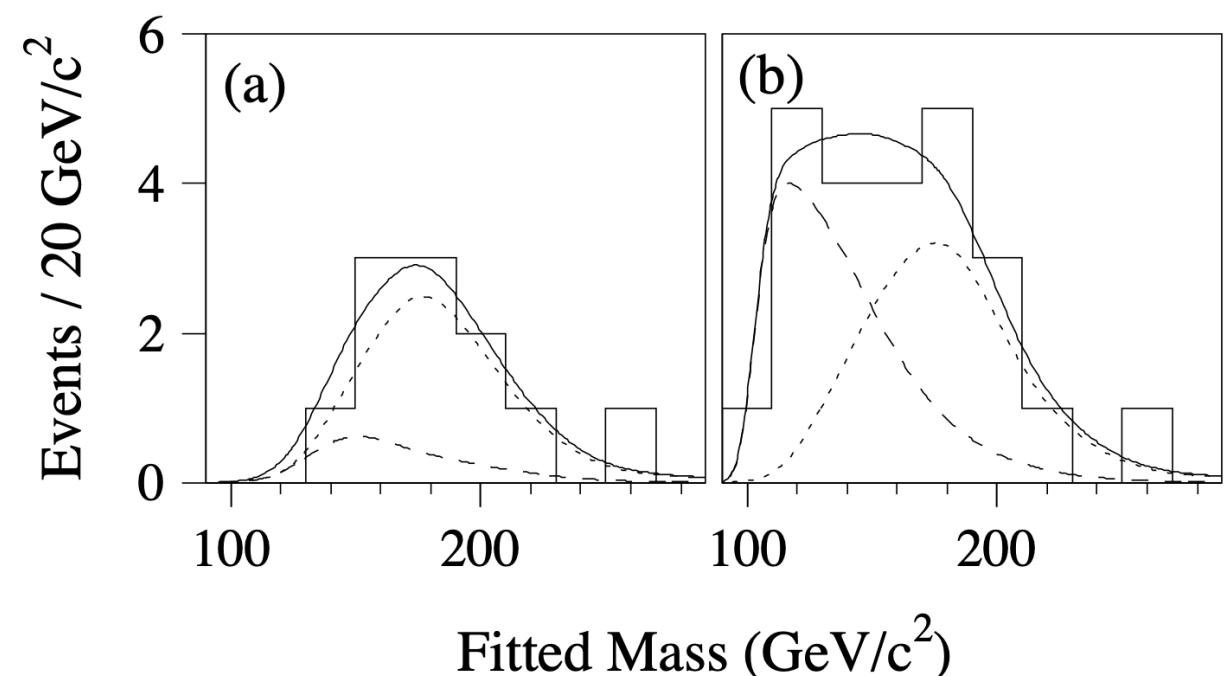
Optimized for
p r e c i s e
t r a c k i n g

First appearance

- Observed at $m_t = 176 \pm 13$ (CDF) and 199 ± 30 (D0)
- Tens of top quark candidates collected
- Top quark mass through kinematic fit
- Perfectly in agreement with the prediction from the EW fit (m_t) and QCD ($\sigma_{t\bar{t}}$)



PRL 74 (1995) 2626

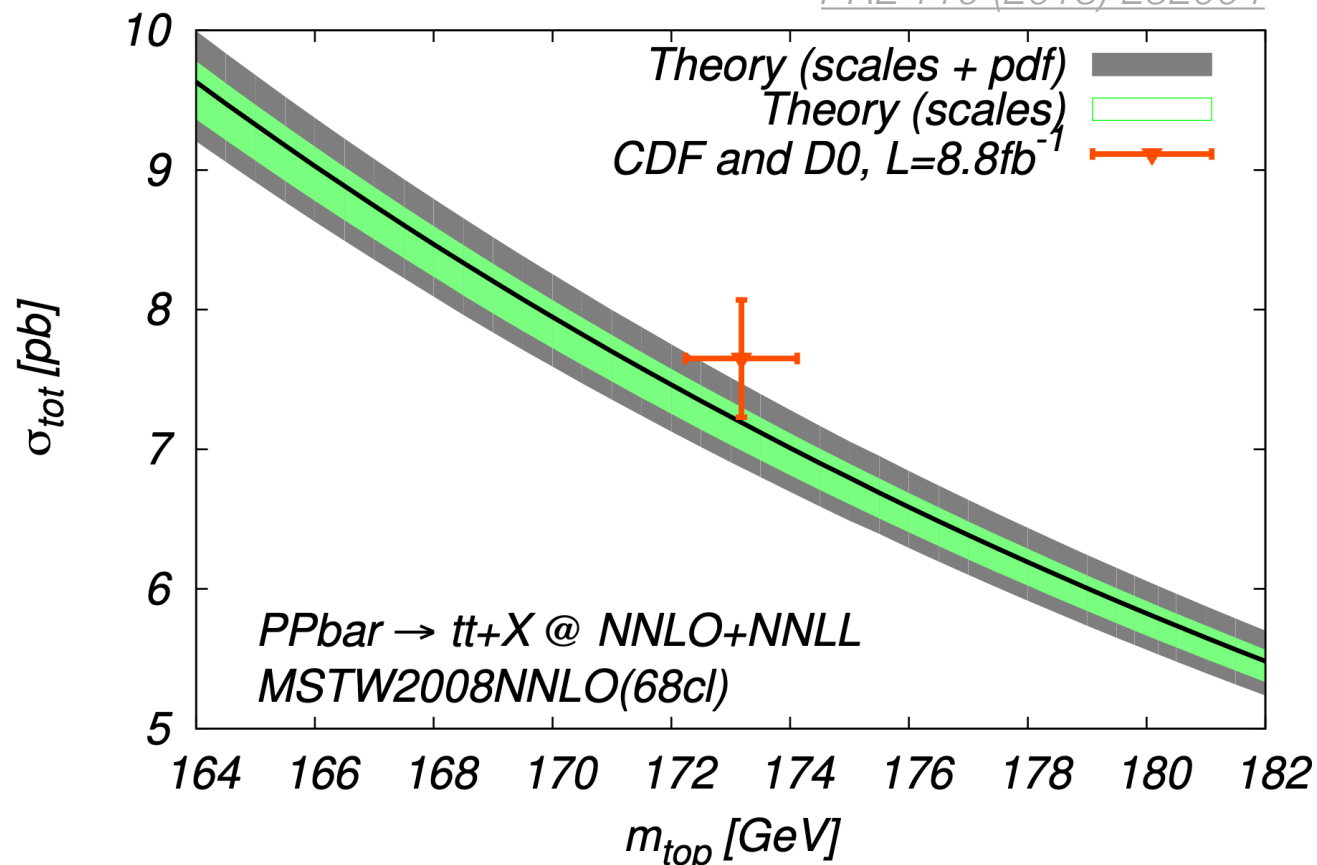


PRL 74 (1995) 2632

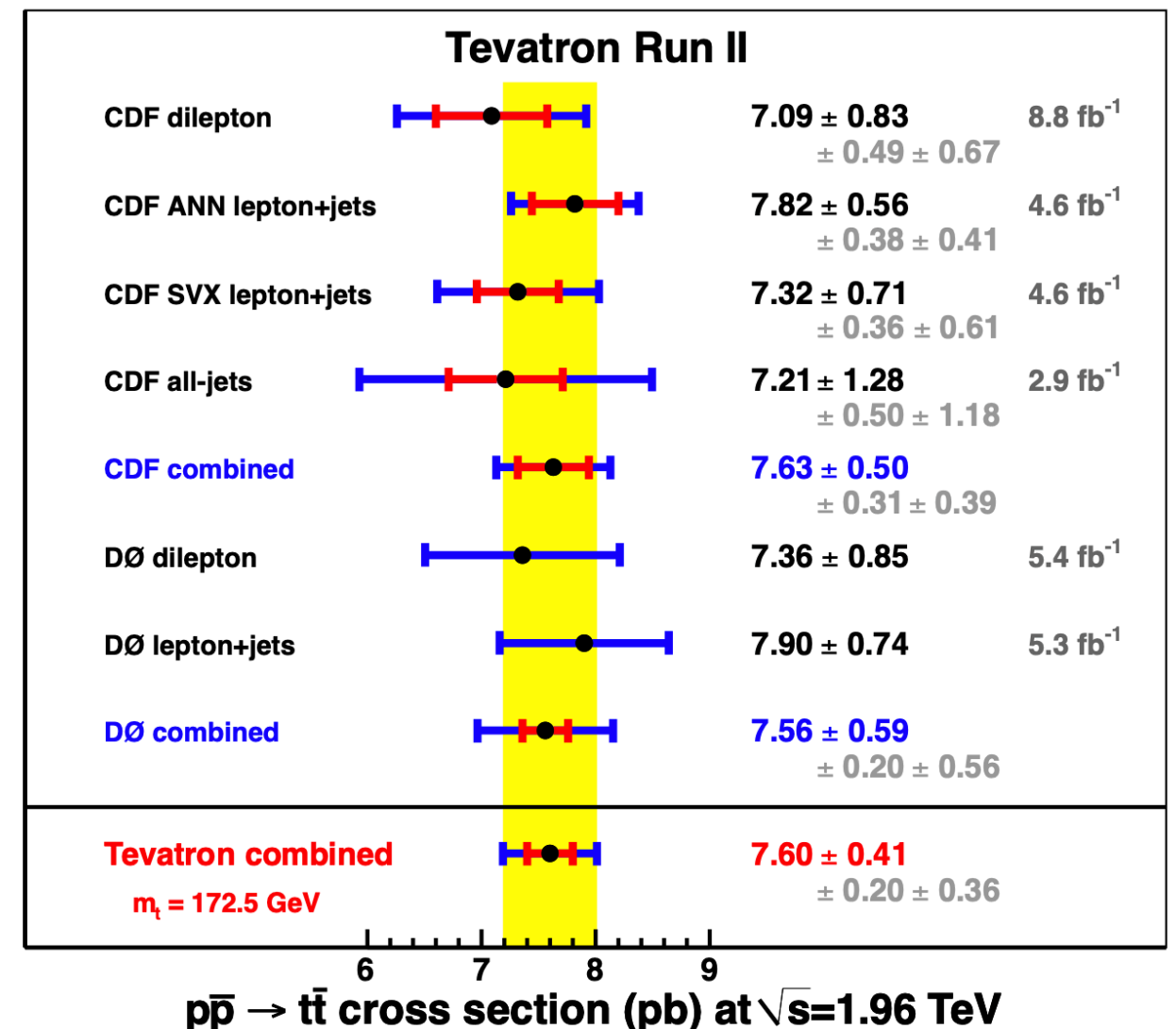
Cross section

- Production is QCD: $\approx 85\% \sigma_{q\bar{q}}, \approx 15\% \sigma_{gg}$
- Known at NLO accuracy during the top quark discovery
- NLO $\rightarrow$ NNLO+NNLL:
 - $+15\% \sigma_{t\bar{t}}$
 - $\delta\sigma_{t\bar{t}}: \pm 25\% \rightarrow \pm 3\%$
- Extract α_S and m_t^{pole}

PRL 110 (2013) 252004

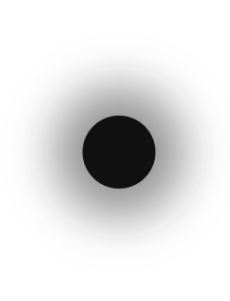


PRD 89 (2014) 072001



What is top mass?

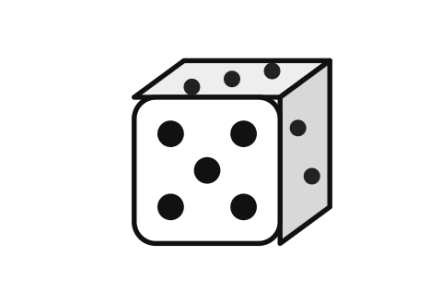
- Not just a simple number
- Quarks are never free, they are dressed in gluons
- The pole of the quark propagator « **pole mass** » $m_t^{\text{pole}} \approx 172.5 \text{ GeV}$: intrinsic uncertainty defined by $\Lambda_{\text{QCD}} \approx 200 \text{ MeV}$
- A short-distance « **running mass** » $\overline{\text{MS}}$, $m_t(m_t) \approx 163 \text{ GeV}$: analogous to α_s
- The MC « **kinematic mass** » $m_t^{\text{MC}} \approx 172.5 \text{ GeV}$: the mass parameter in MC event generators
- **The mass interpretation problem**: the exact relation between the MC and pole/ $\overline{\text{MS}}$ mass is not known



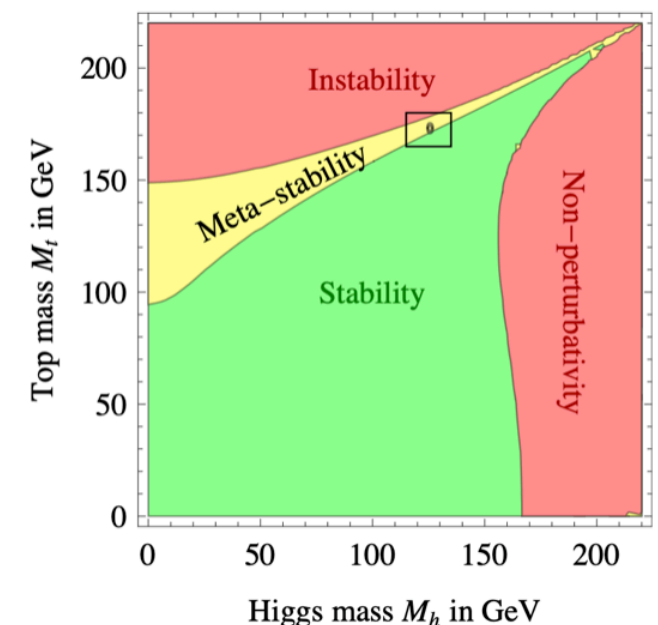
Pole mass
 $\approx 172.5 \text{ GeV}$



MS-bar mass
 $m(m_t) \approx 163 \text{ GeV}$

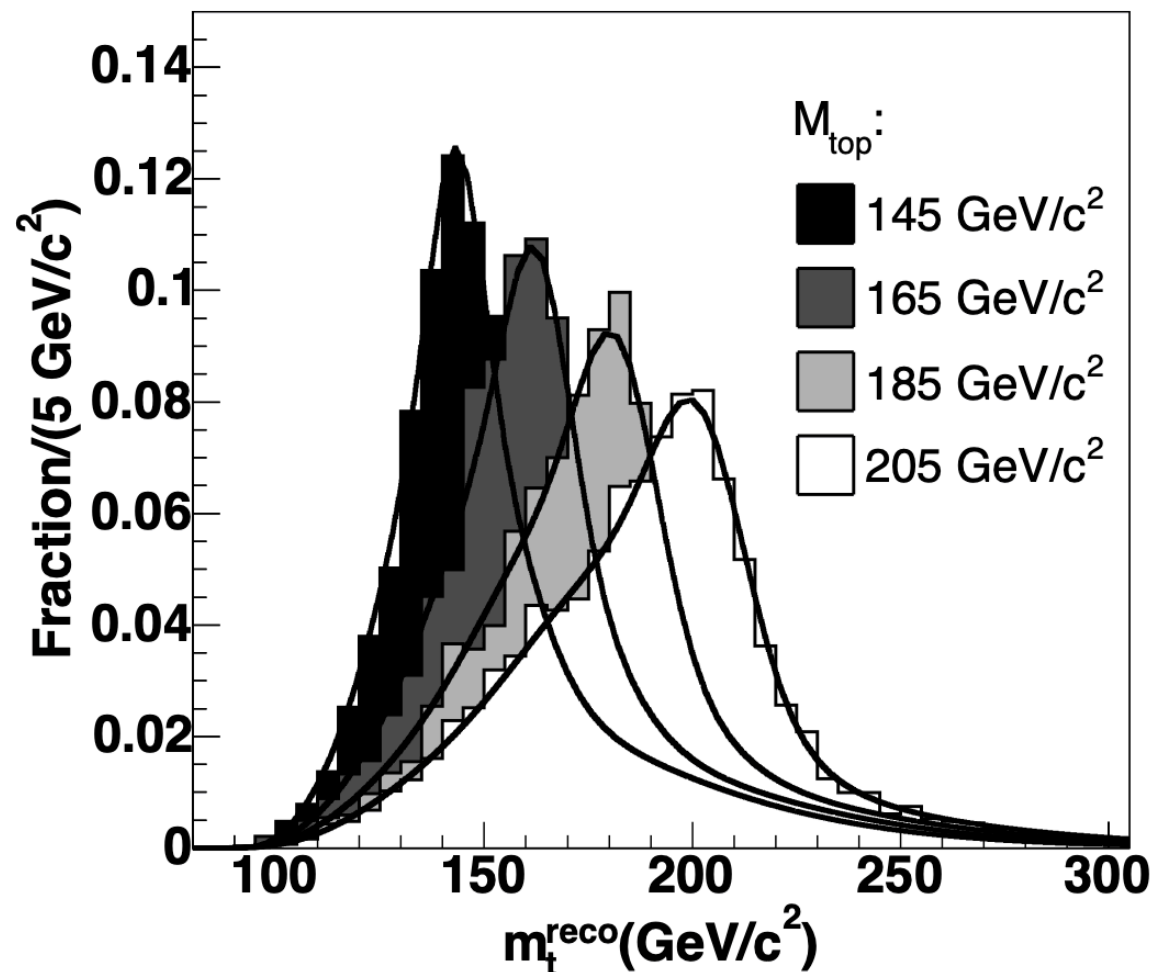
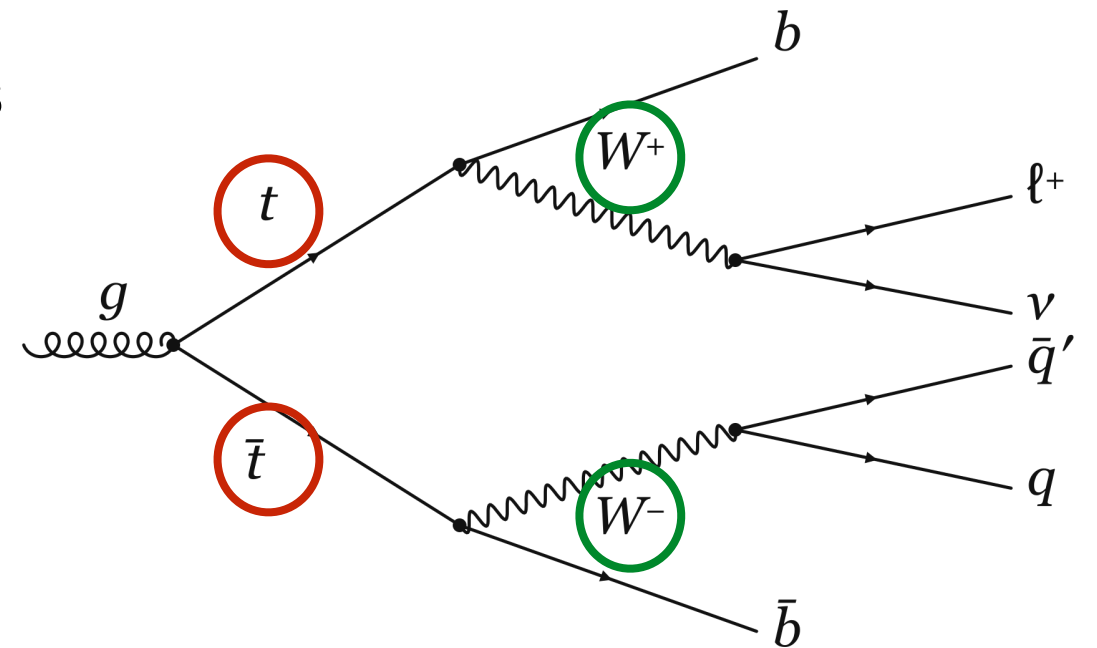


MC / kinematic mass
 $\approx 172.5 \text{ GeV}$



Kinematic reconstruction

- Reconstruct top quark « kinematic » mass from its **decay products**
- Resolve lepton-jet permutations using χ^2 minimization
- Fit data using top mass templates

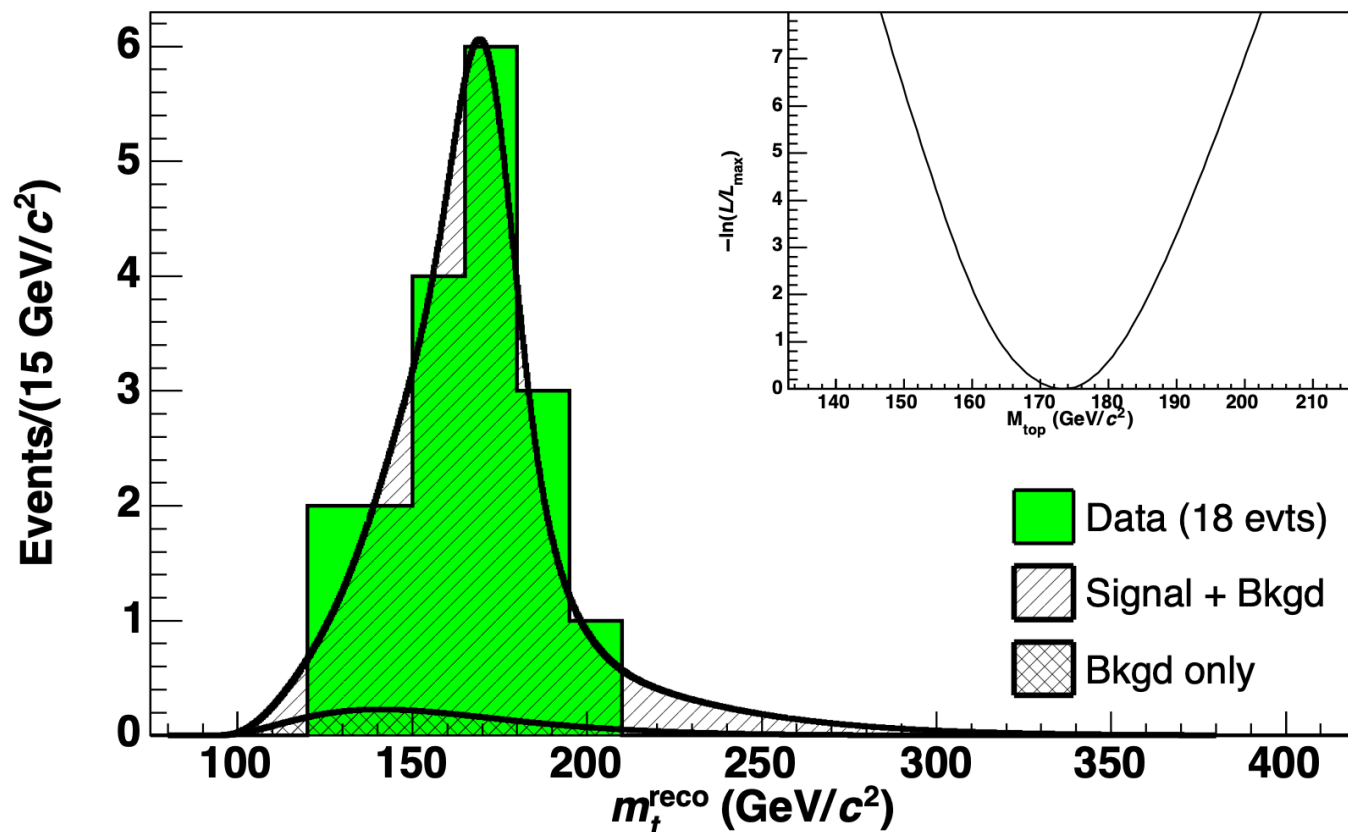


$$\chi^2 = \sum_{i=\ell, 4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_{UE}^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{b\ell\nu} - m_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2}$$

Fitted mass

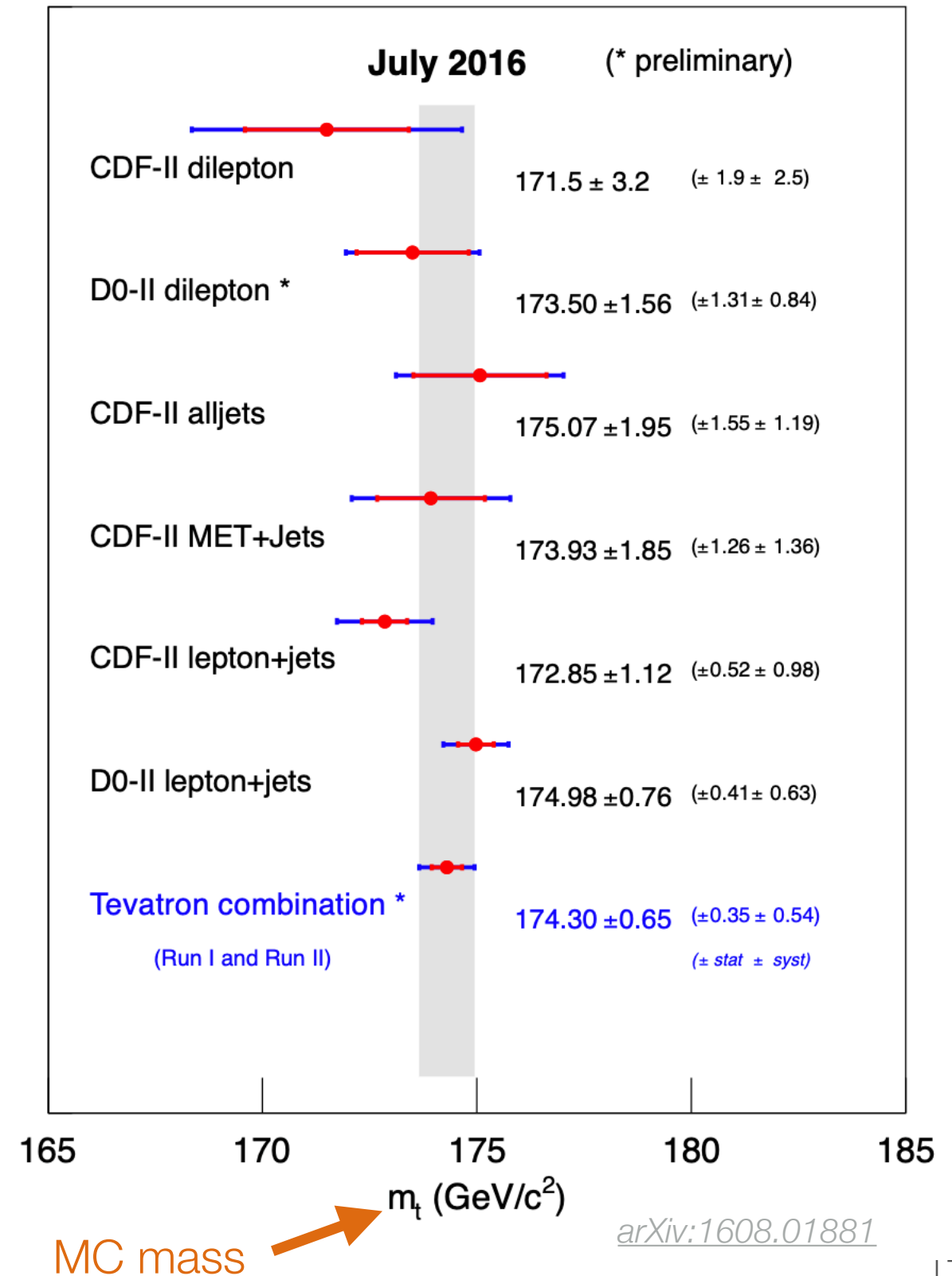
$$L(m_t) = \prod_{\text{events}} \left[f_s P_s(m^{\text{reco}} | m_t) + (1 - f_s) P_b(m^{\text{reco}}) \right]$$

Probability of m^{rec} given m_t (blue arrow pointing to P_s)
 Signal fraction (red arrow pointing to f_s)
 Background template (green arrow pointing to P_b)



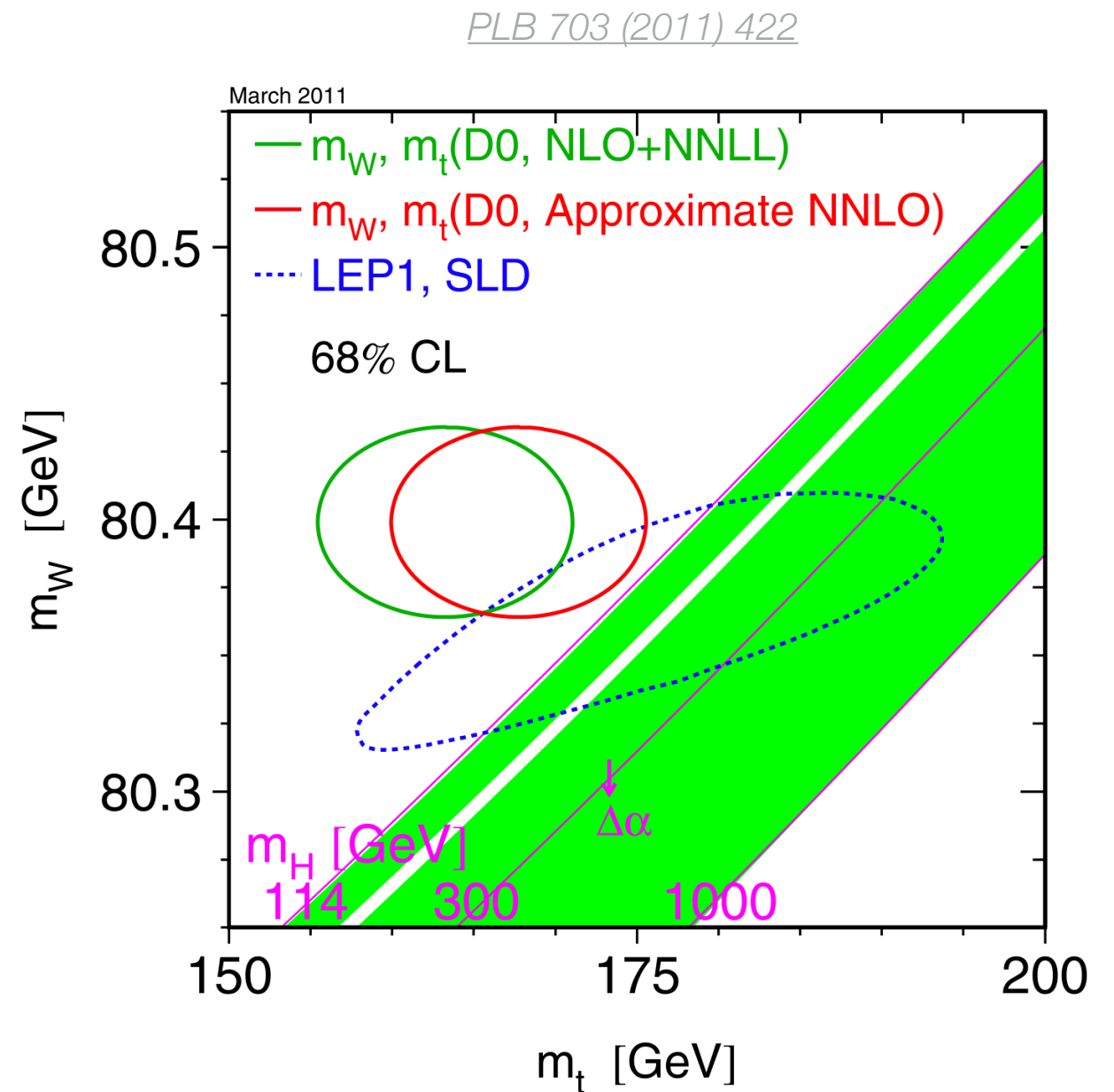
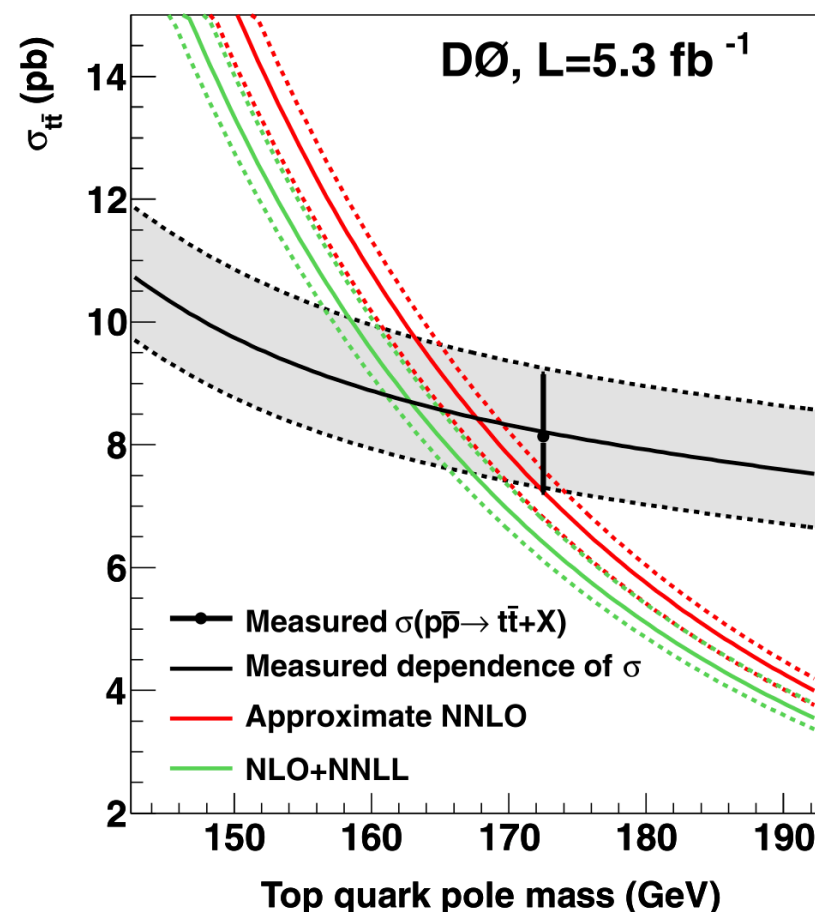
PRD 73 (2006) 032003

Mass of the Top Quark



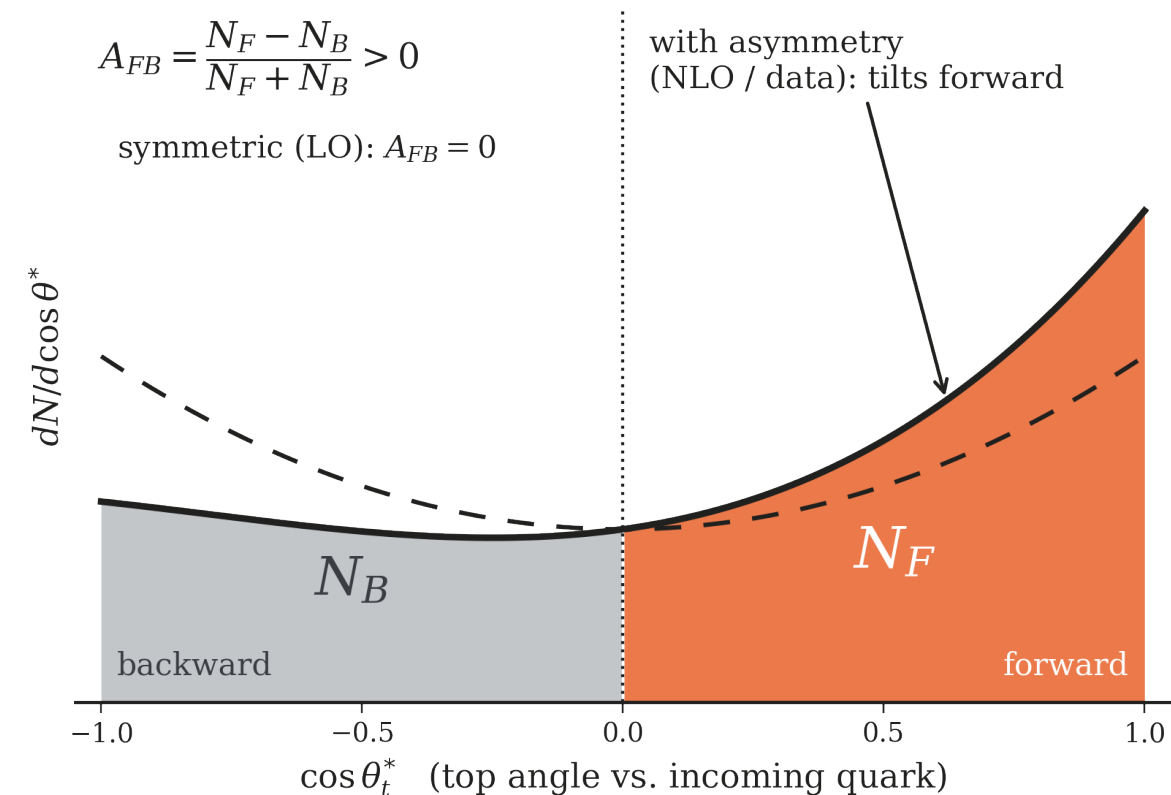
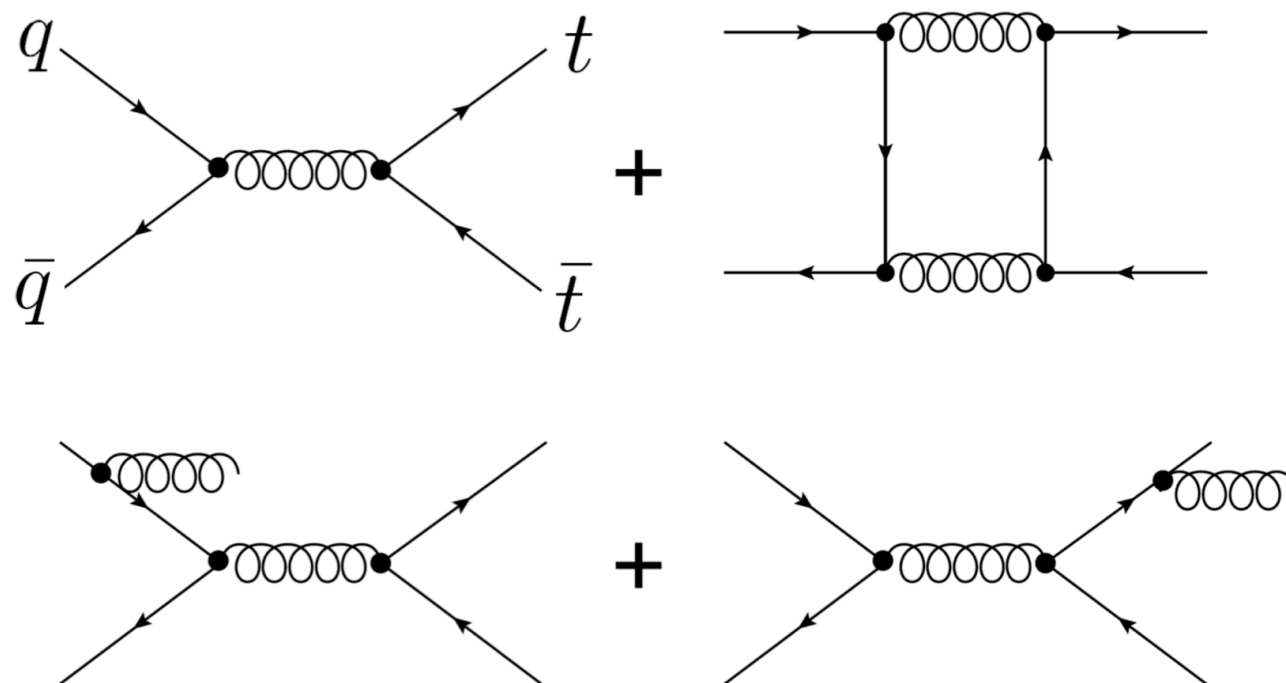
Extracting pole mass

- Use **inclusive** $t\bar{t}$ cross section to extract m_t^{pole}
- No dependence on kinematics, only acceptance effects (from simulation)
- Find m_t^{pole} such that $\sigma_{\text{theory}}(m_t^{\text{pole}}) = \sigma_{\text{meas}}$



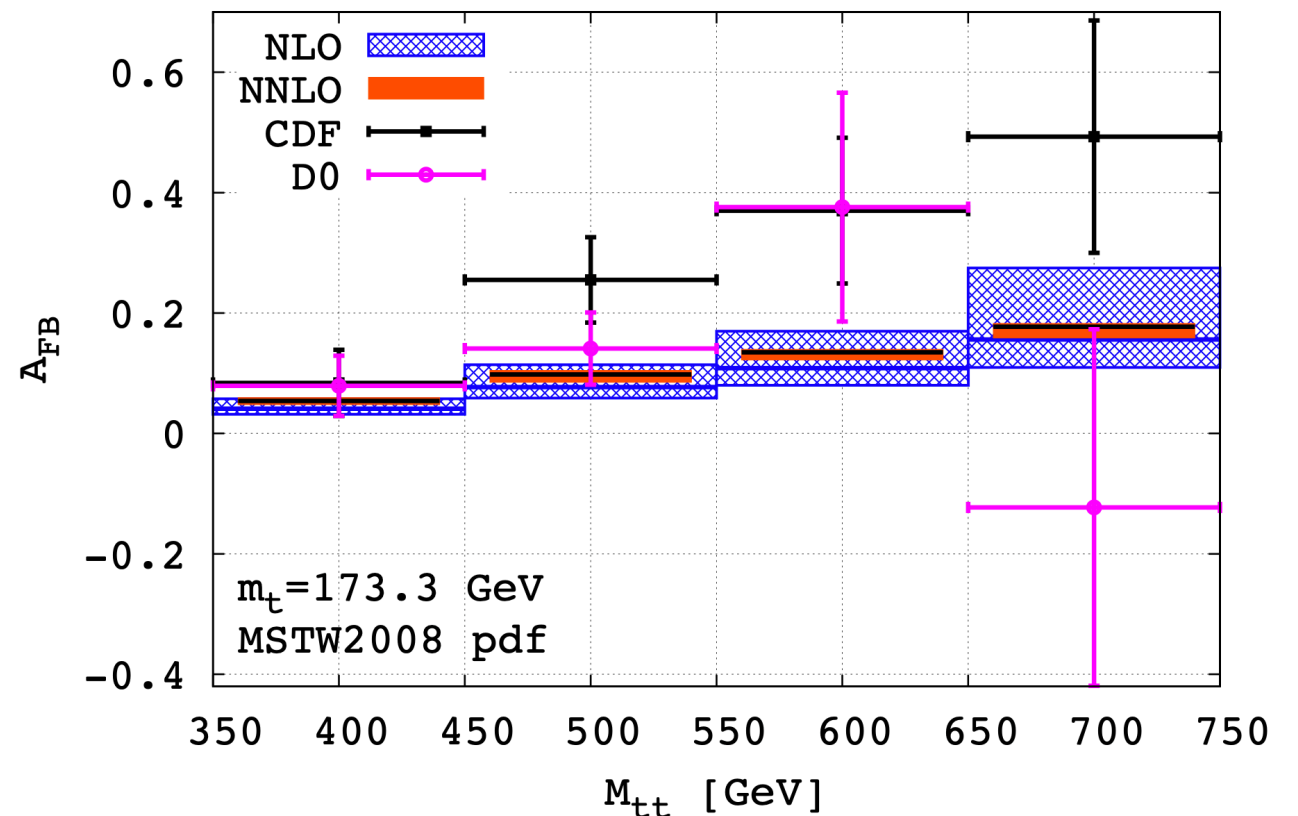
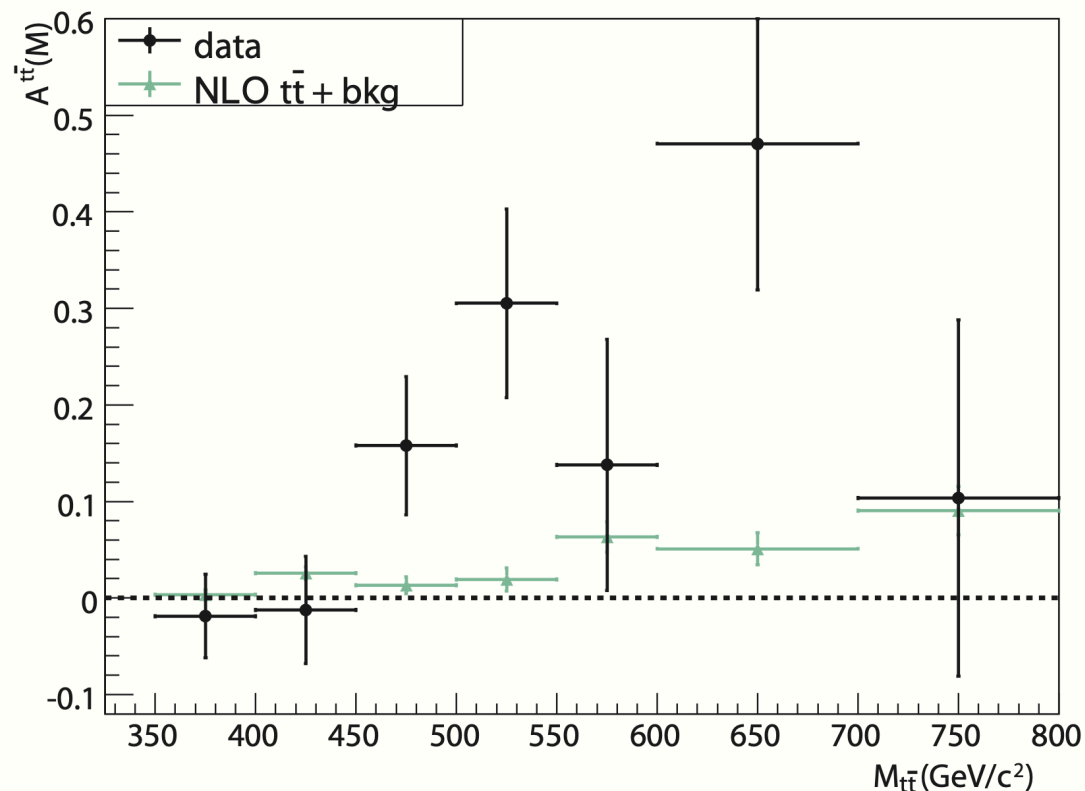
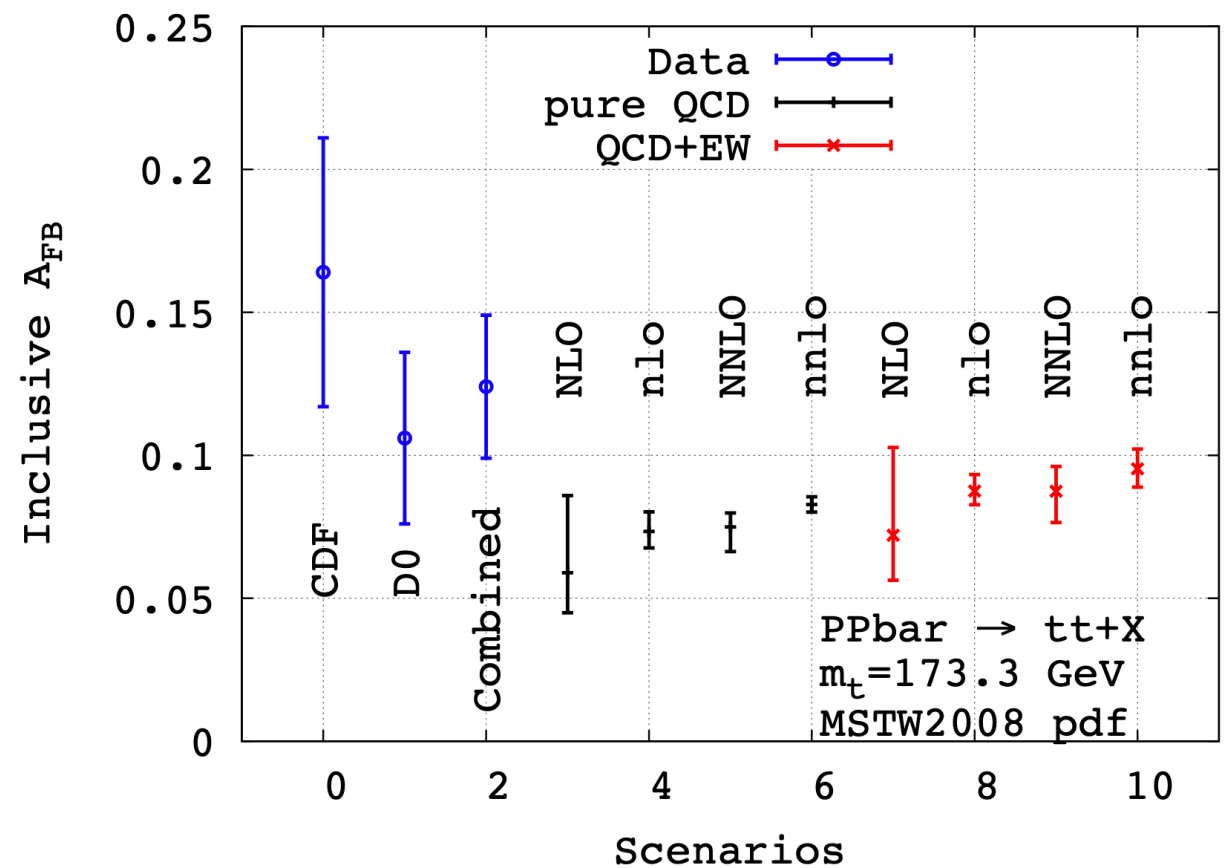
Asymmetry

- At a $p\bar{p}$ collider the direction of incoming quark is known
- Define asymmetry $A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$, where $\Delta y = y_t - y_{\bar{t}}$
- At LO QCD, $A_{FB} = 0$
- Small $A_{FB} > 0$ at NLO QCD from diagram interference: top tends to follow the incoming quark



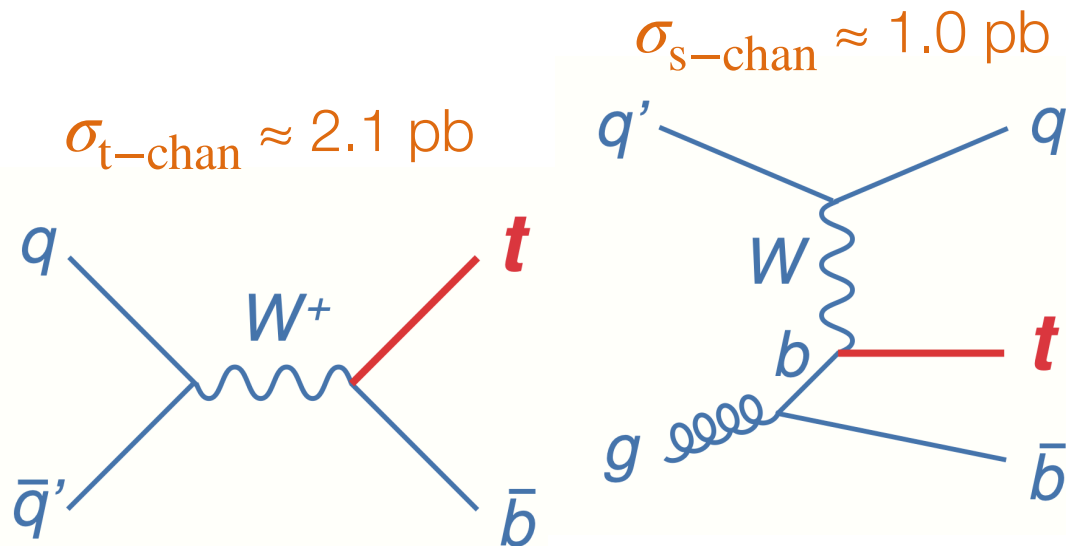
A_{FB} anomaly?

- Measured at 0.128 ± 0.025 (CDF+D0)
- Prediction of 0.073 (NLO) $\rightarrow$ NNLO (0.095)
- Significant **high-order corrections**
- Overall good agreement



Single top

- Produced via **EW**
- Direct access to Wtb structure $\rightarrow |V_{tb}|$
- Observed in t- and s-channels



Tevatron Run II single top quark summary

Measurement

Cross section [pb]

s-channel:

CDF [25]

D0 [22]

Tevatron [26]

t-channel:

CDF [21]

D0 [22]

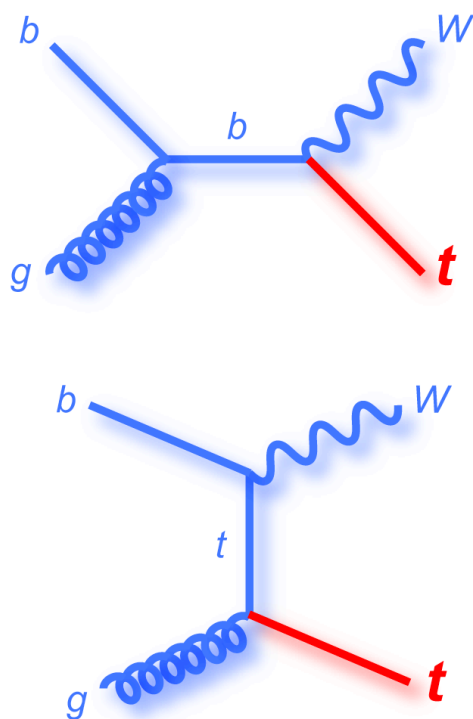
Tevatron [this Letter]

s+t:

CDF [21]

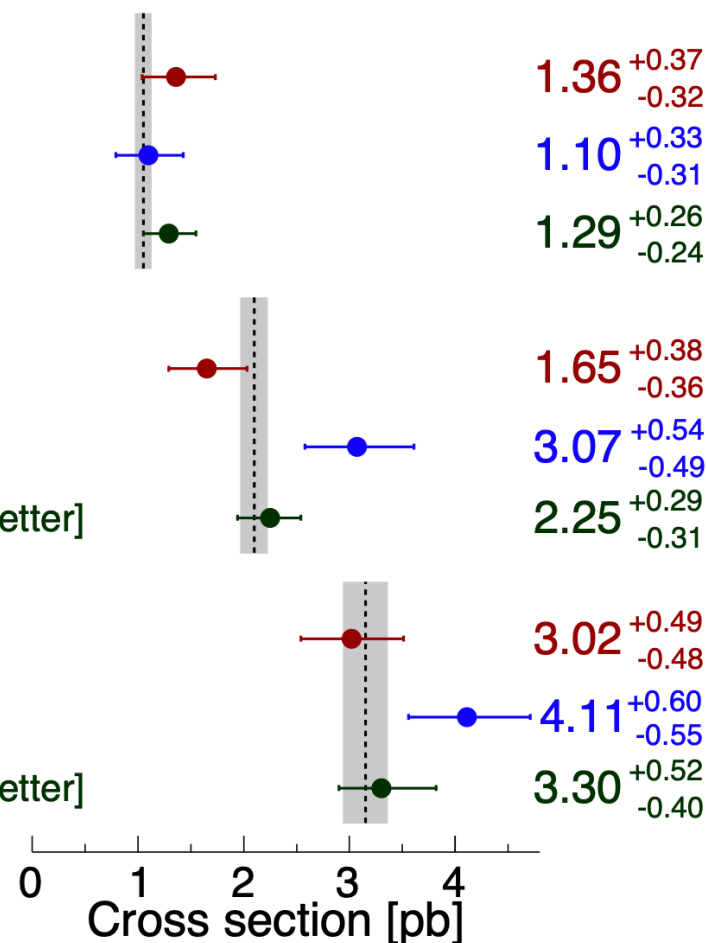
D0 [22]

Tevatron [this Letter]



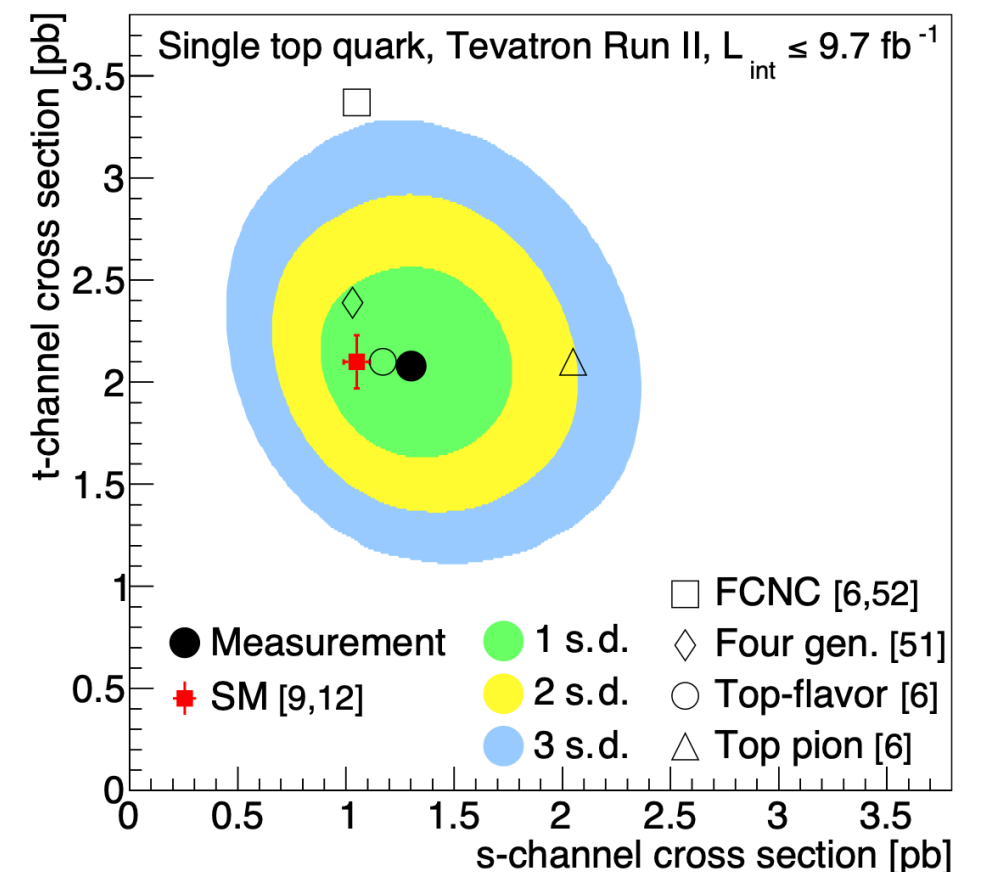
$\sigma_{tW} \approx 0.1 \text{ pb}$

PRL 115 (2015) 152003



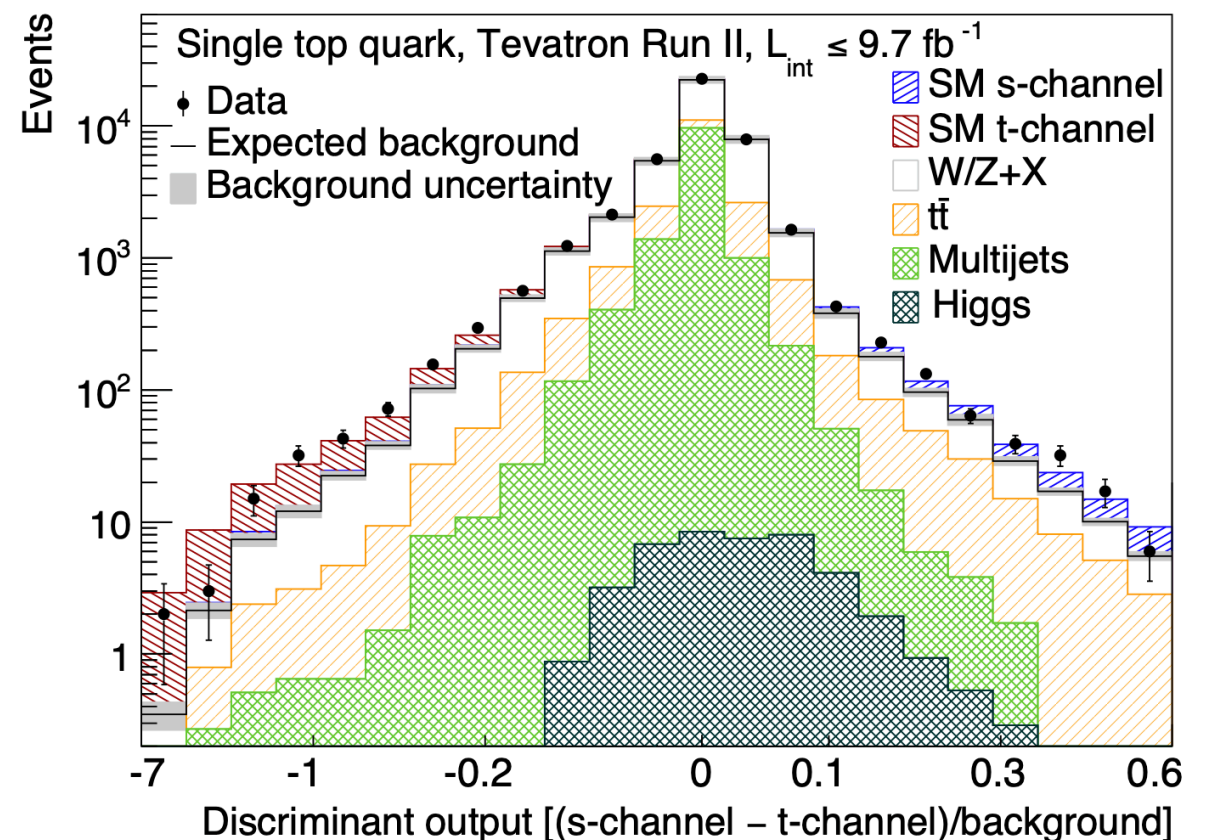
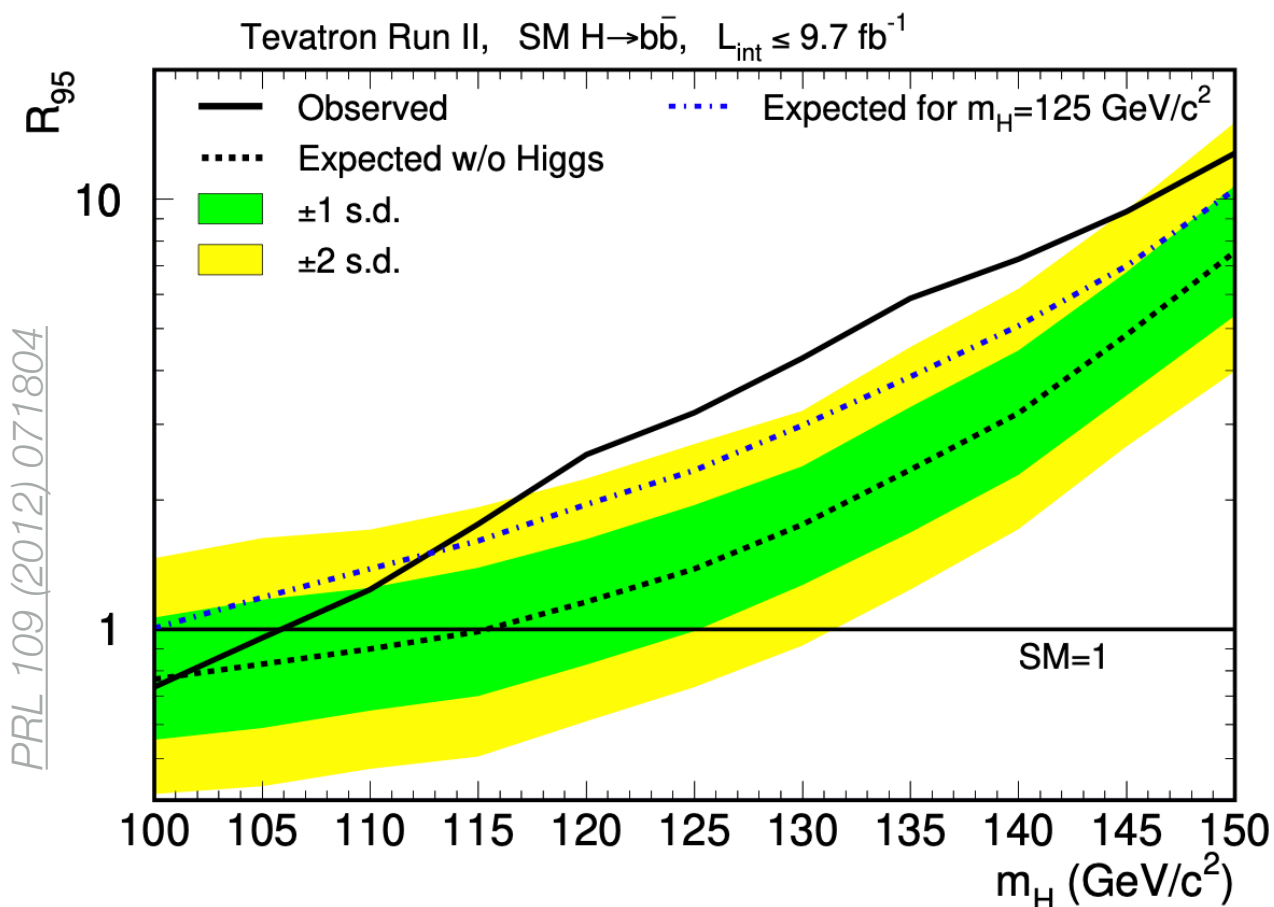
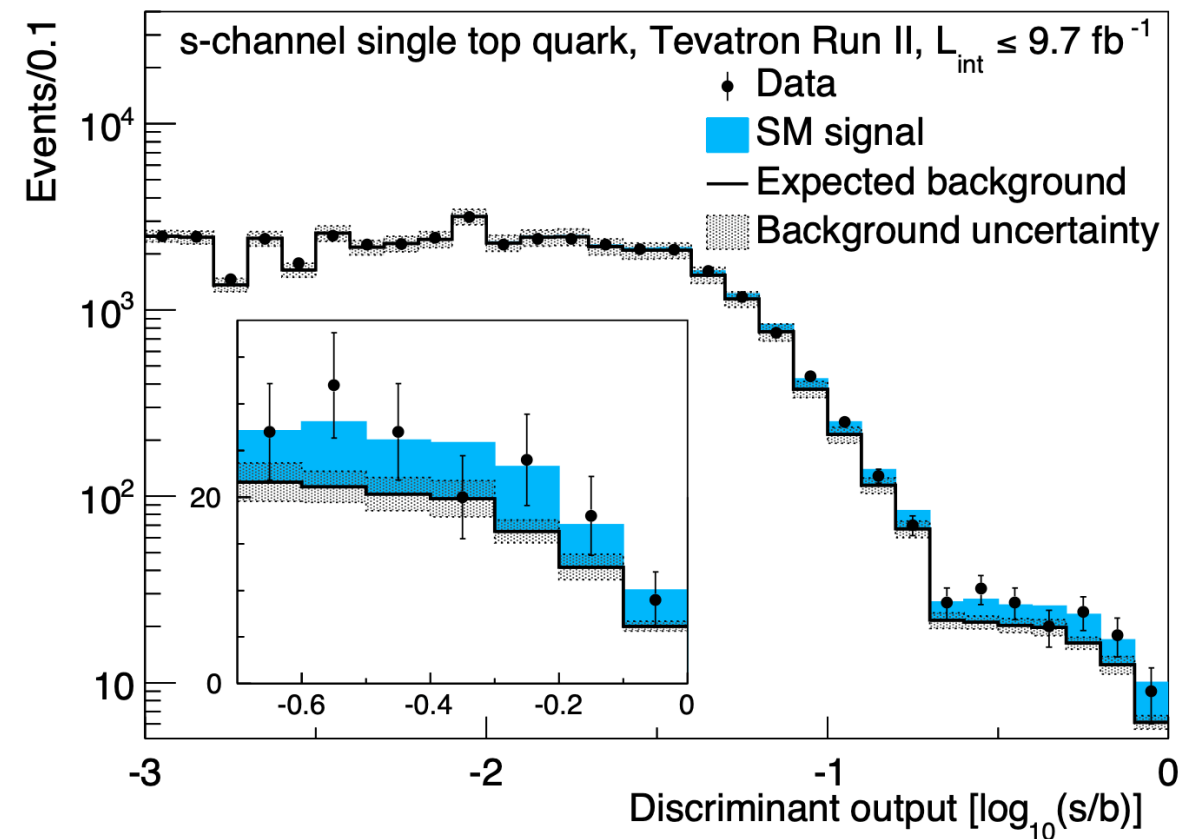
■ Theory (NLO+NNLL) [9,12]

$m_t = 172.5 \text{ GeV}$

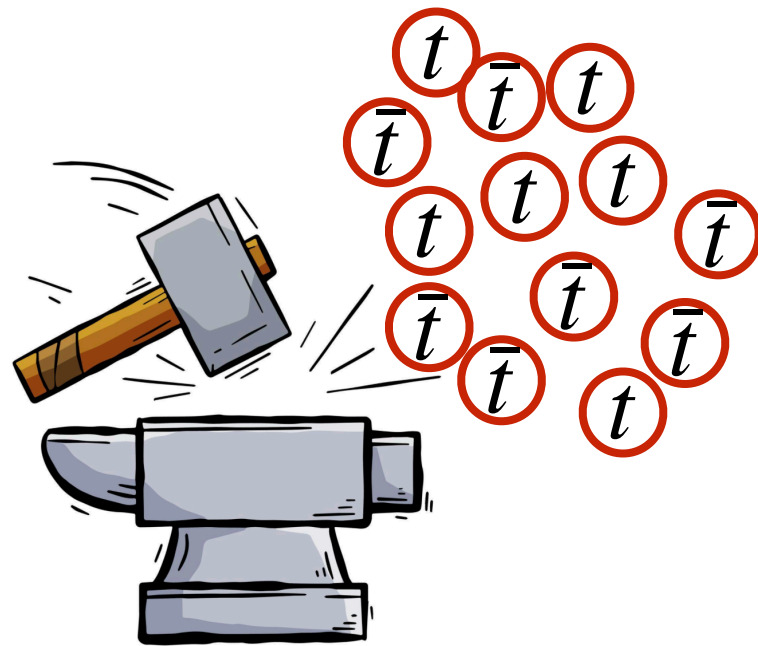


Machine learning for tops

- Large W +jets, QCD multijet, and $t\bar{t}$ backgrounds
- Pioneering use of **MVA methods**: heavy-flavor jet tagging and S/B event kinematics
- Similar methodology allows searching for the Higgs boson



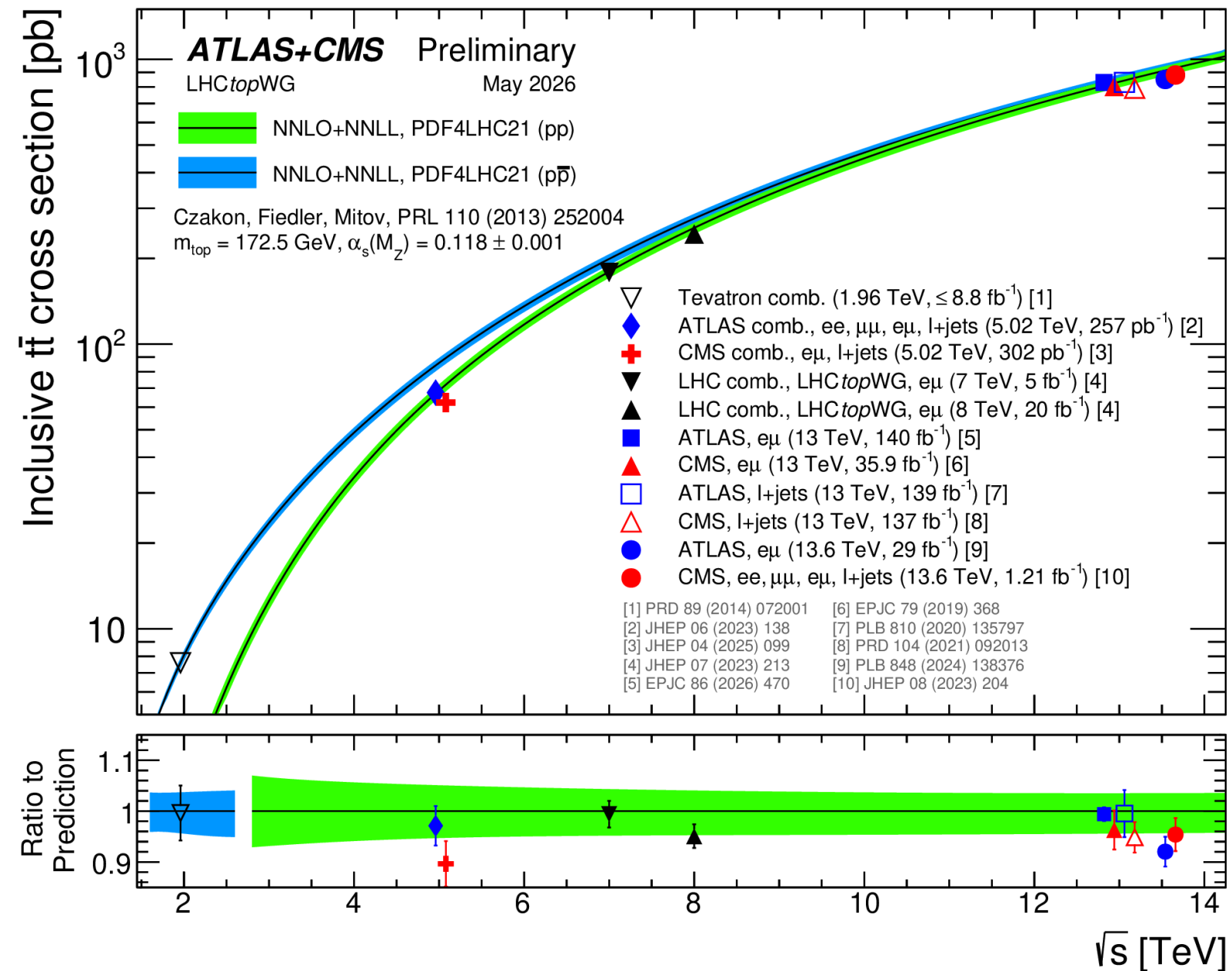
The top factory



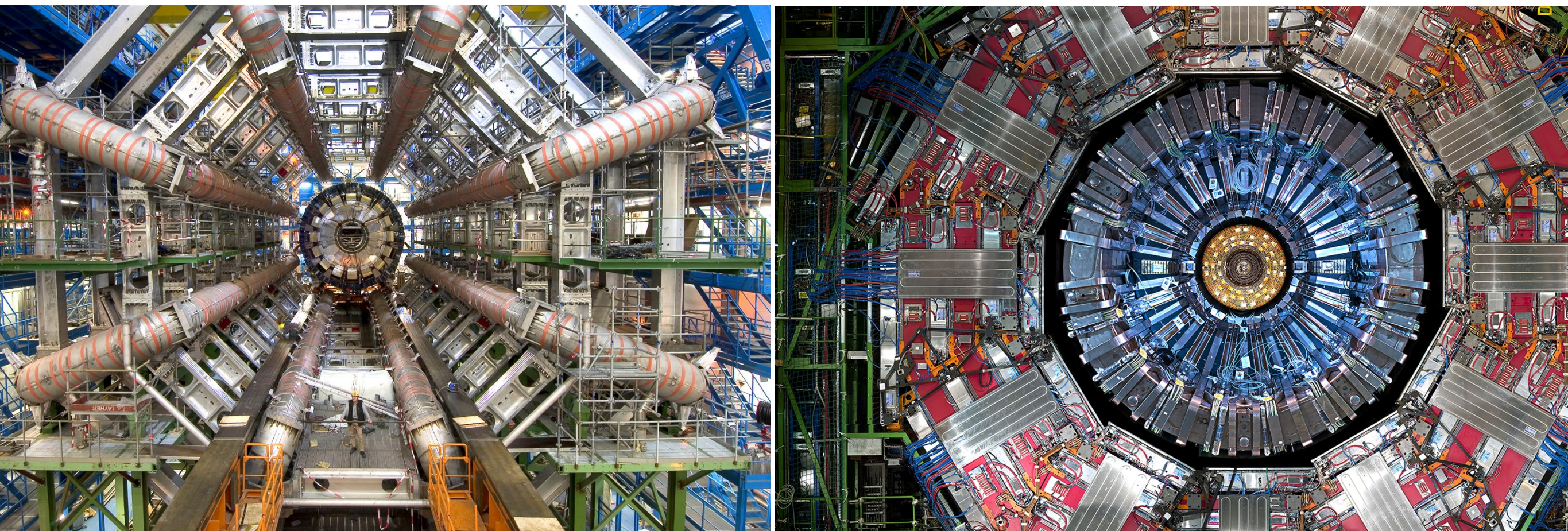
Top quark at the LHC

LHCtopWG Summary Plots

- **Faster, Harder, Stronger**
- From discovery to precision
- High energy:
 $\approx 7\times$ Tevatron
- Cross section:
 $\approx 120\times$ Tevatron
- Luminosity:
 $\approx 20 \text{ } t\bar{t}$ pairs per second!
- Predominantly produced by gluon fusion ($\approx 90\%$)



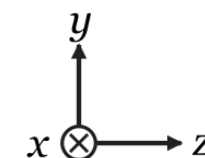
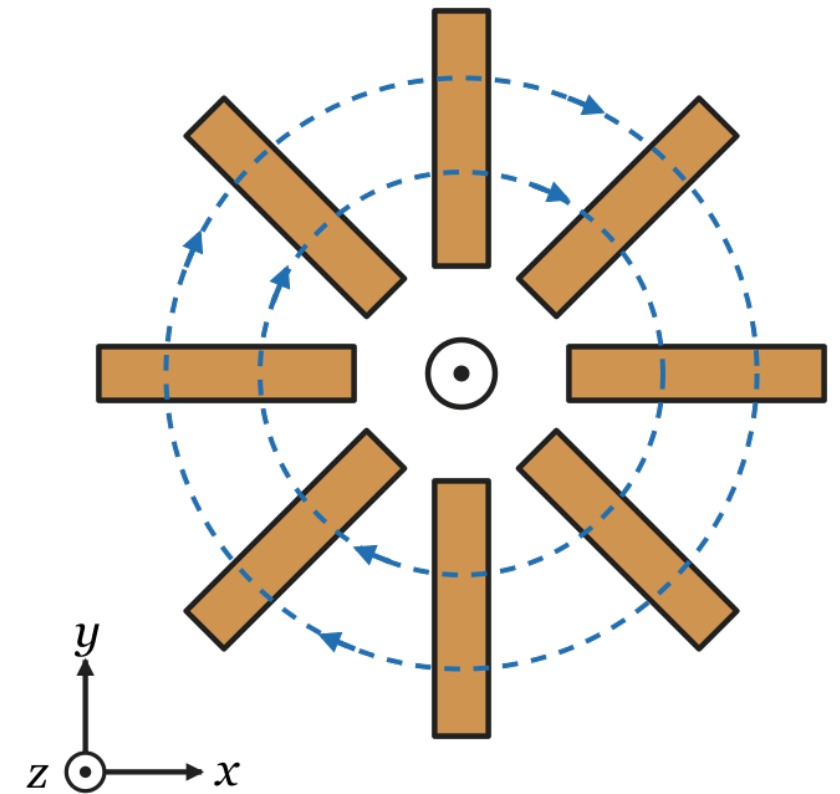
Catching tops



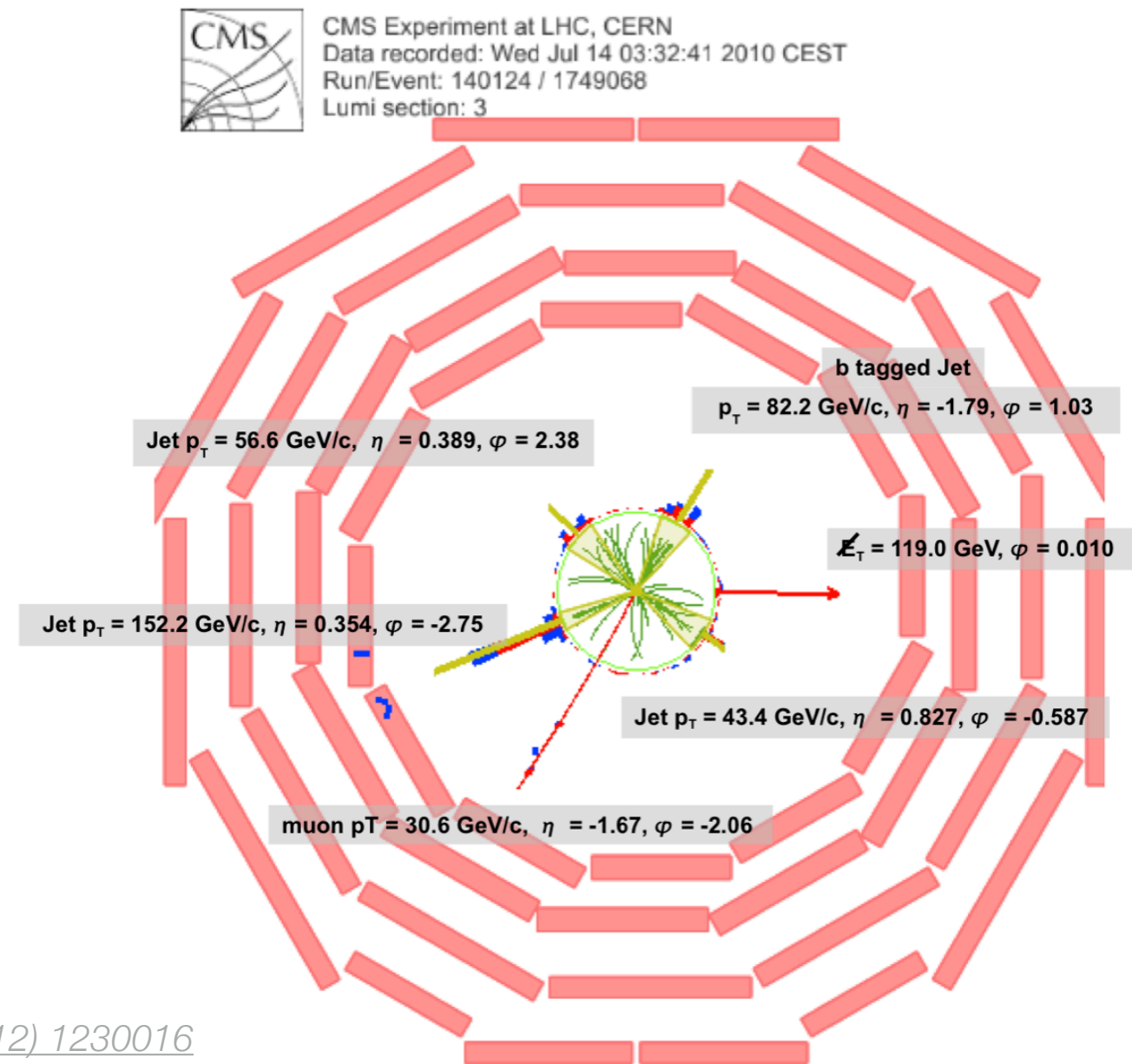
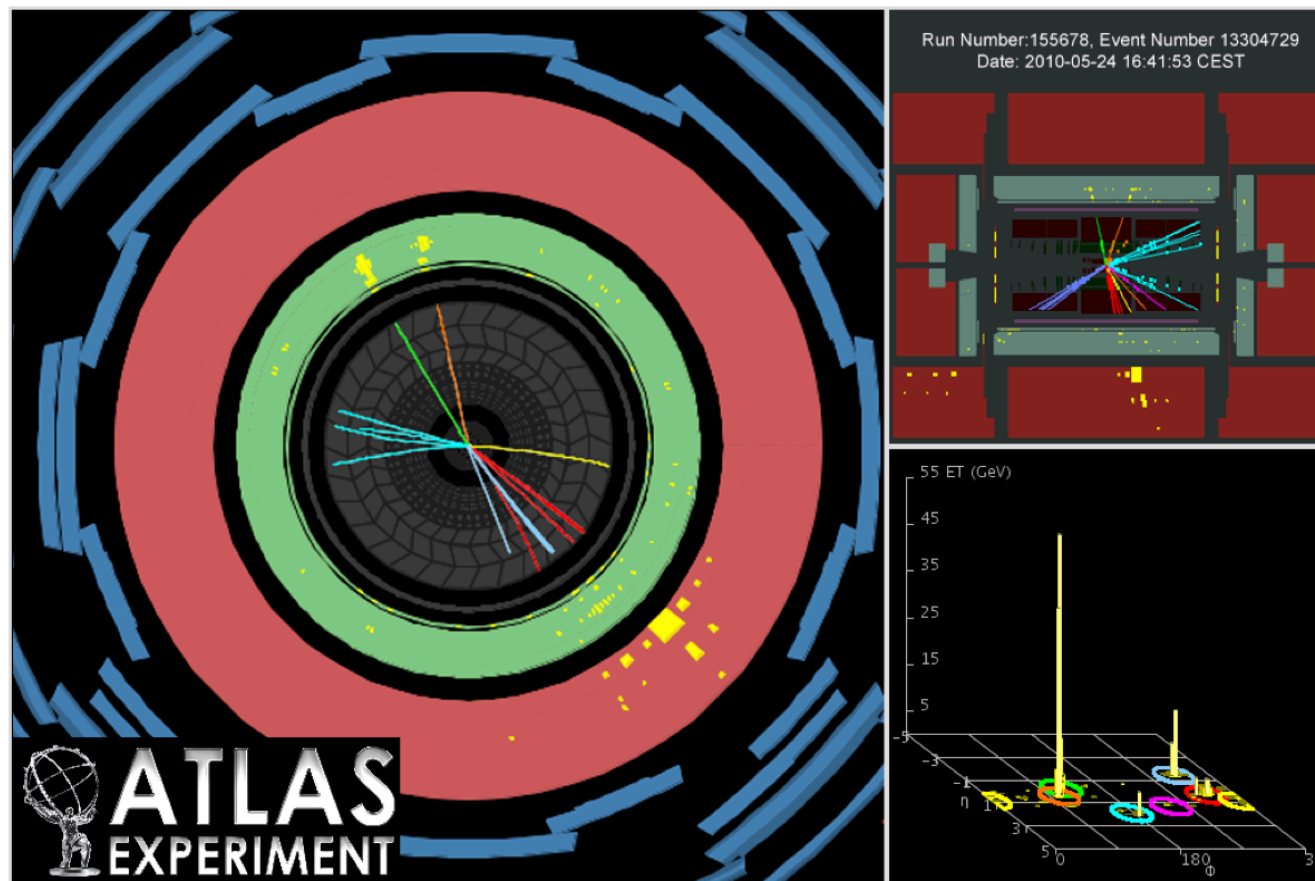
- Two **general-purpose** detectors: ATLAS and CMS
- Advanced silicon trackers → finer granularity and higher rate
- Precise vertexing and deep-learning heavy flavor taggers
- Pileup challenge: 30-60 simultaneous collisions per bunch crossing
- Higher energies → boosted top production

Engineering choices

- ATLAS: A **Toroidal** LHC ApparatuS (huge but light)
 - A huge air-core toroid for a standalone muon spectrometer, outside calorimeters
 - A thin 2T solenoid for the inner tracker
 - Calorimeters sit outside the solenoid → large, finely-segmented LAr calorimeter
- CMS: Compact Muon **Solenoid** (compact but heavy)
 - One strong 3.8T 6-meter-wide solenoid
 - All expect muon system inside of the solenoid → a compact, dense calorimeter (lead-tungsten)
 - Iron yoke instrumented with the muon chambers



Re-discovering the top



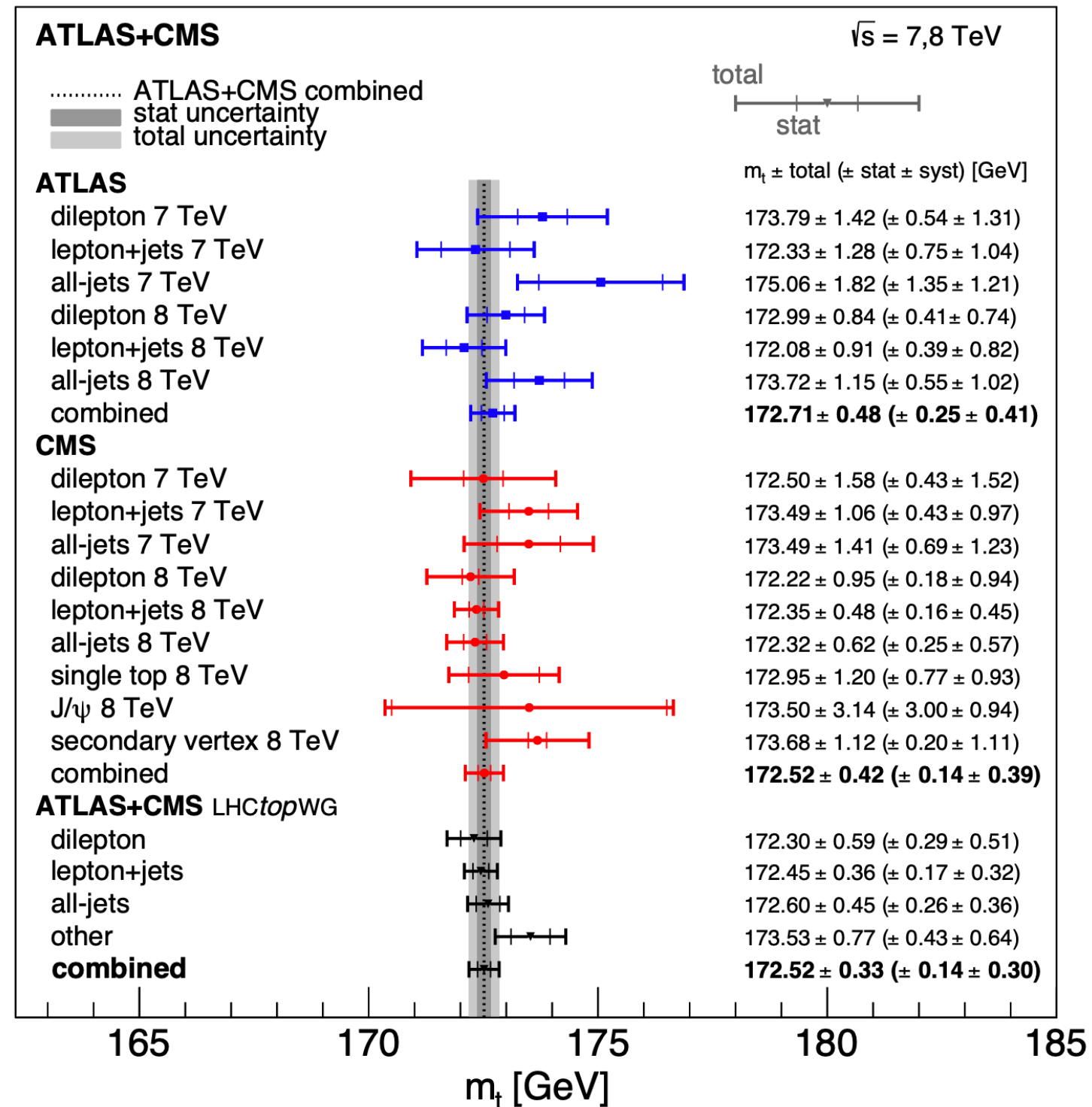
IJMP A 27 (2012) 1230016

- Happened **almost immediately** (120x cross section wrt Tevatron)
- After a few months of data taking (circa 2010) using just a few pb^{-1}

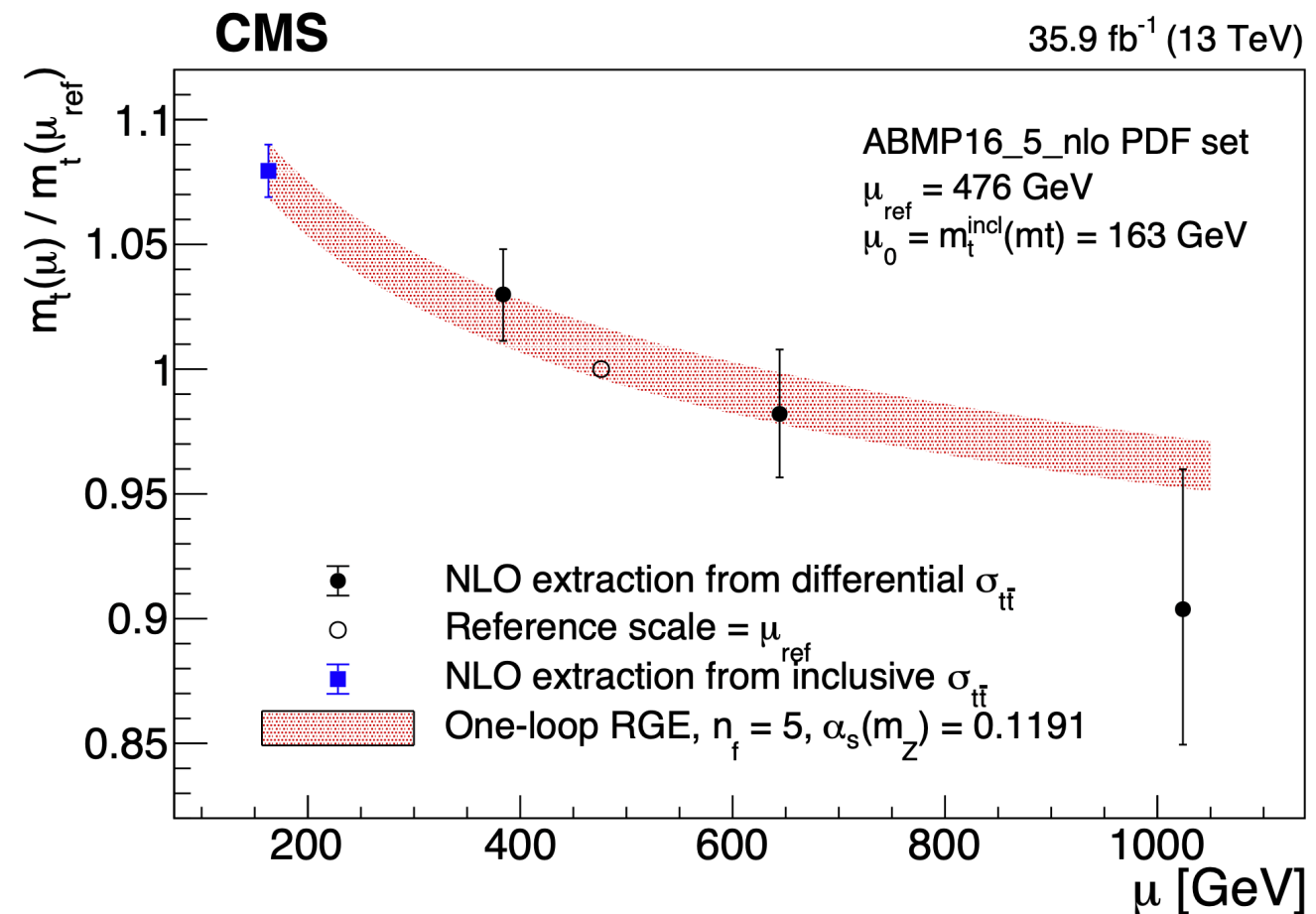
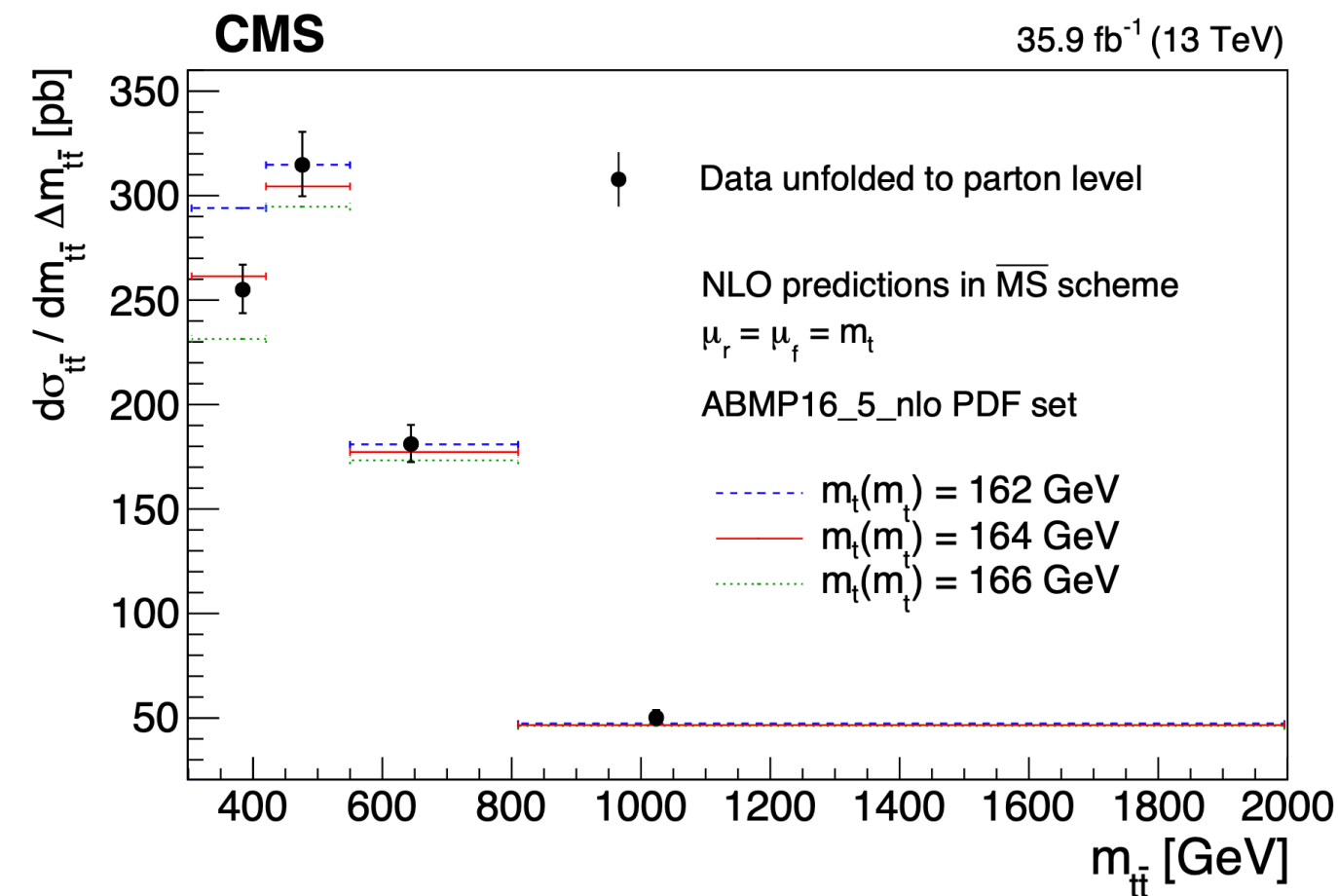
Re-weighing the top

PRL 132 (2024) 261902

- **Best known quark mass** to date (2024): $m_t = 172.52 \pm 0.33$ GeV ($< 0.2\%$)
- Not anymore limited by statistics
- Precision dominated by systematics: JES & modeling (ISR/FSR, color reconnection, etc.)
- Comparable to the top quark mass definition 'uncertainty'
- Does not yet include Run 3 measurements!



Catch me if you can



- Top mass is not the constant of nature
- Its value depends on the energy scale, driven by α_s , and predicted by QFT
- First experimental evidence for **running top mass**
- Consistent with QCD to first order

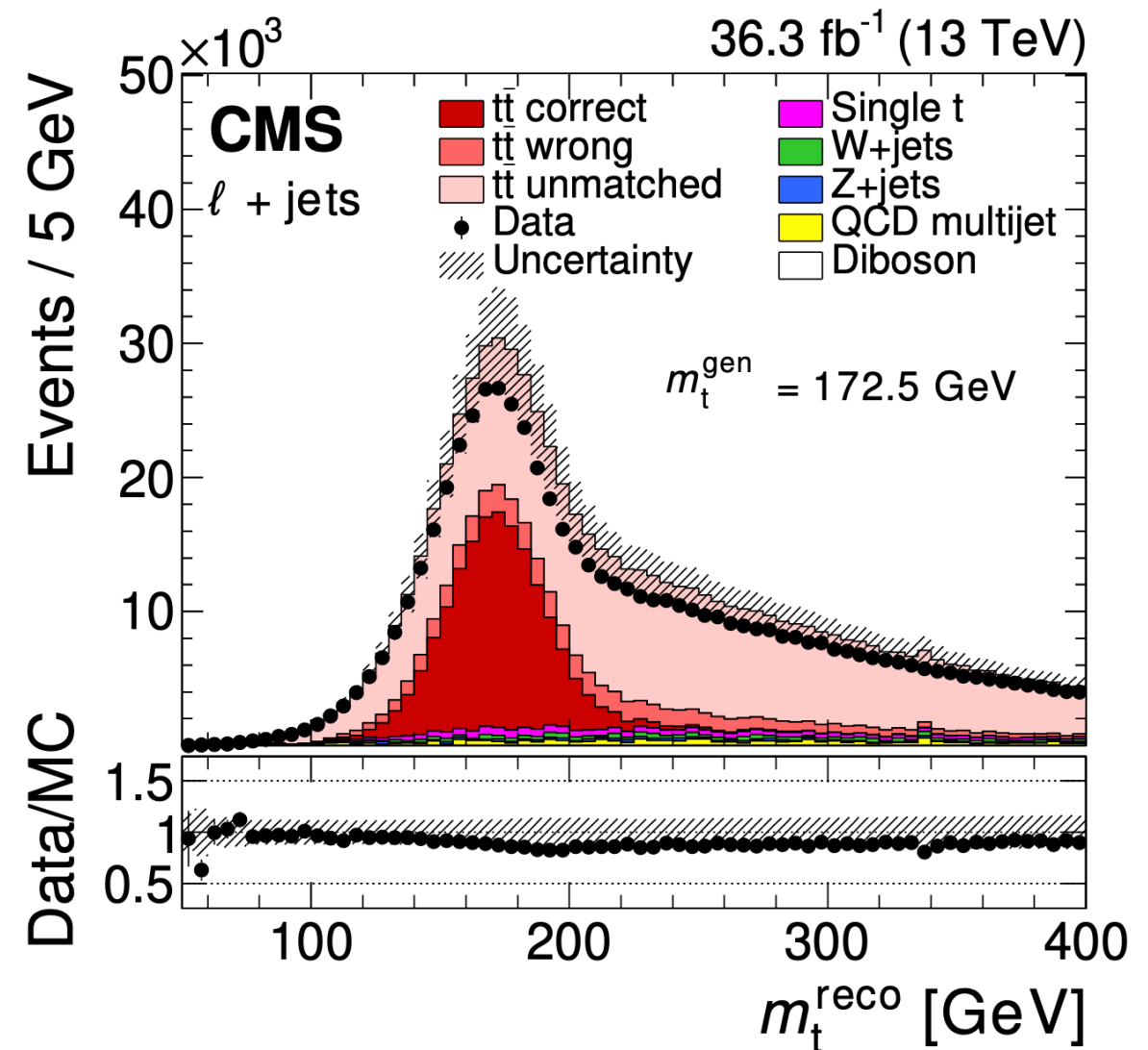
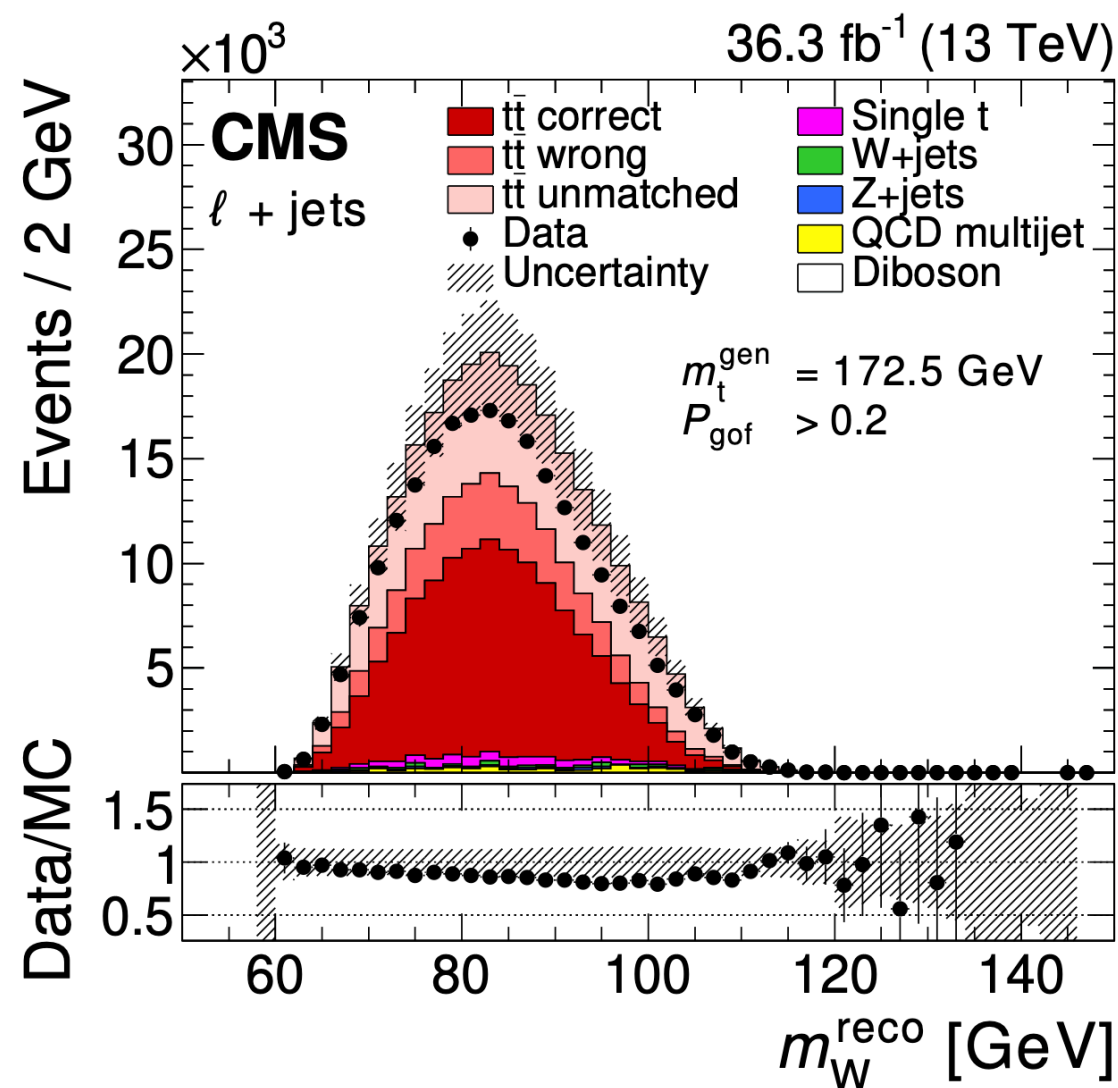
$$\mu^2 \frac{dm(\mu)}{d\mu^2} = -\gamma(\alpha_s(\mu)) m(\mu)$$

PLB 803 (2020) 135263

The precision frontier

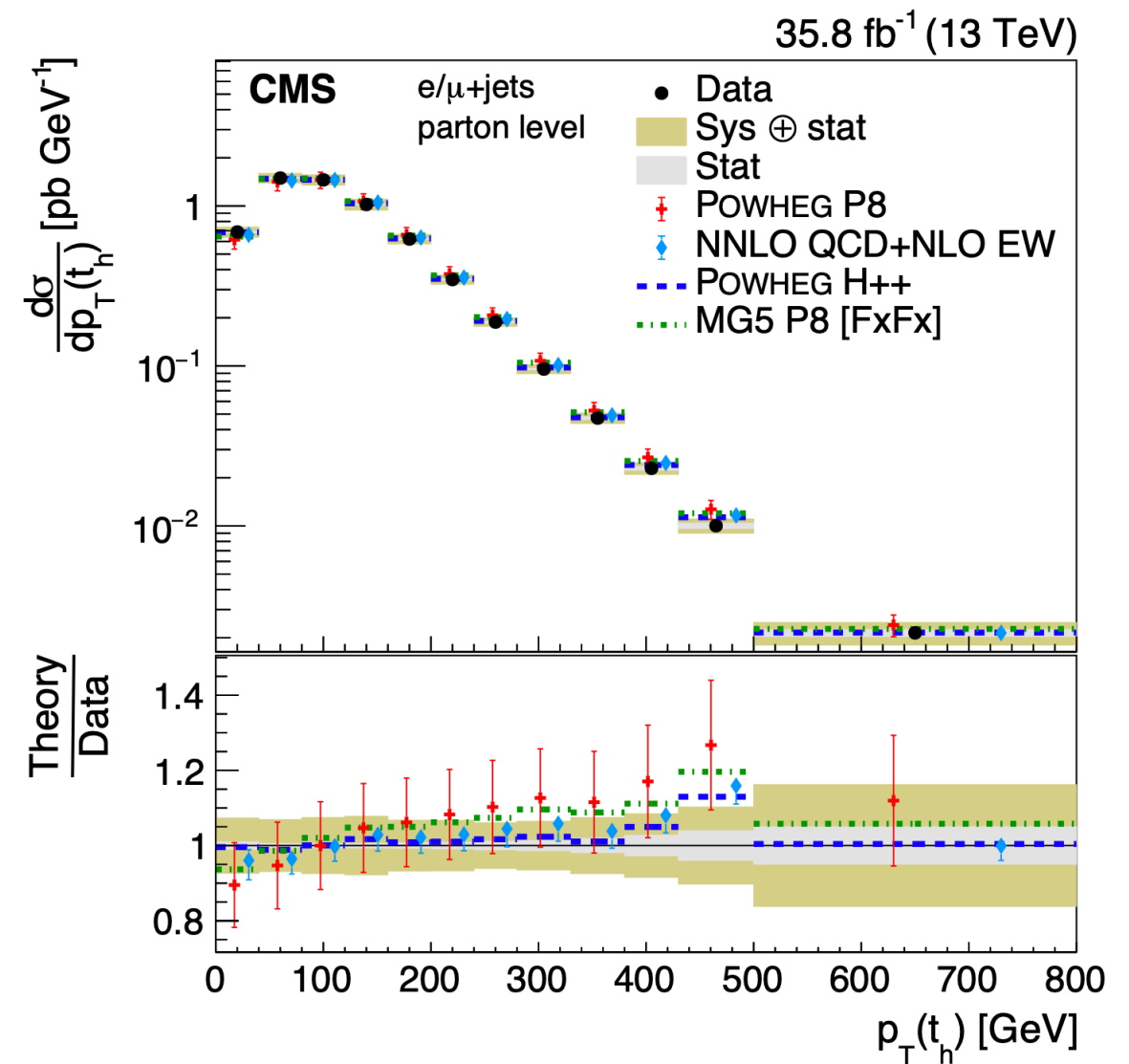
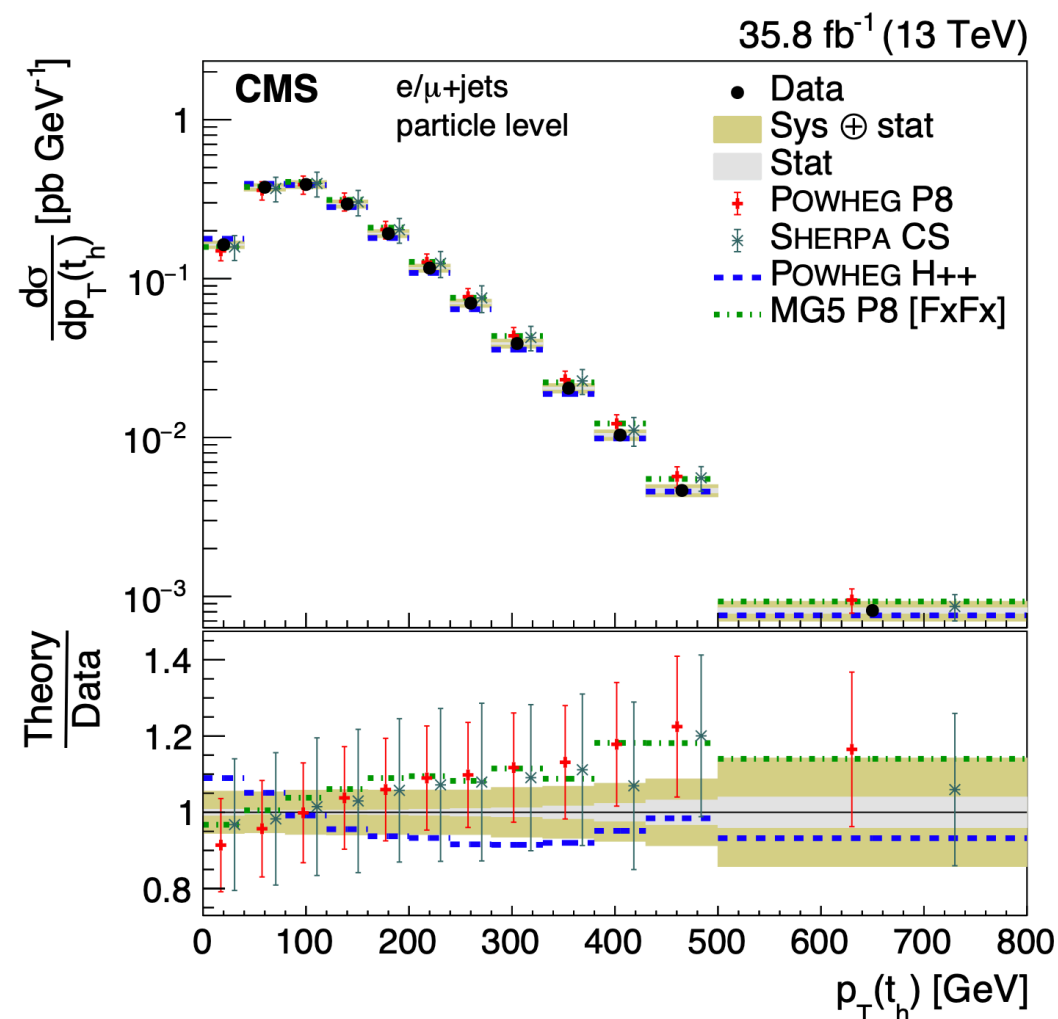
- The **most precise** top (MC) mass measurement to date: 171.77 ± 0.37 GeV
- Reconstruction of $t\bar{t}$ system for best jet-parton assignment
- Simultaneously fit multiple observables and control relevant uncertainties
- Dominated by systematics (b jet response, fragmentation, modelling)

EPJC 83 (2023) 963



Top goes differential

- Large data sample enables detailed measurements of top quark properties and kinematics
- Compare to theory (**unfolding**): detector $\rightarrow$ particle $\rightarrow$ parton
 - Detector = reconstruction
 - Particle = fiducial
 - Parton = full phase space



PRD 97 (2018) 112003

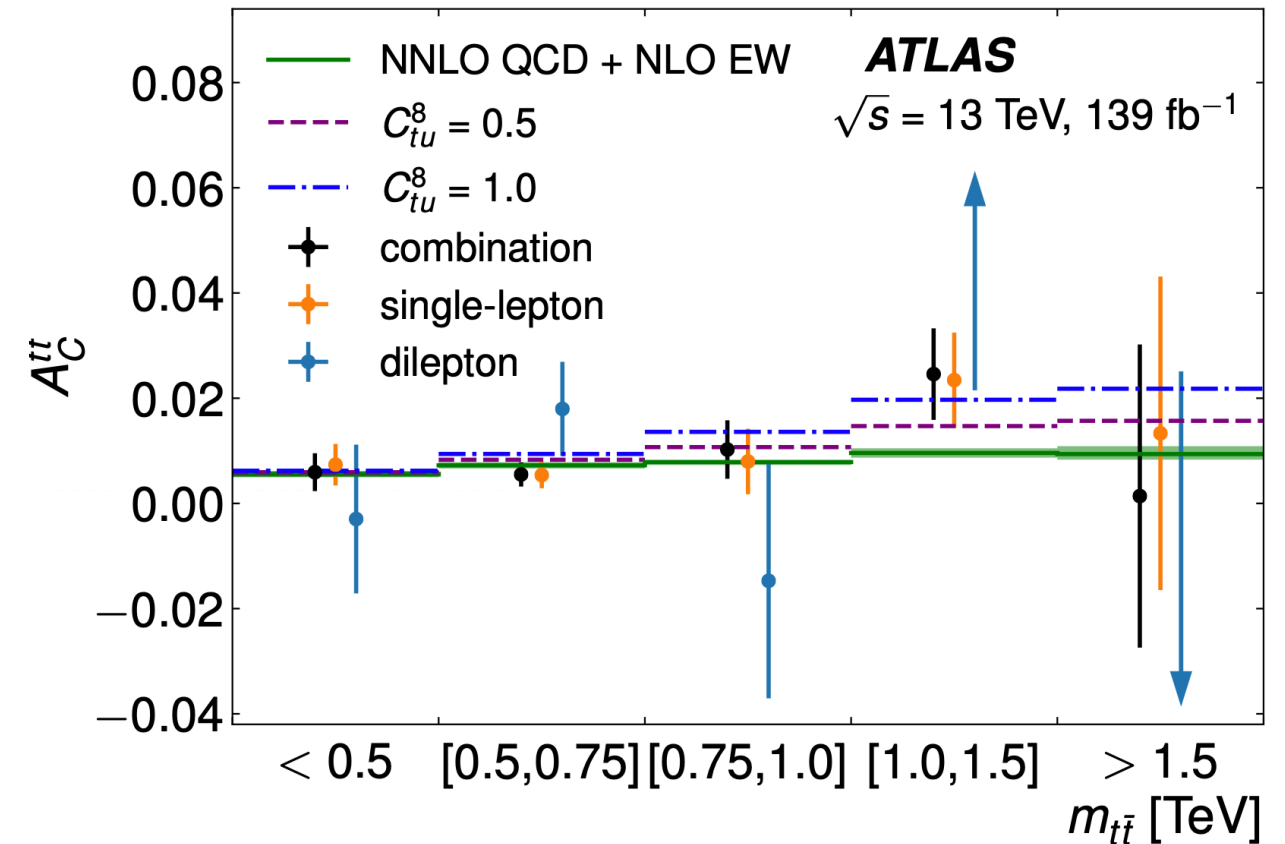
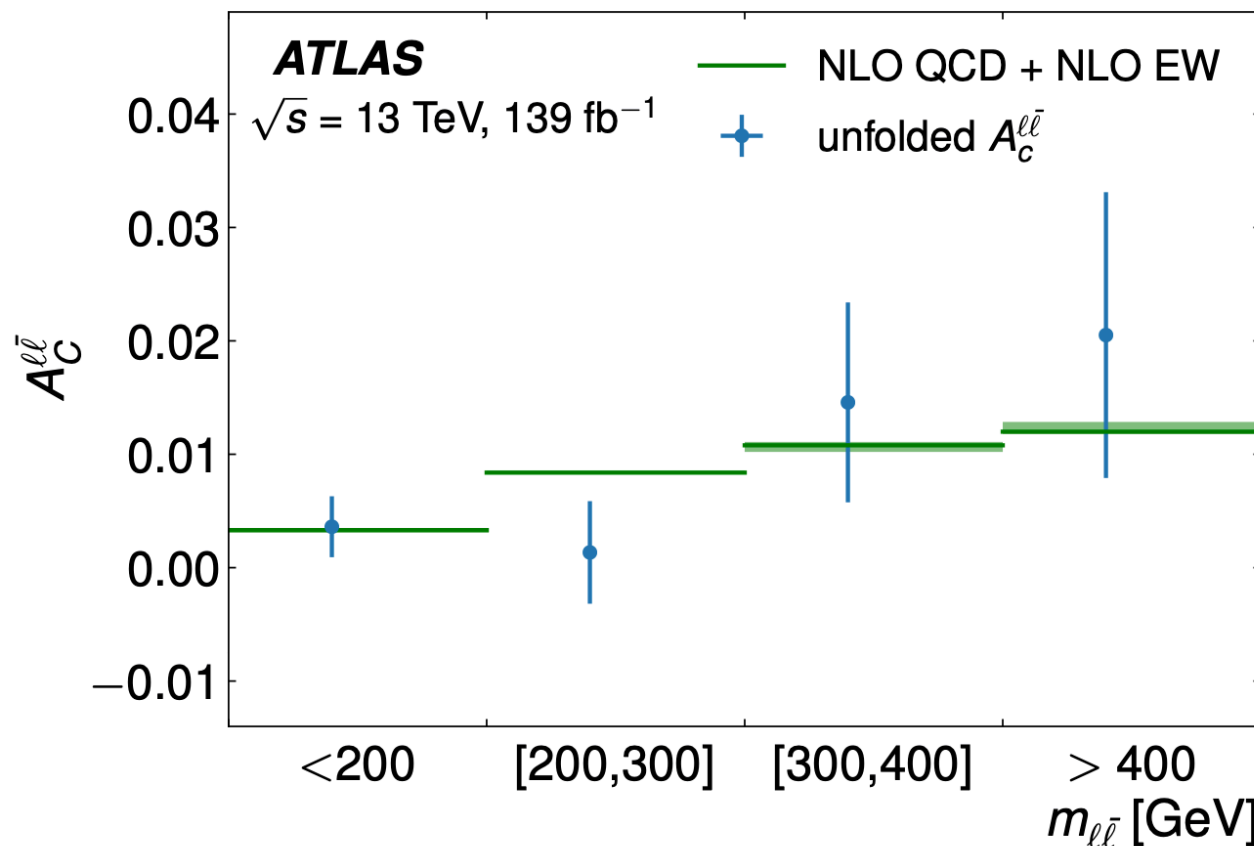
Charge asymmetry

- There is no A_{FB} at pp collider
- The initial state is symmetric: no forward or backward
- But underlying QCD asymmetry is still there
- Tops are pushed to larger rapidity, anti-tops stay central
- Small effect ($A_C \approx 0.6\%$)

JHEP 08 (2023) 077

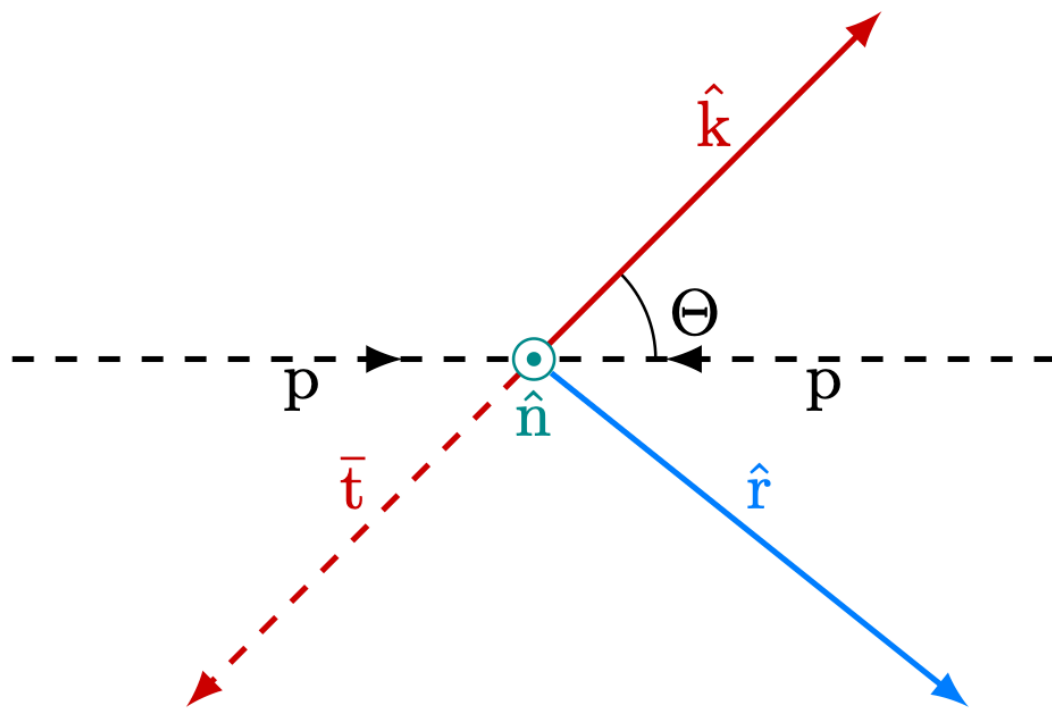
$$\Delta y = |y_t| - |y_{\bar{t}}|$$

$$A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$$

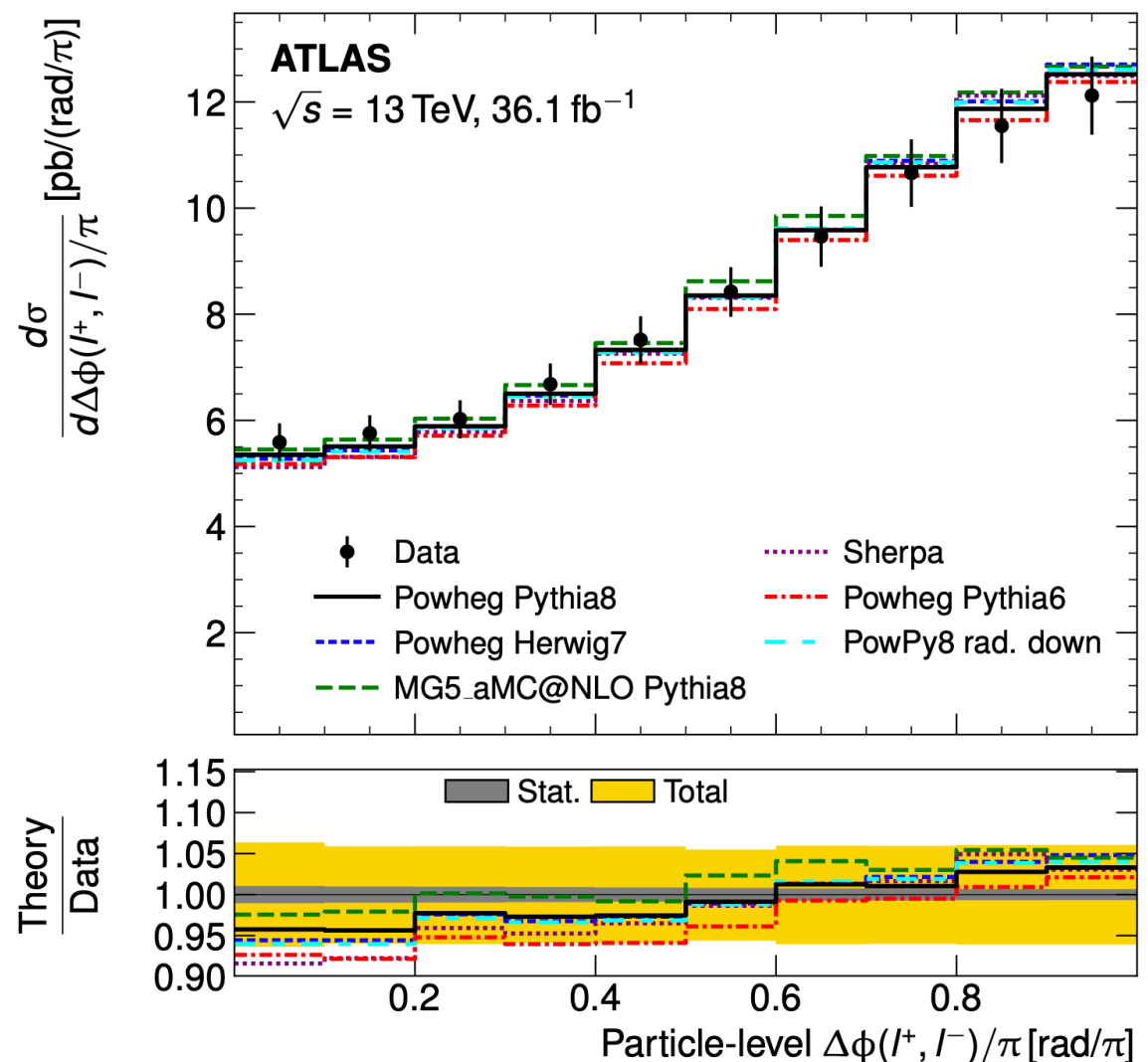


Spinning tops

- Top decays before it hadronizes or depolarizes $\rightarrow$ spin information is preserved
- Top lifetime ($\approx 5 \times 10^{-25}$ s) $<$ hadronization ($\approx 10^{-24}$ s) $<$ spin-flip ($\approx 10^{-21}$ s)
- $t \rightarrow Wb \rightarrow \ell \nu b$: lepton is a near-perfect spin-analyzer
- Spins of top and anti-top are **correlated** by QCD production



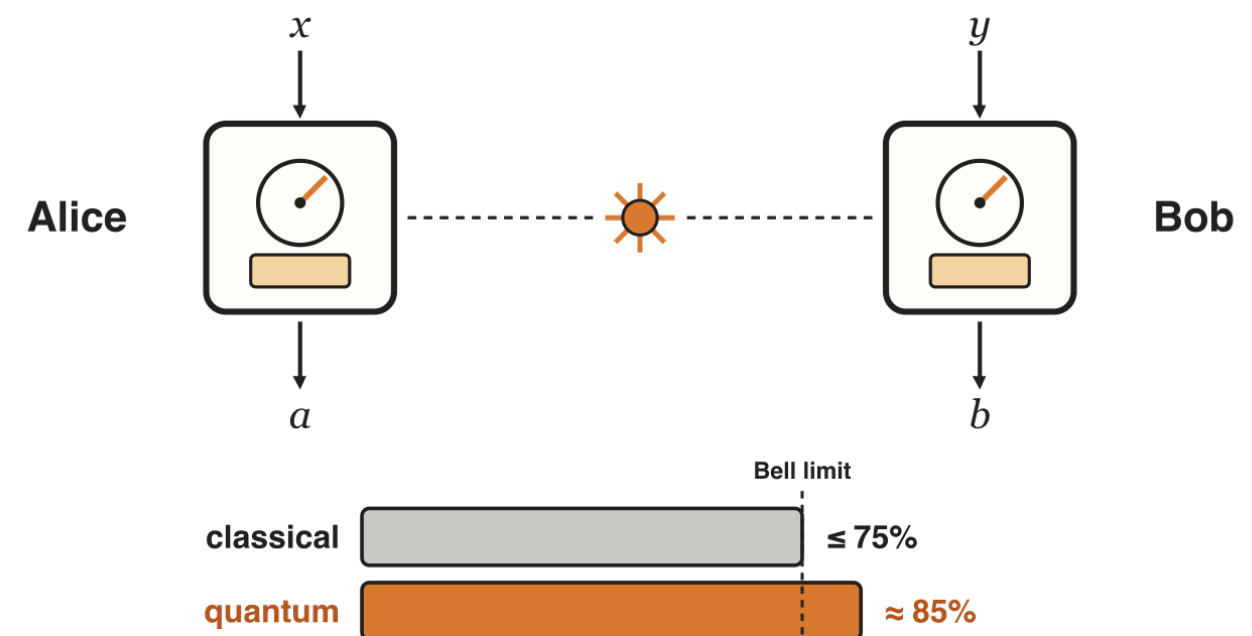
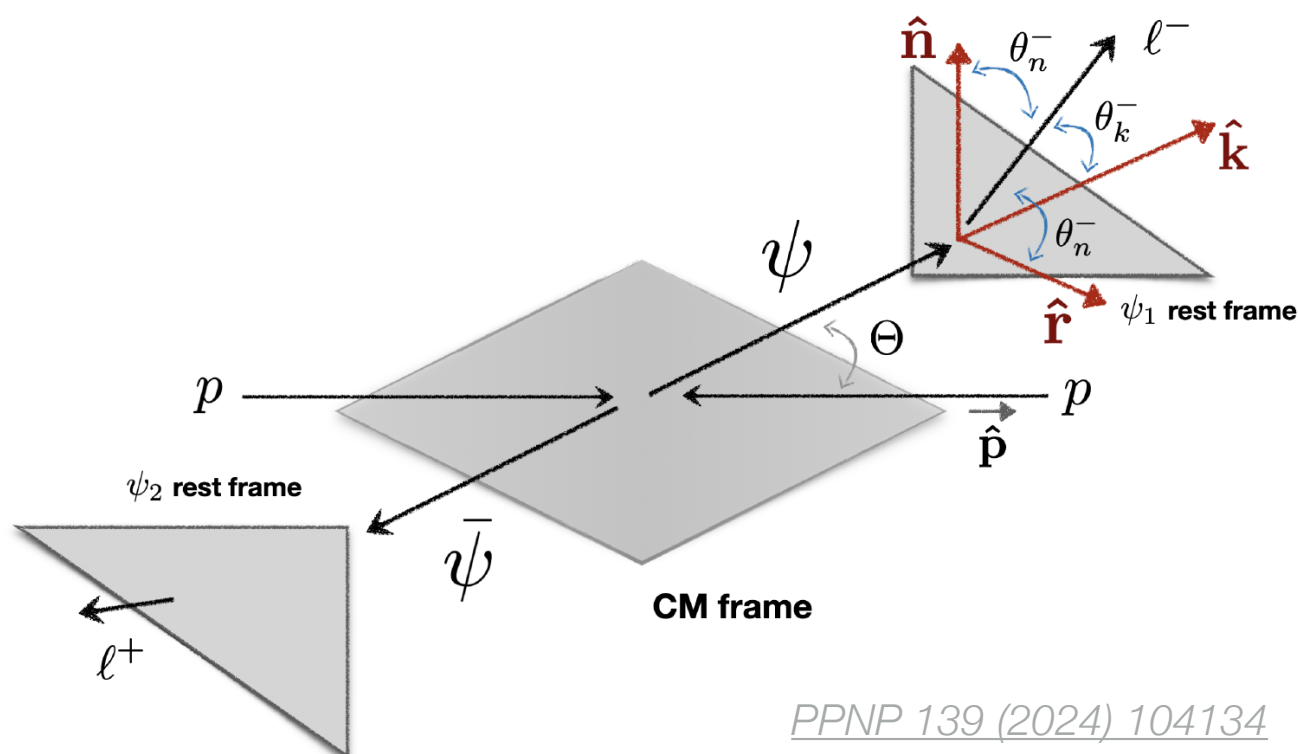
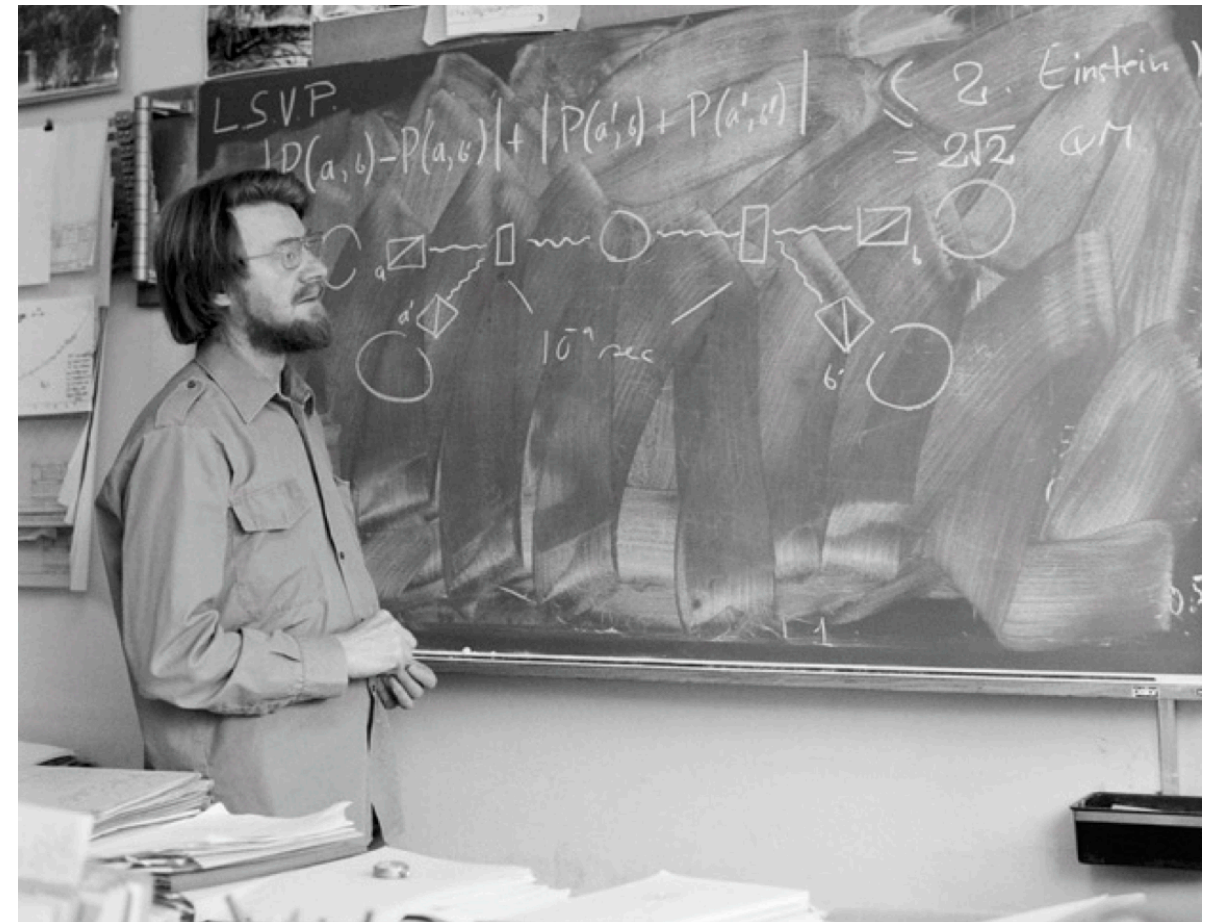
PRD 100 (2019) 072002



EPJC 80 (2020) 754

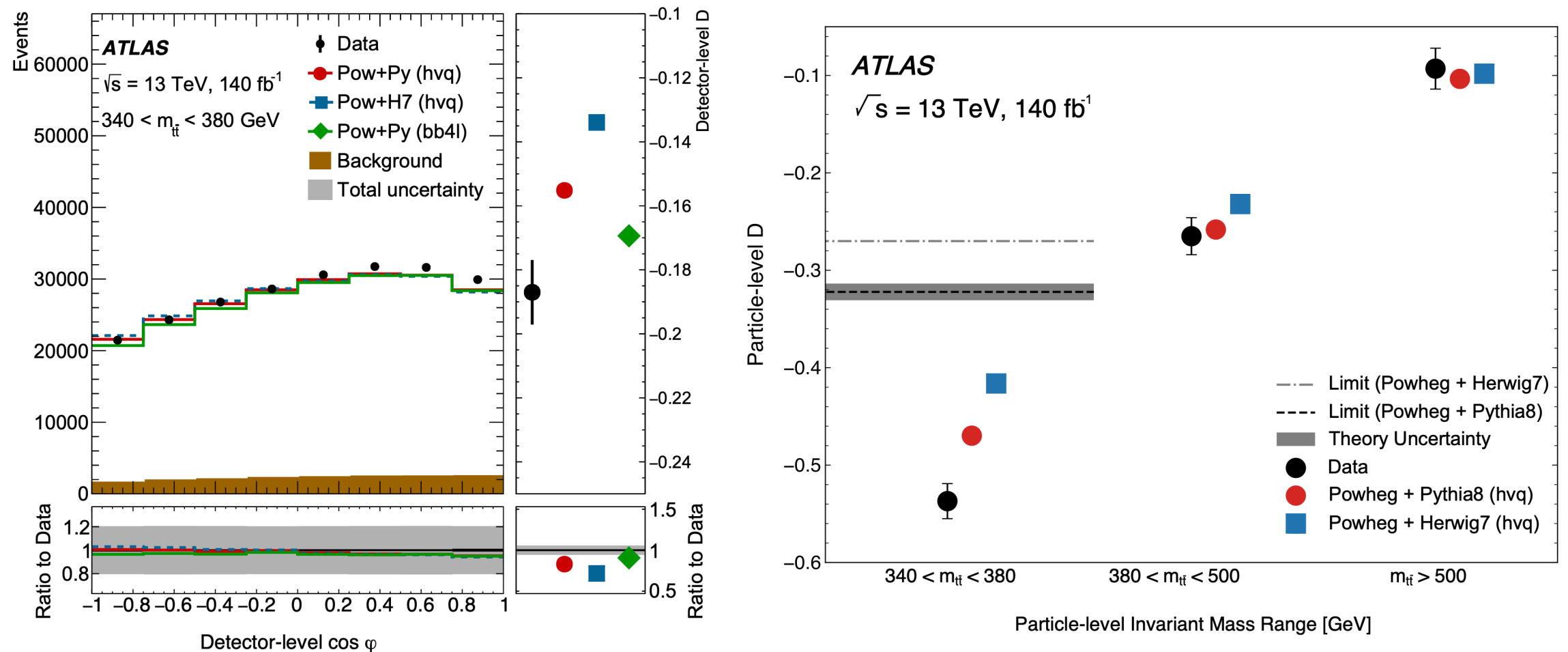
Going quantum

- Classical bit = 0, 1
- **Quantum bit** = 0, 1, and infinite superposition states
- Two bits $\rightarrow$ entanglement: correlations too strong for any classical system
- Bell's inequality: quantum correlations exceed the classical limit $\rightarrow$ outcomes are not predetermined



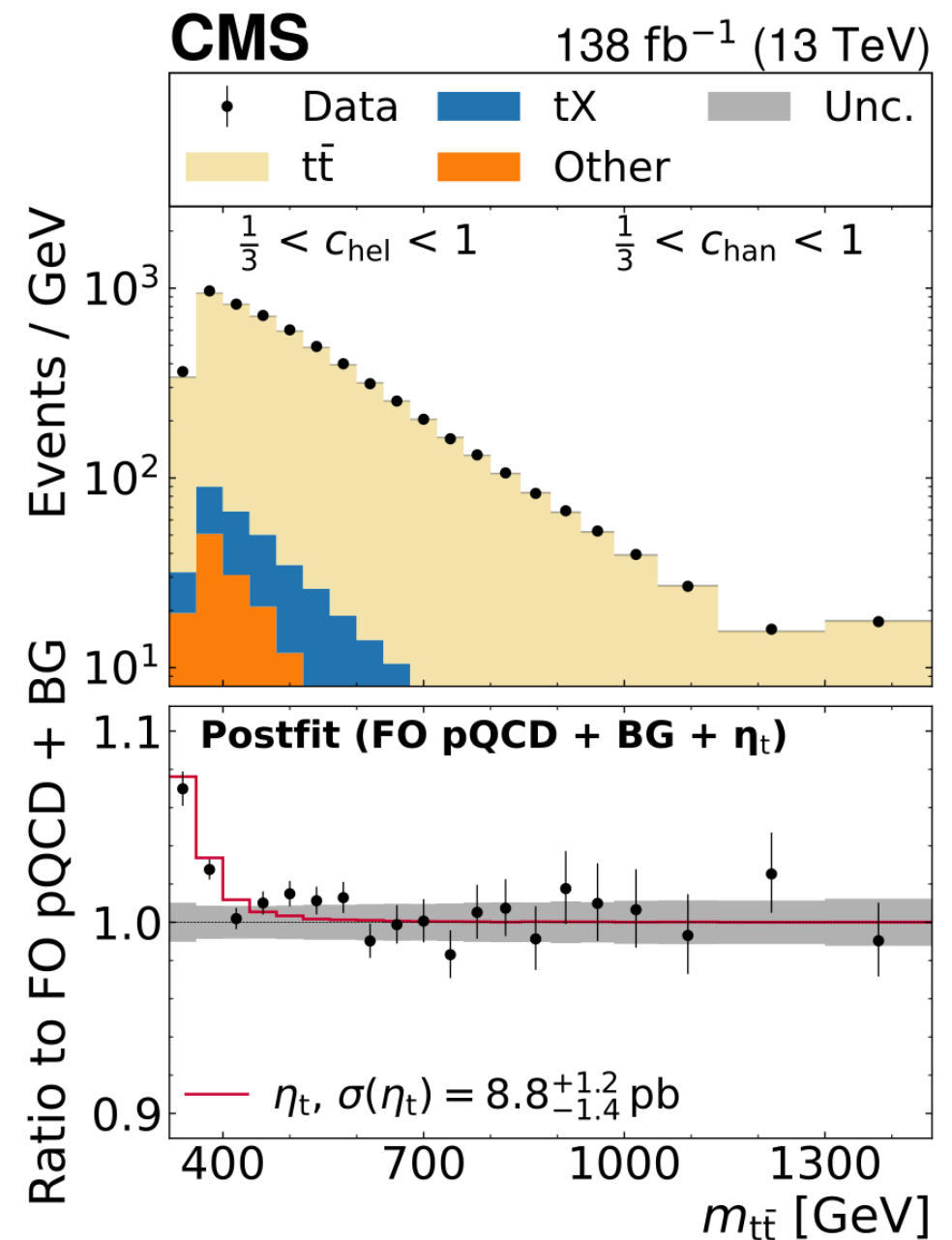
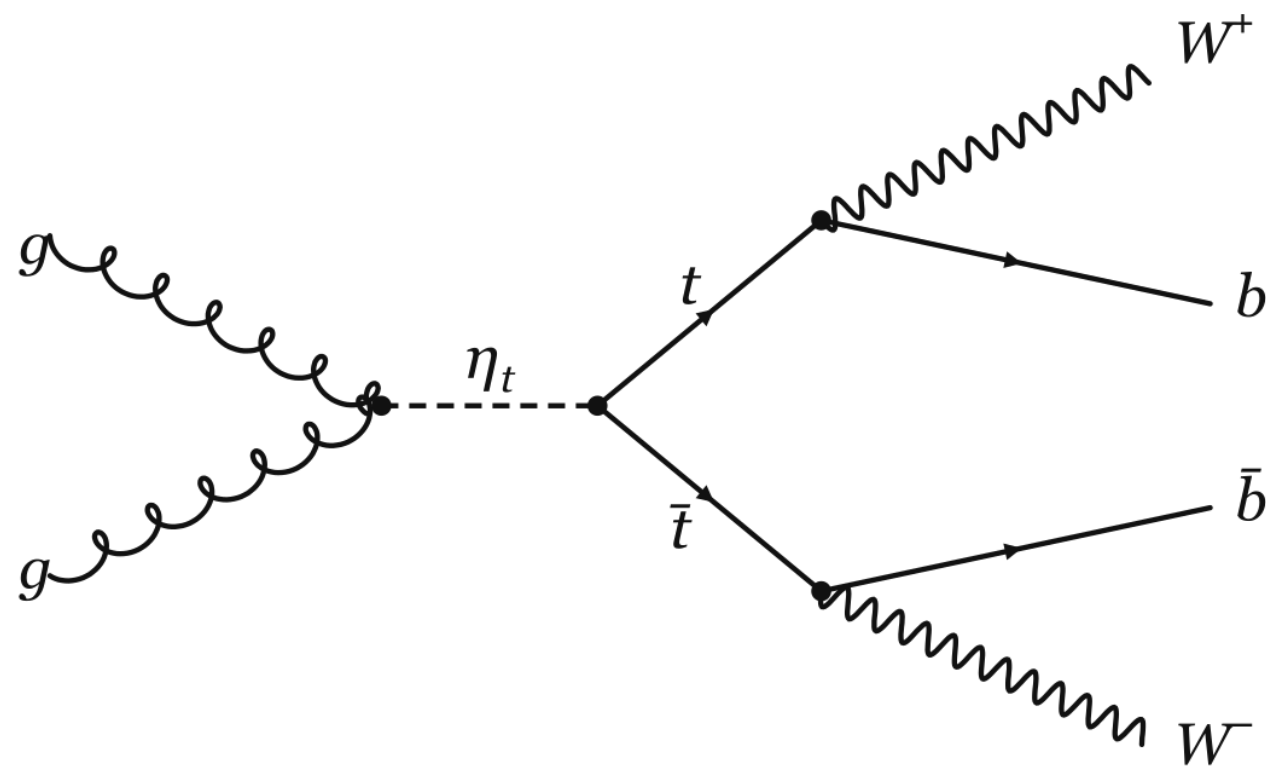
Entanglement

- Spins in a $t\bar{t}$ system form a two qubit state
- Top quark spins **maximally correlated** near the threshold
- Construct spin correlation matrix ($\mathbf{C}$) from two lepton directions
- Entanglement parameter: $\mathbf{D} = \text{Tr}[\mathbf{C}]/3$
- Classical correlation $\rightarrow$ entanglement ($\mathbf{D} < -1/3$) $\rightarrow$ Bell nonlocality
- Recently observed!



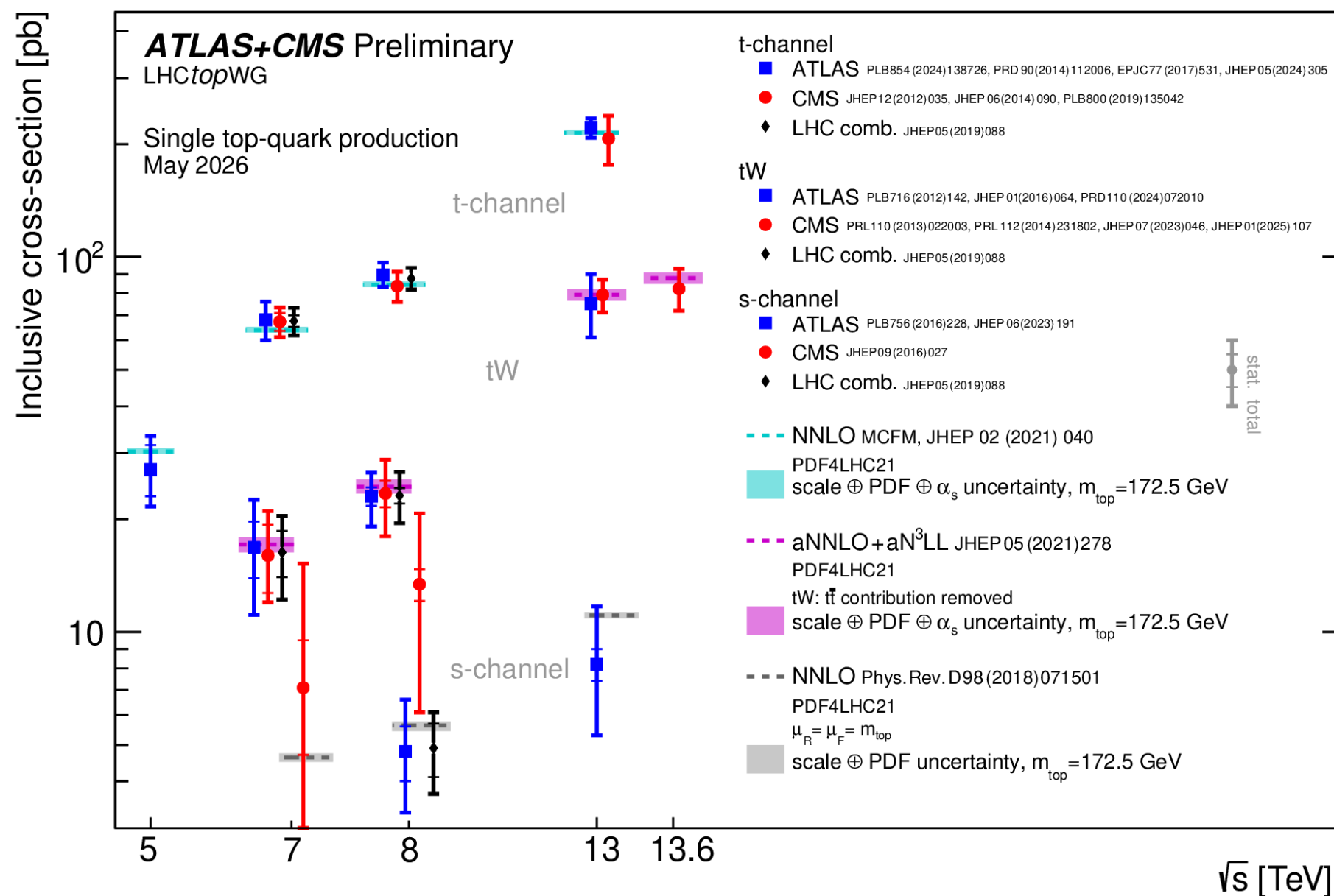
Toponium

- Top quarks can form **quasi-bound states**
- Non-relativistic QCD predicts a threshold enhancement
- A color-singlet pseudo-scalar η_t ($m \approx 343$ GeV, width ≈ 2.8 GeV)
- Same threshold physics as entanglement
- Observed as well!
- Hard to simulate: simplified models are used



Single top

- Precision EW physics
- **All three channels** established at the LHC
- Special modeling treatment for tW at NLO (interferes with $t\bar{t}$)
- A powerful BSM probe and rare process study



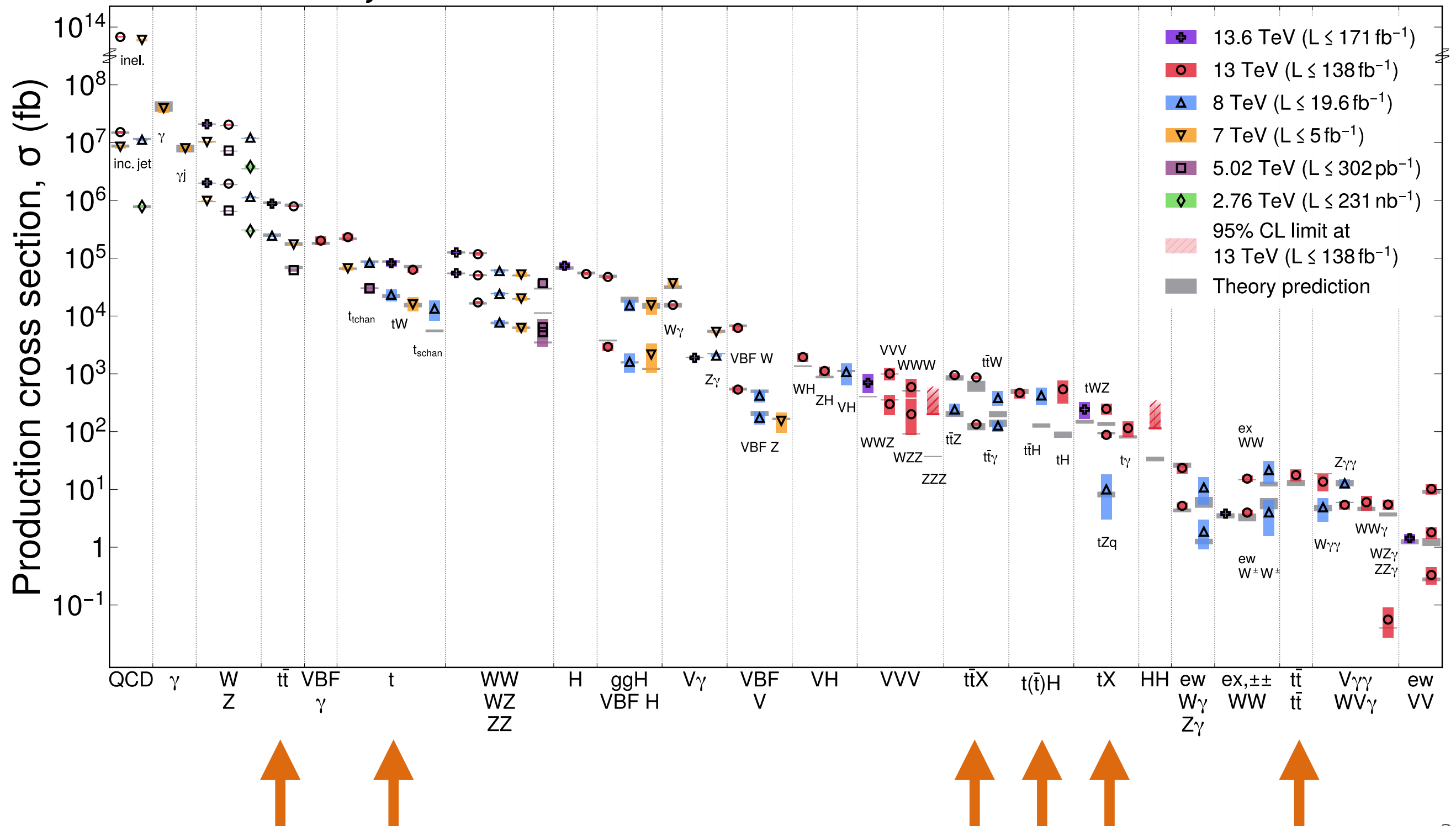
LHCtopWG Summary Plots

SM ladder

CMS Preliminary

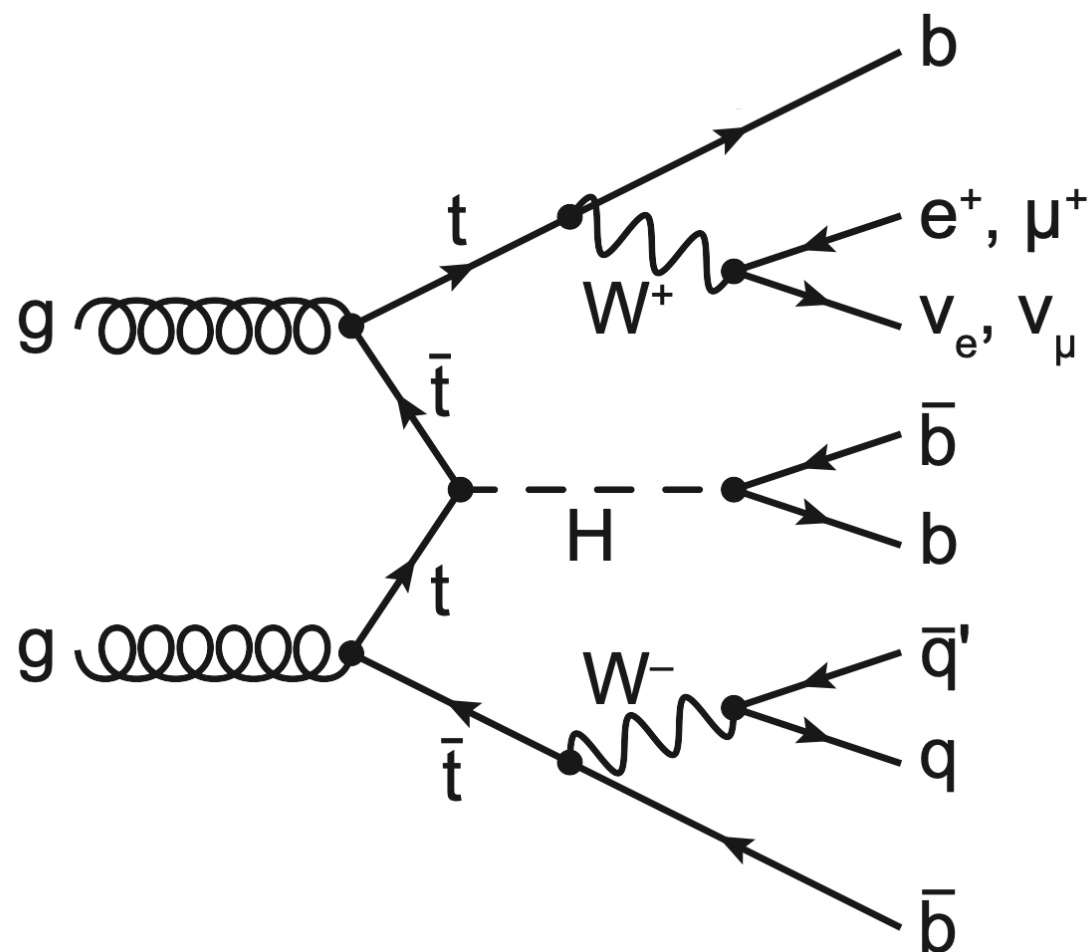
CMS SM Summary Plots

March 2026

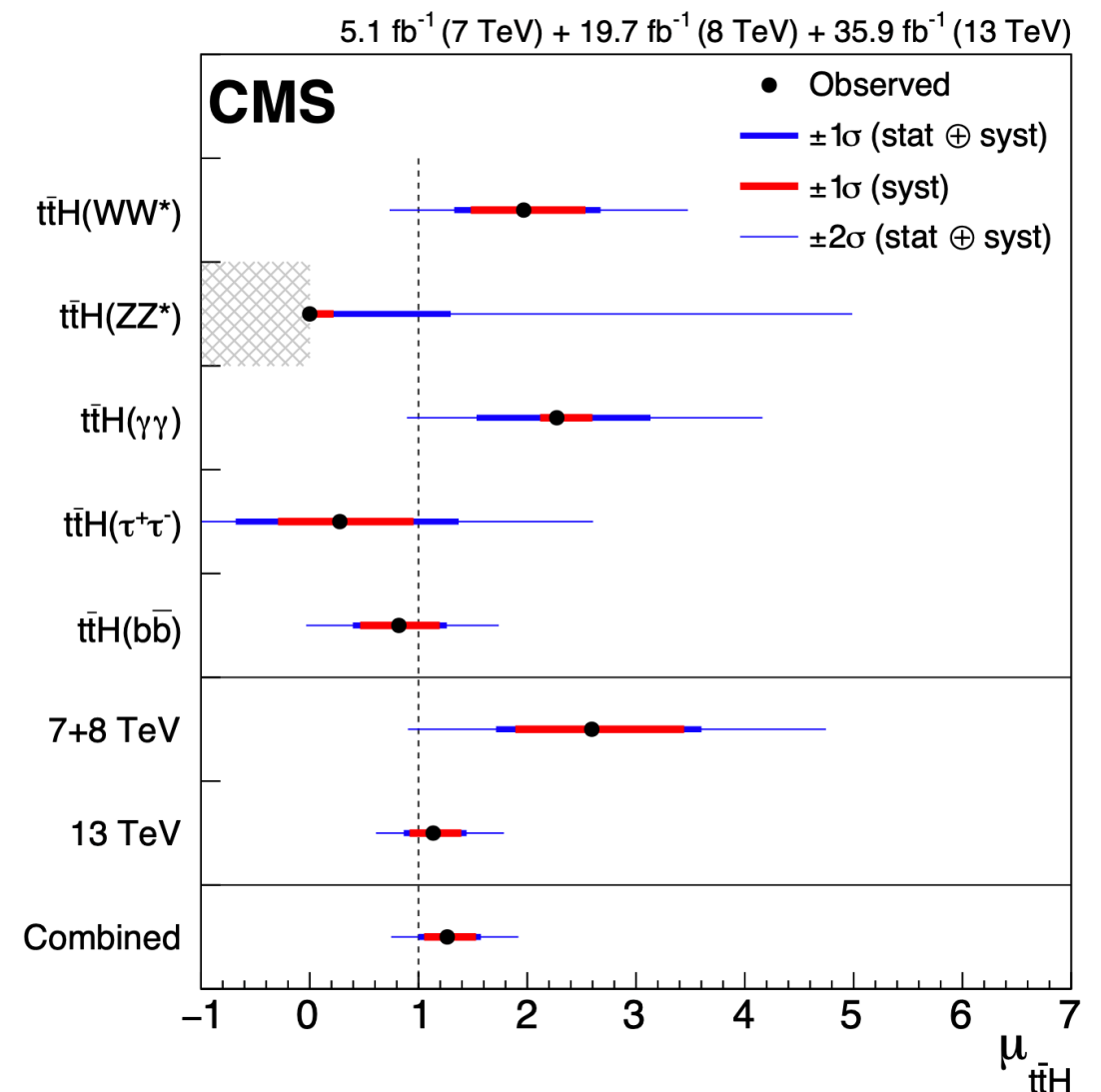


Top meets Higgs

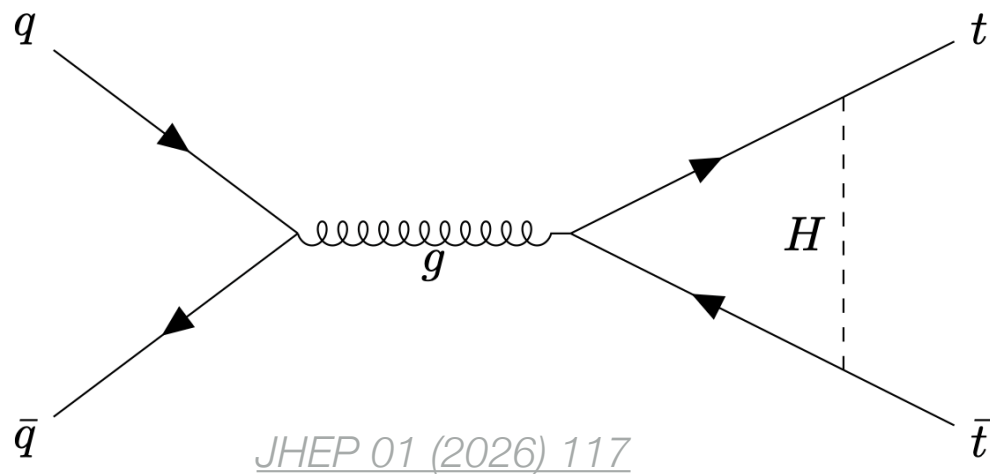
- **Yukawa** interaction: fermion coupling to the Higgs field
- The only access to the tree-level top quark Yukawa (y_t): the $t\bar{t}h$ process
- Large $y_t \approx 1$ due to the heavy top, $y_f = \sqrt{2}m_f/v_{\text{ev}}$
- Rare process with complex final states



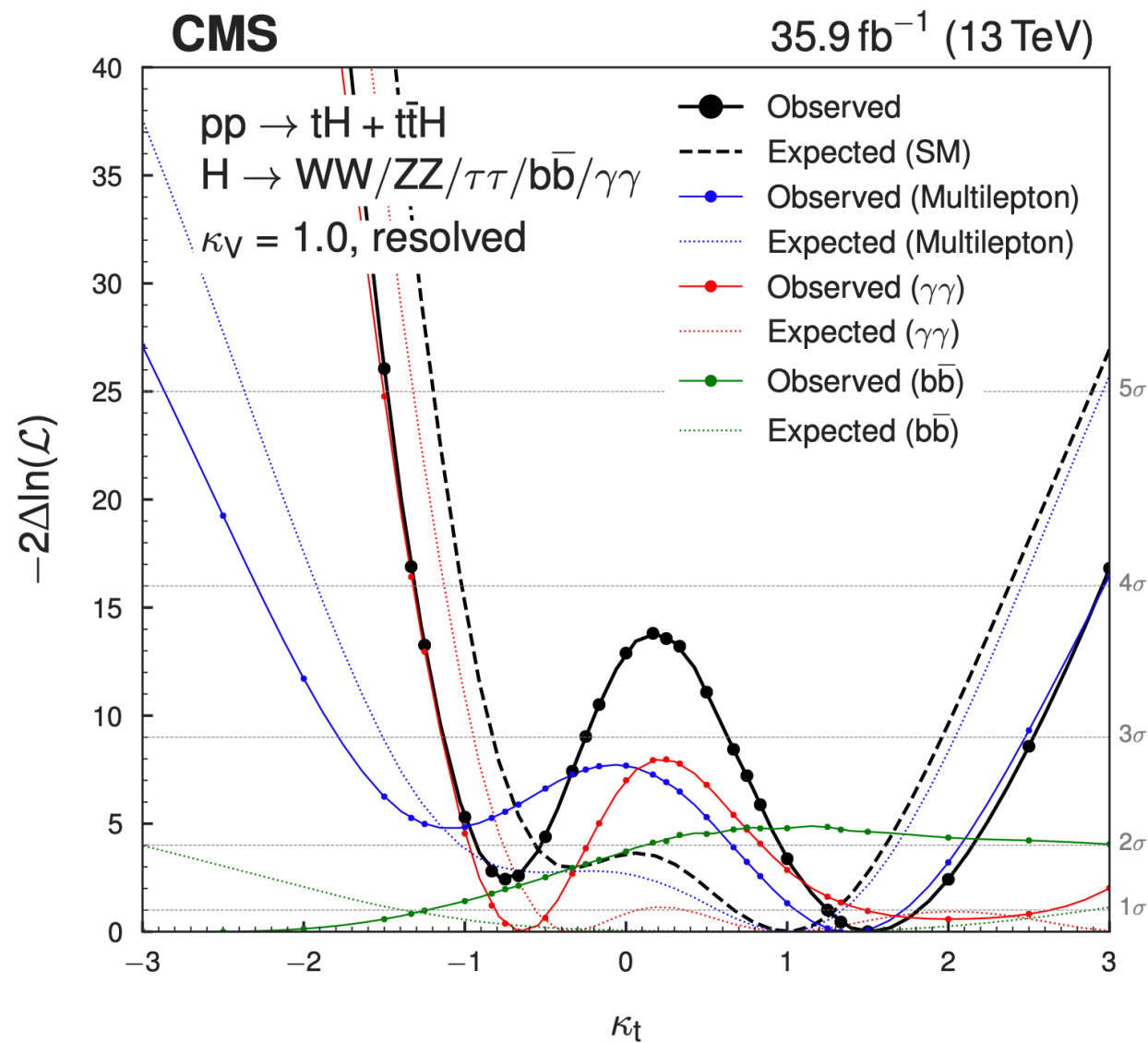
JHEP 03 (2019) 026



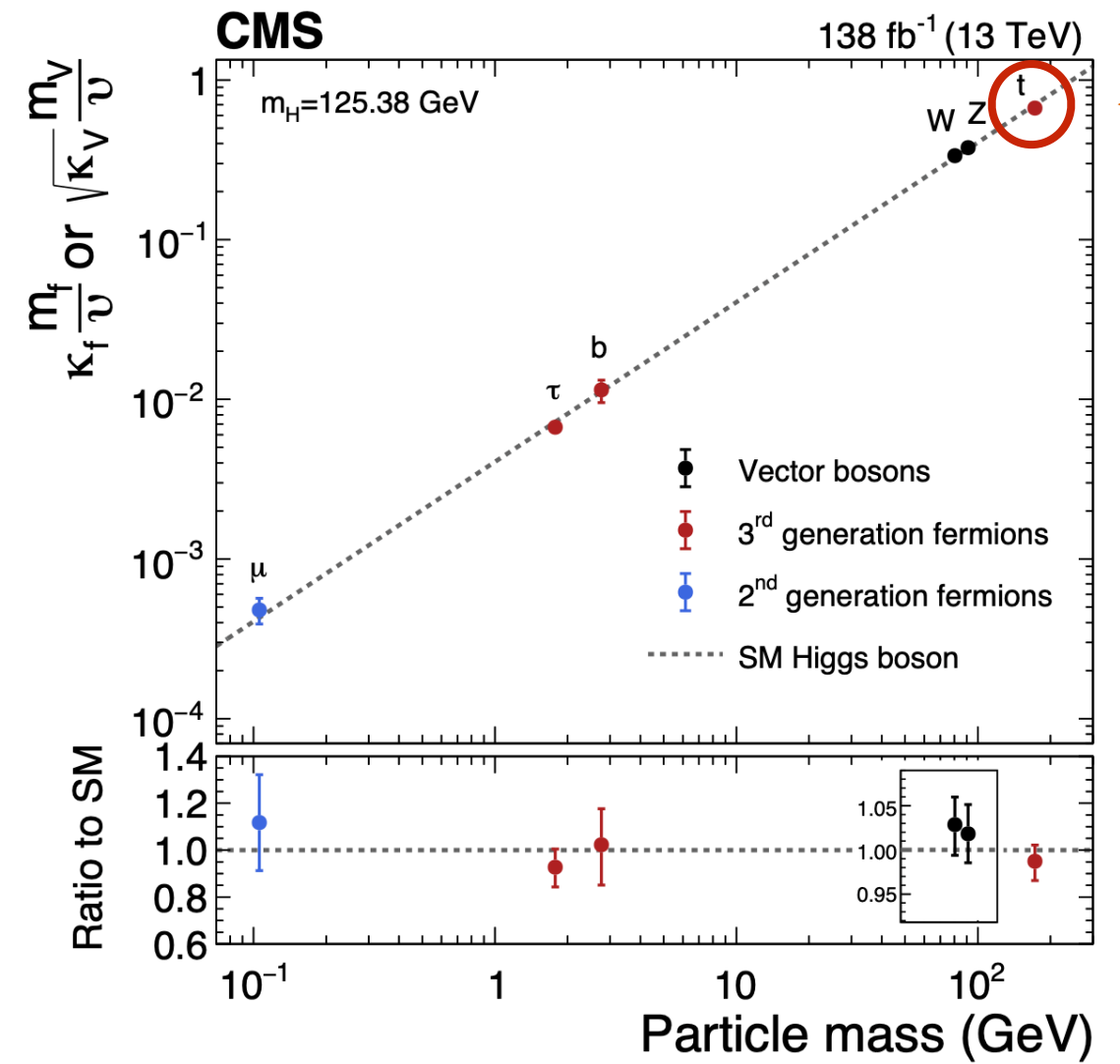
Top Yukawa



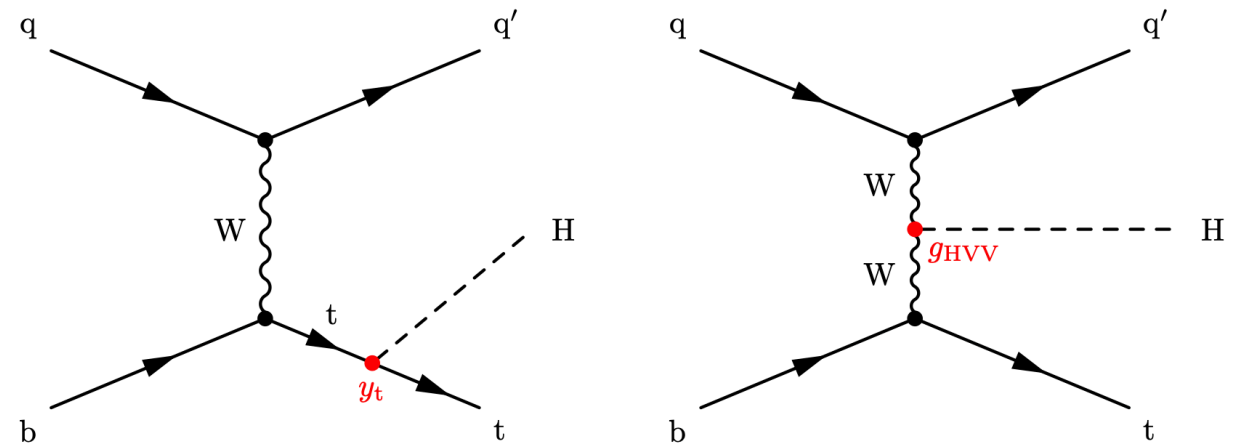
JHEP 01 (2026) 117



PRD 99 (2019) 092005

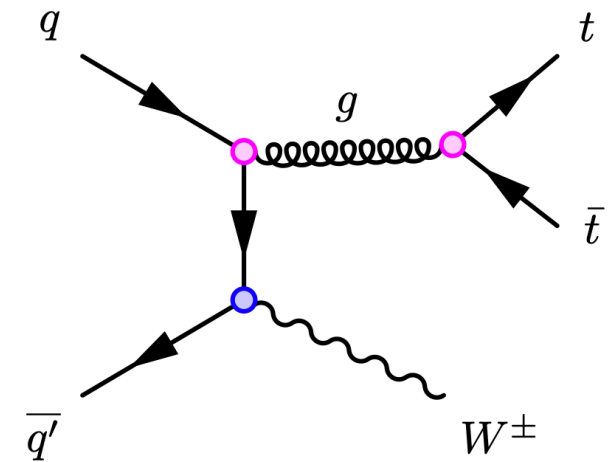


Nature 607 (2022) 60

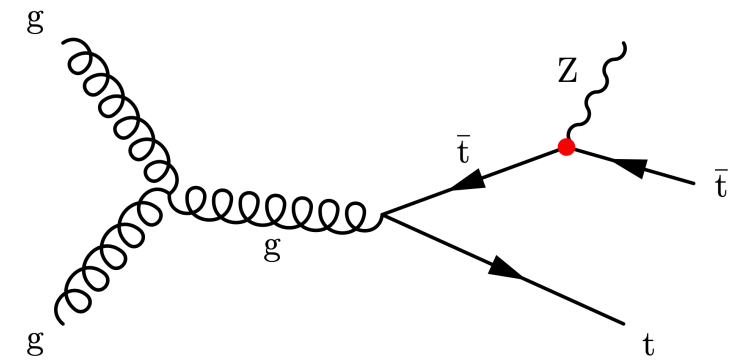


Top friends

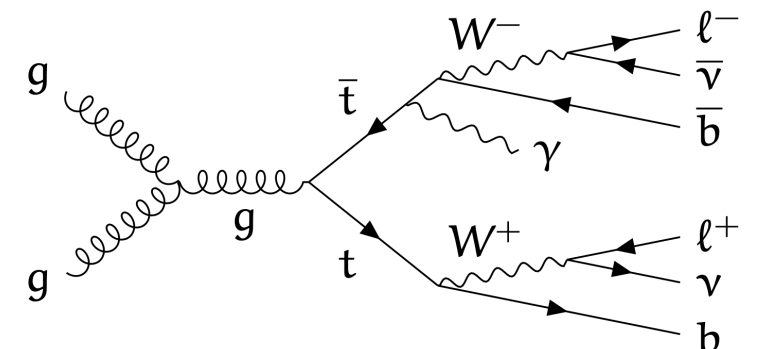
- The LHC provided the first direct access to top EW couplings
- **Associated production** of top with vector bosons (Z , W , γ)
- Considerable interplay among different $t\bar{t}X$ processes in multi-lepton channels



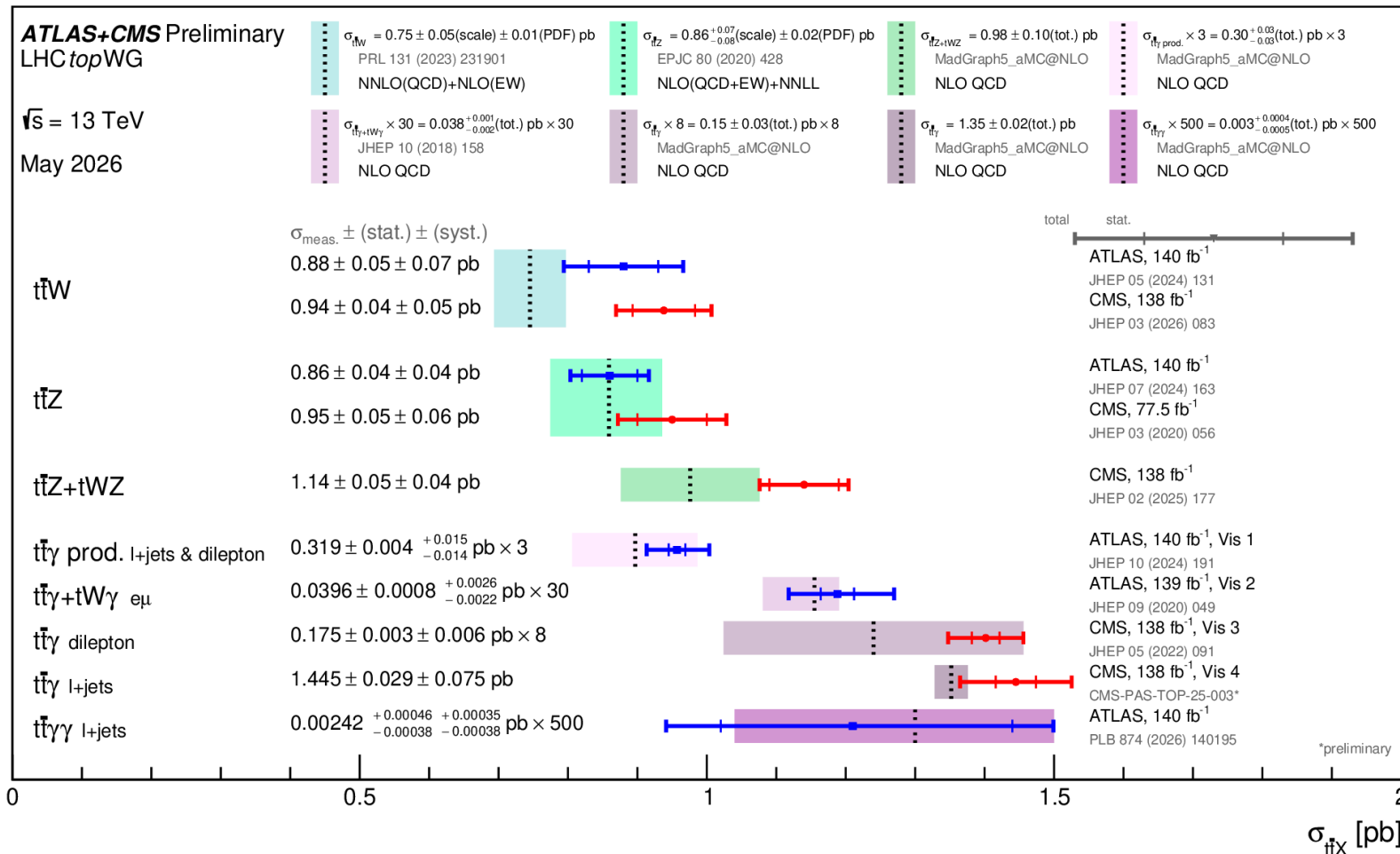
JHEP 05 (2024) 131



PLB 869 (2025) 139857

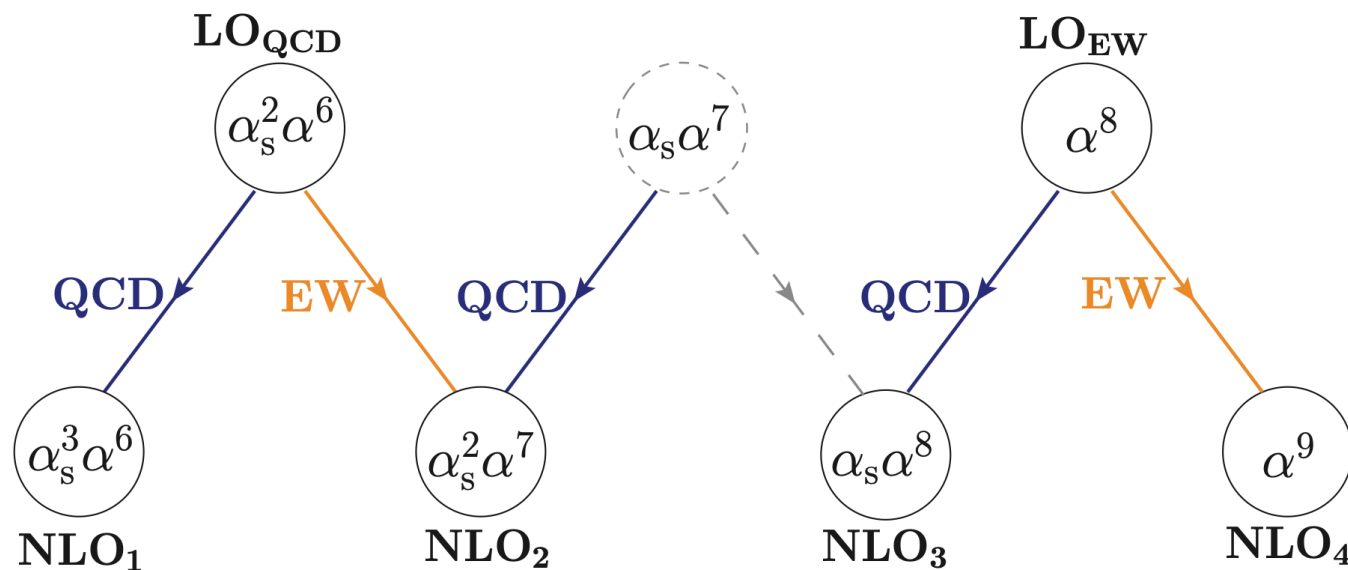


JHEP 05 (2022) 091

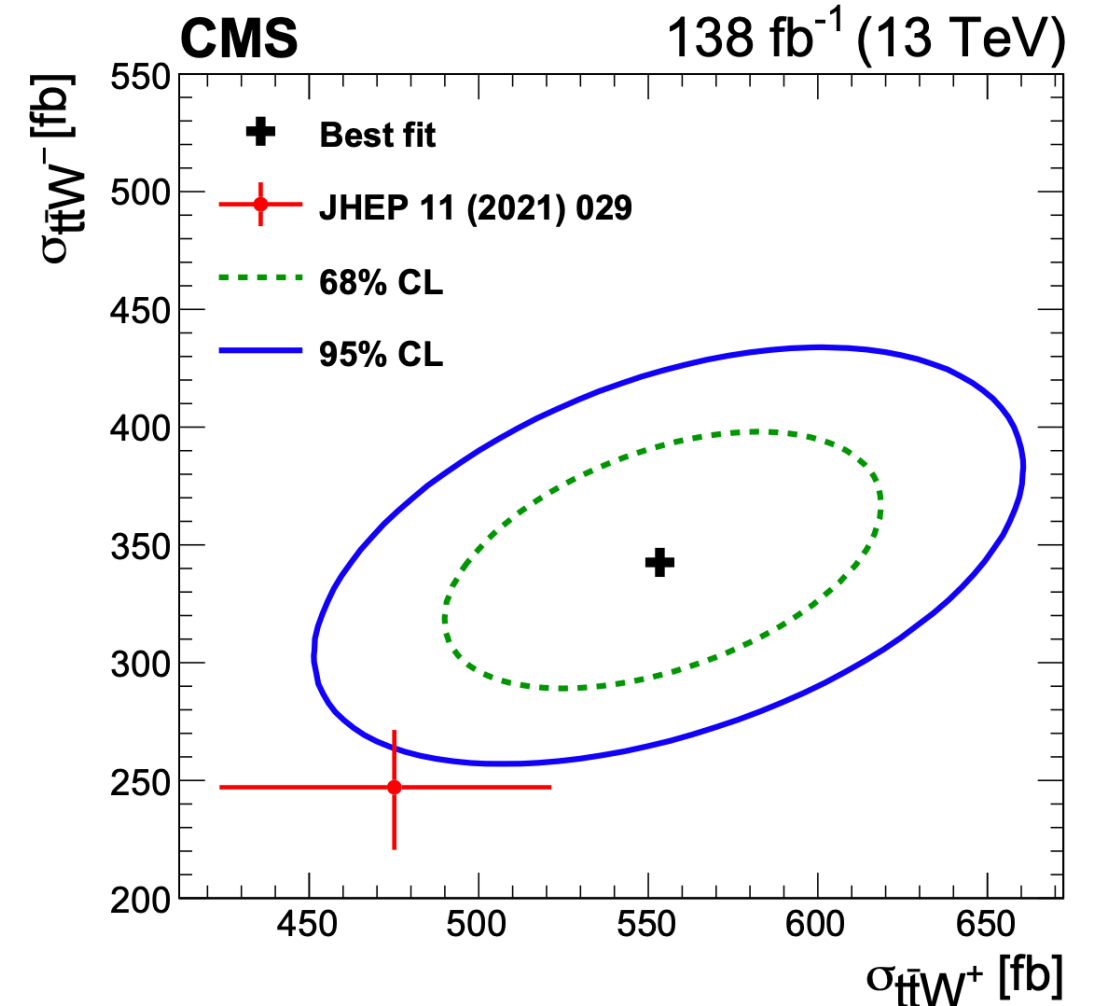


The $t\bar{t}W$ process

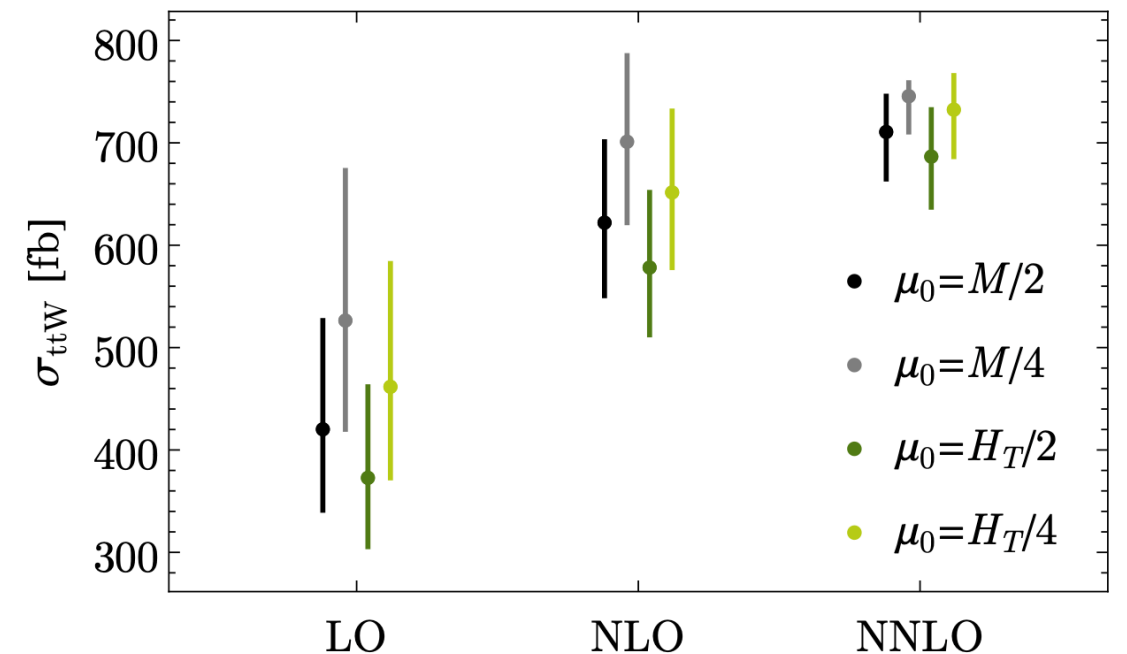
- Probes PDFs via W boson charge asymmetry
- Observed cross section larger than prediction
- Motivated advanced theoretical calculations (**very challenging**)
- Subleading EW corrections are important
- Addition of high-order corrections improves the agreement



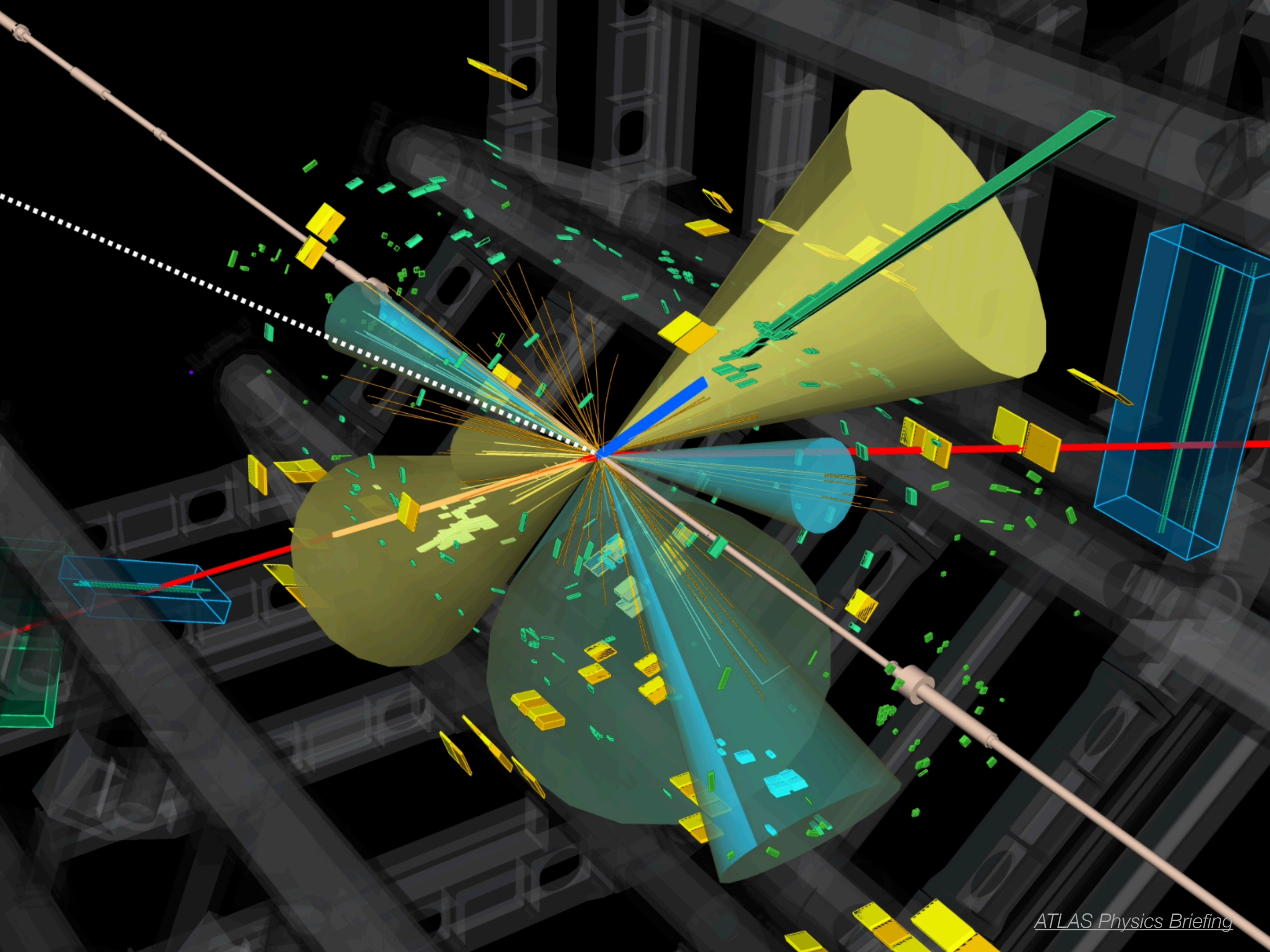
EPJC 81 (2021) 354

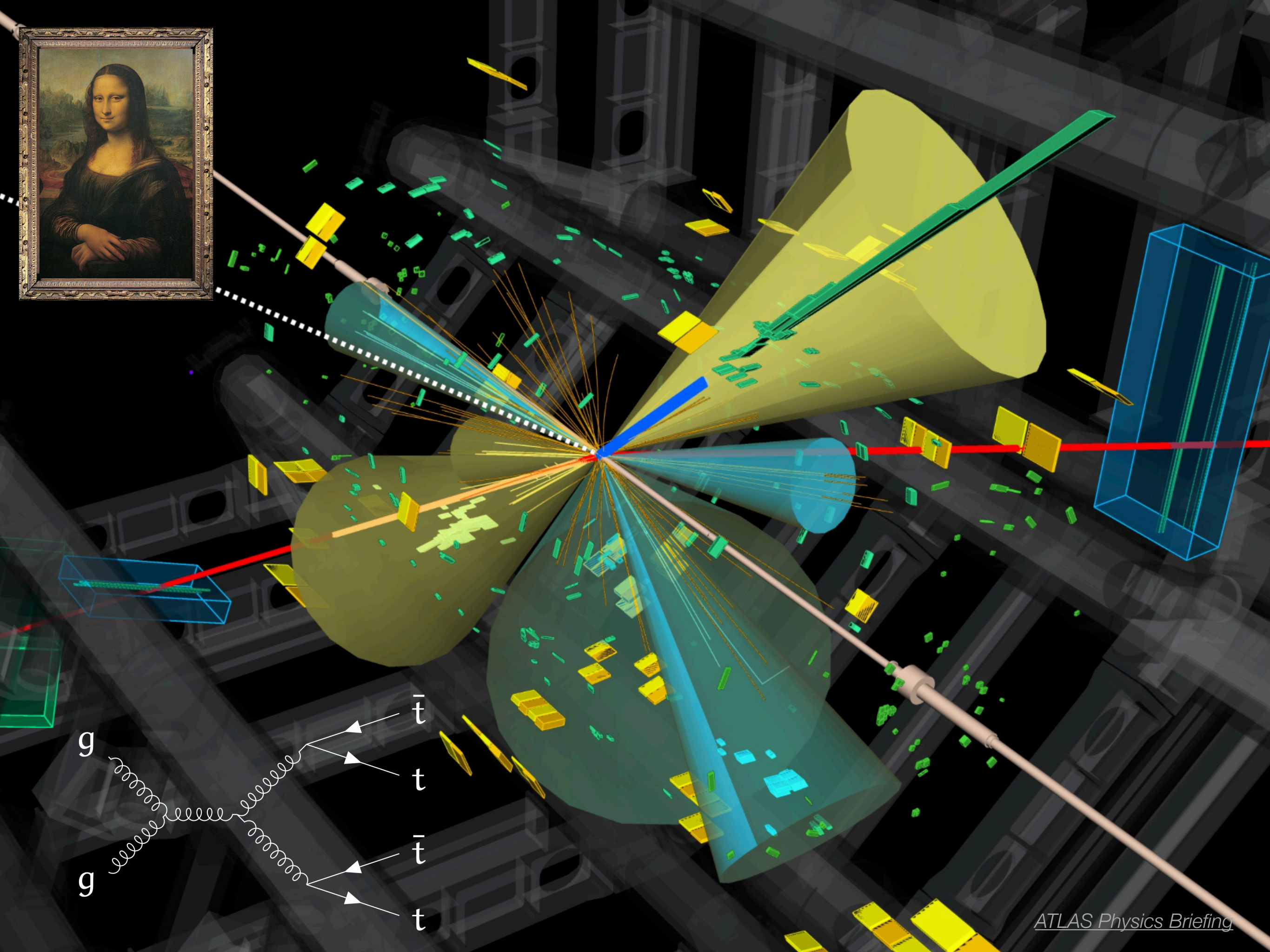


JHEP 07 (2023) 219



PRL 131 (2023) 231901



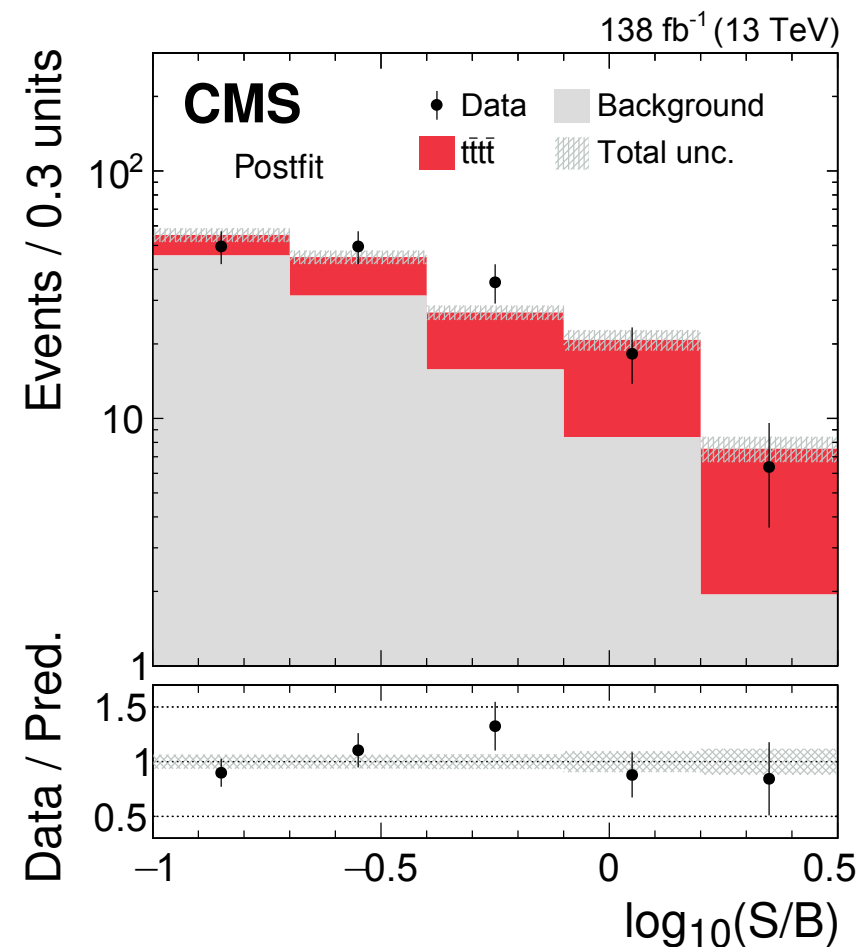
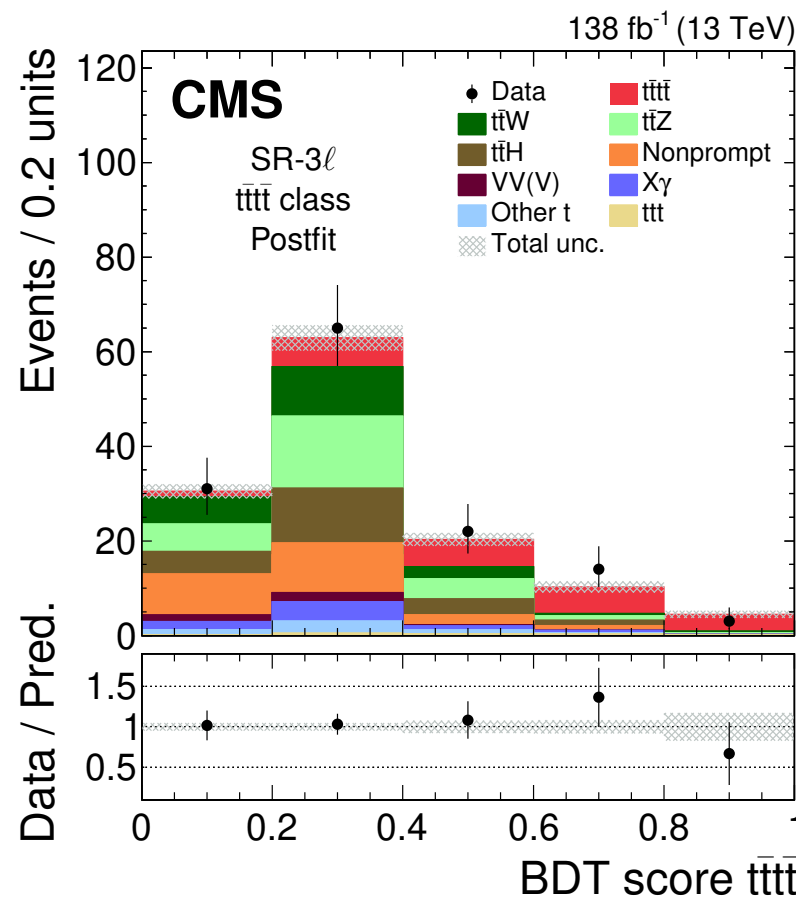
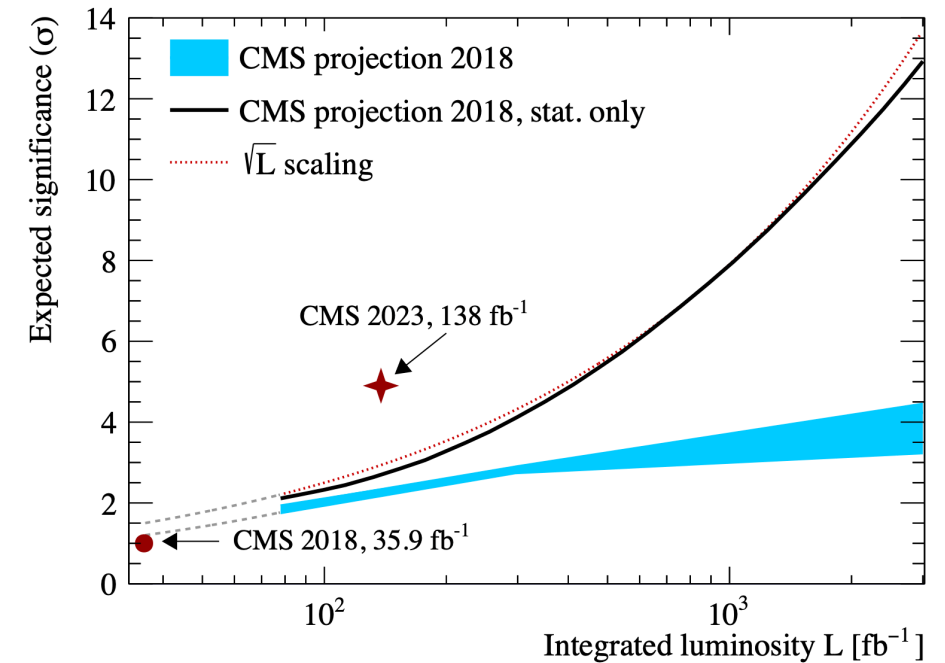


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Four tops

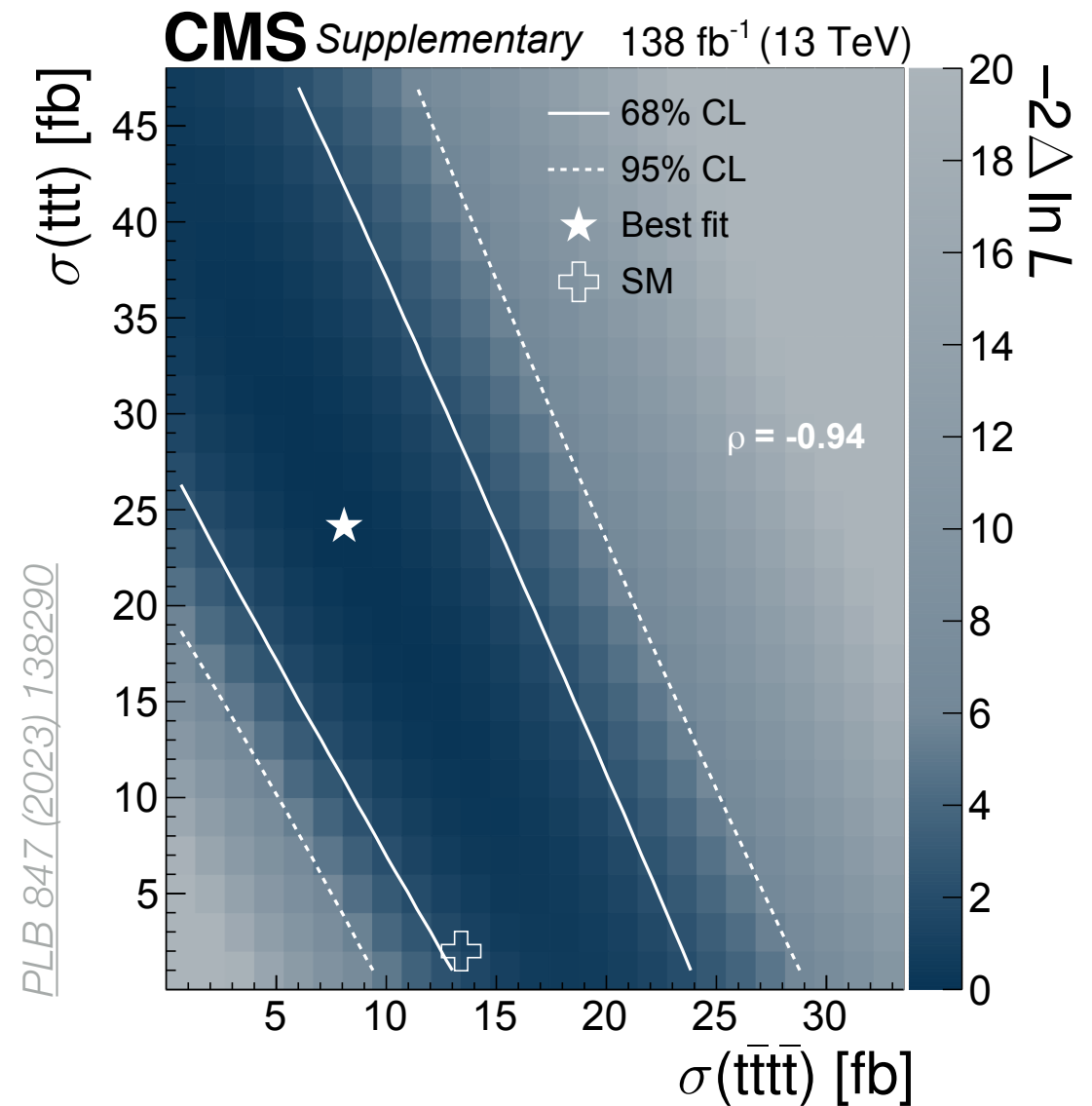
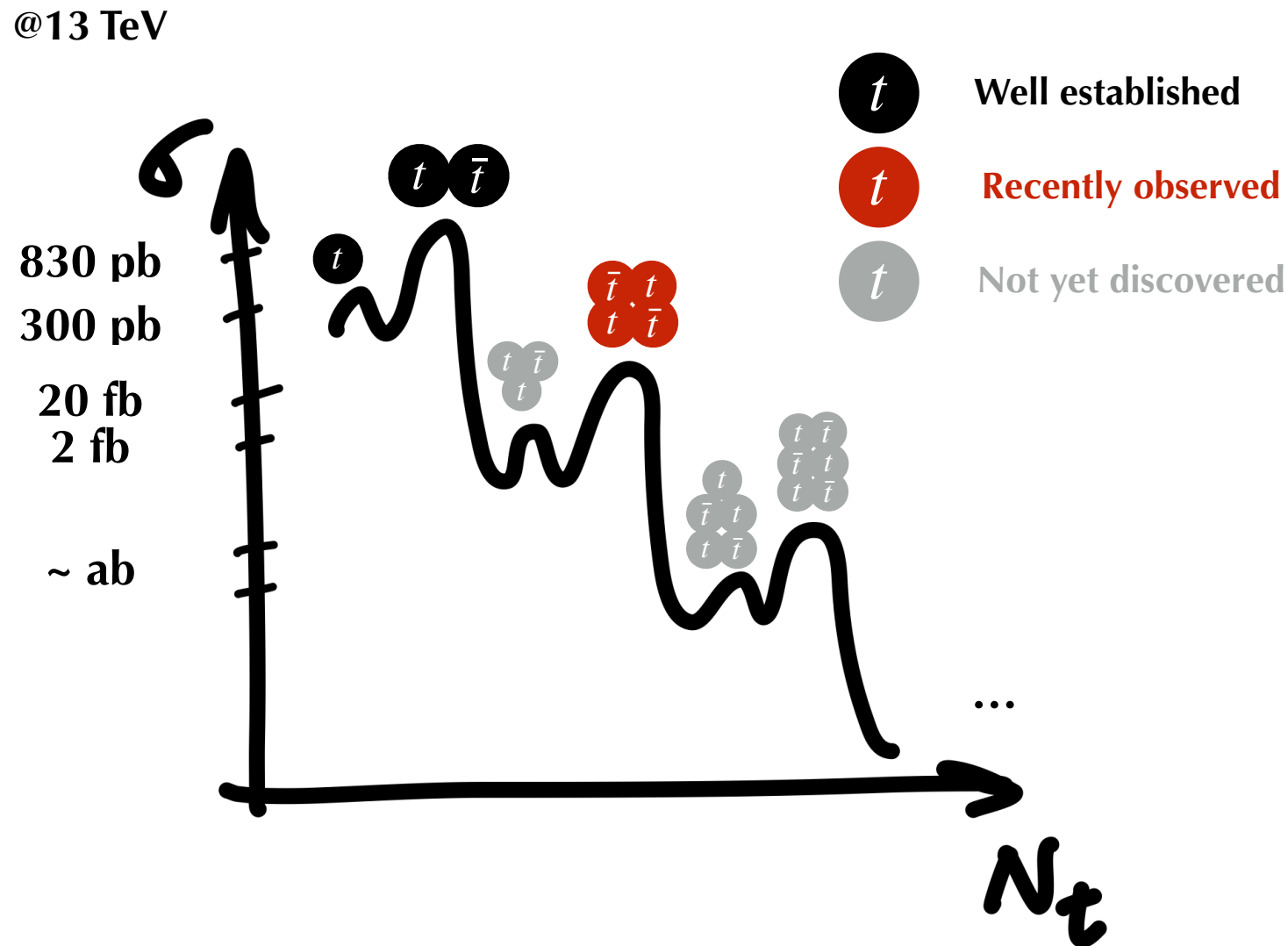
EPJC 84 (2024) 715

- The **heaviest final state** ever observed
- Very rare (≈ 10 fb)
- Thought to have been possible only at HL-LHC
- Knowledge about $t\bar{t}X$ backgrounds is vital
- Sensitivity to top-philic new physics

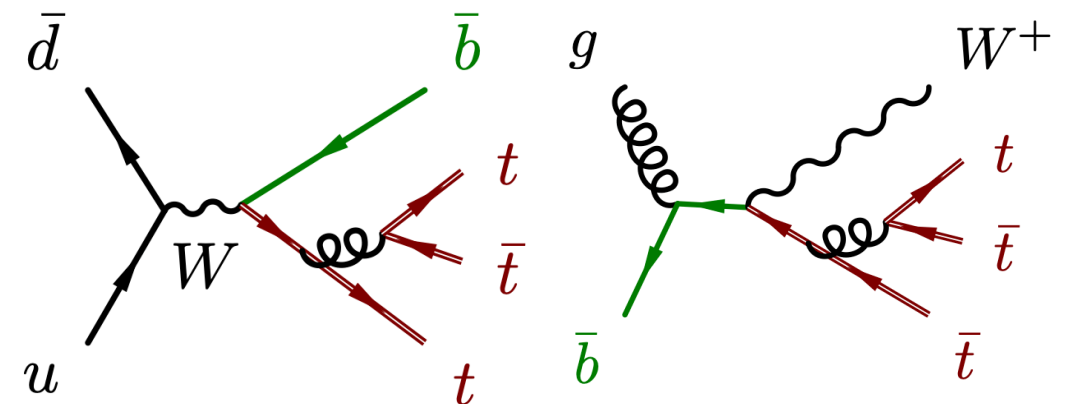


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Multi-tops

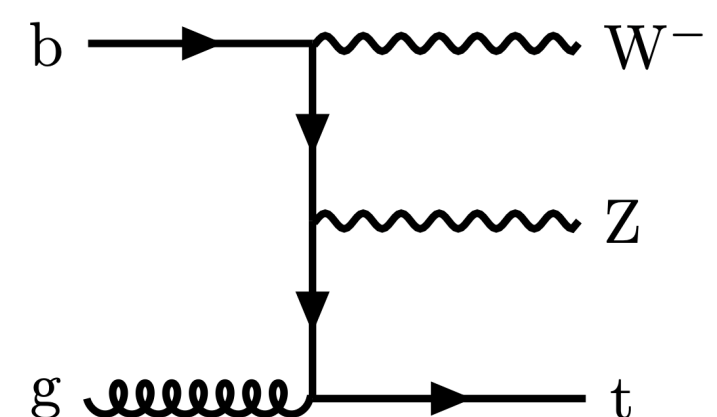
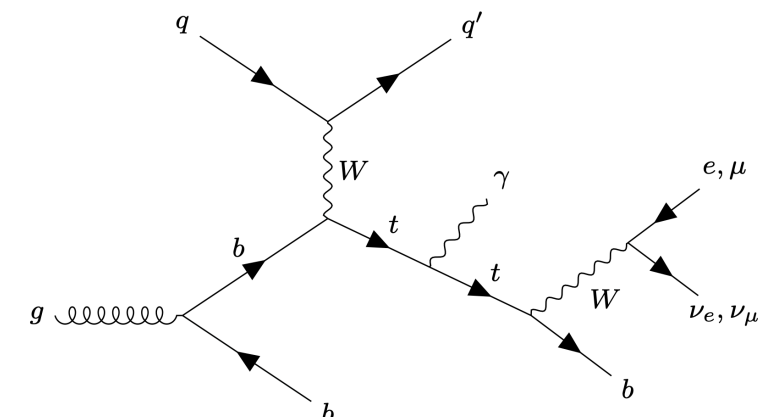
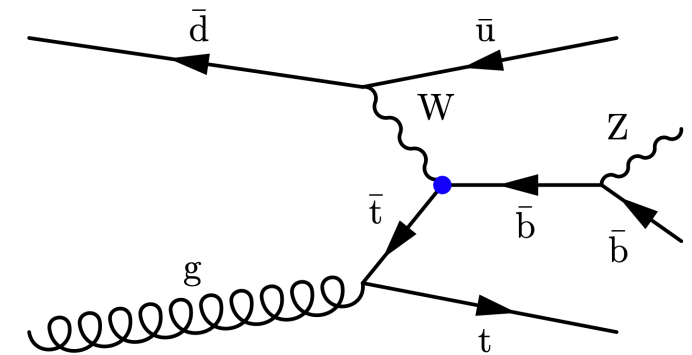
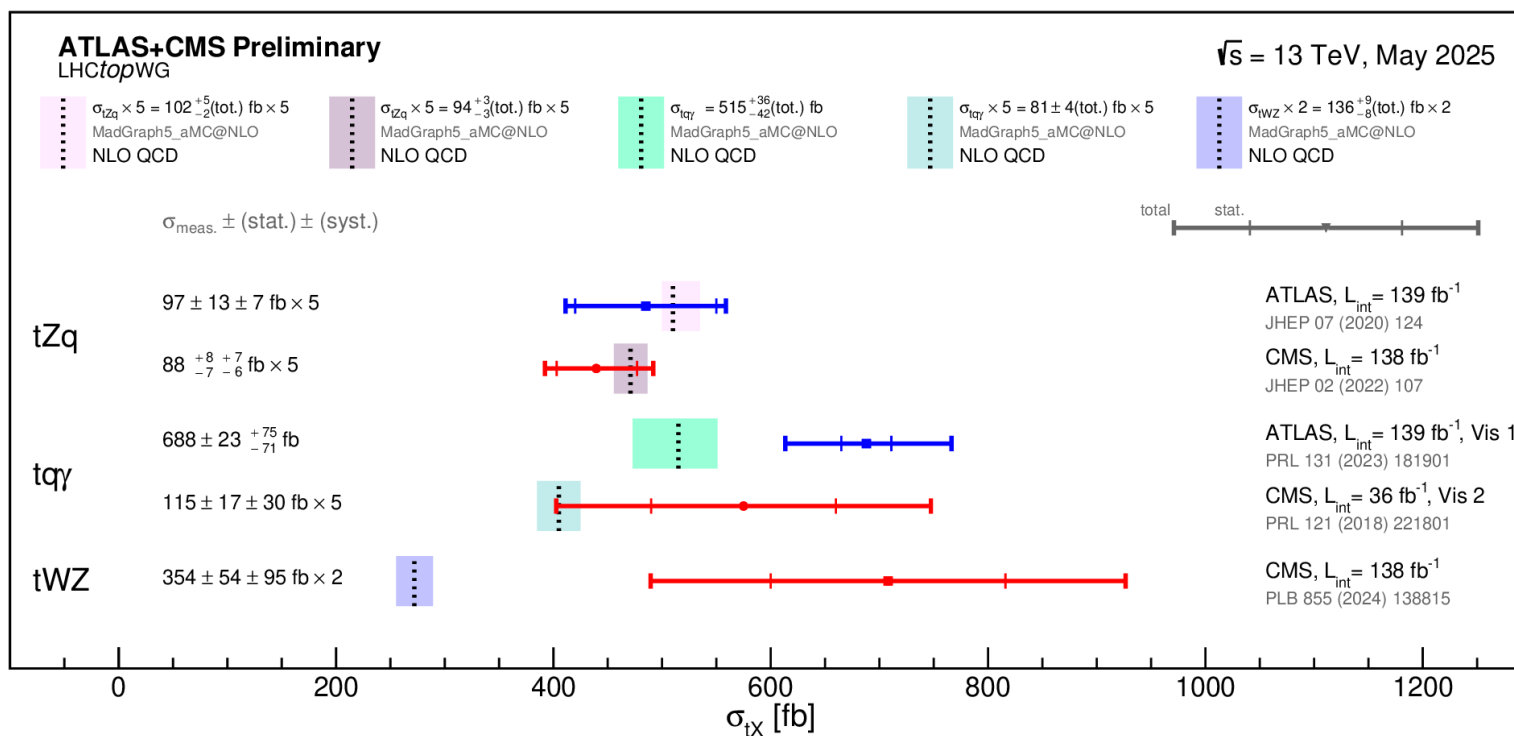


- Did we actually measure four tops?
- Strong correlation between $t\bar{t}t\bar{t}$, $tttW$, and $tttq$ processes
- Interference effects in the modelling of the two processes

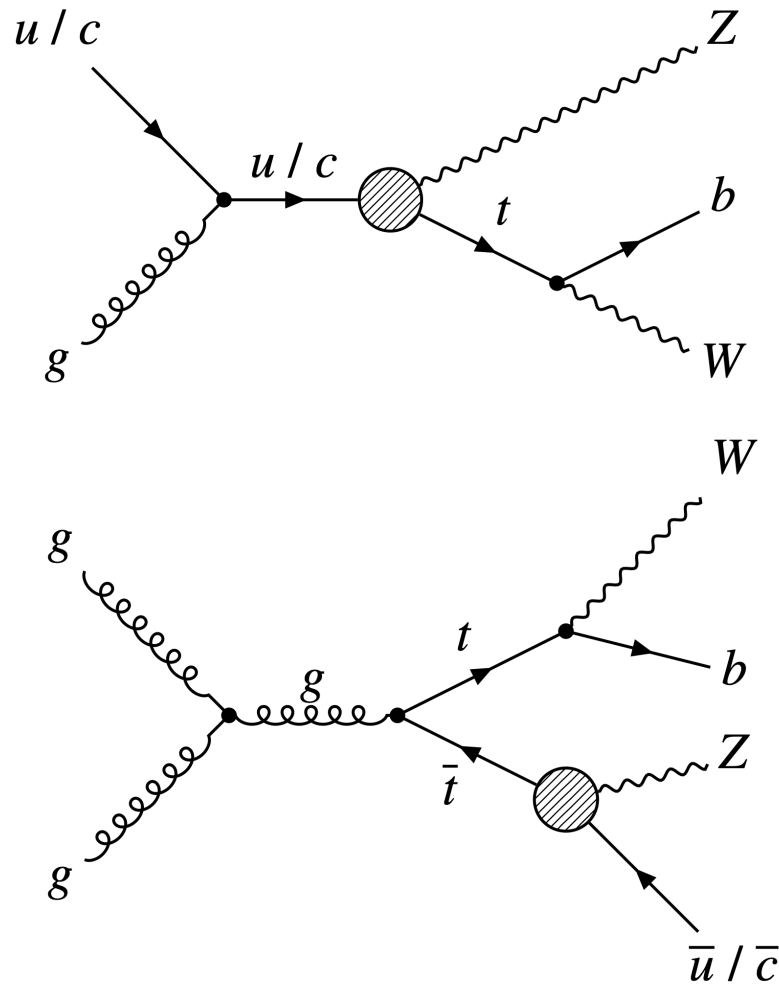


Top+X

- Among the **rarest top production** processes
- Driven by EW couplings
- Individual amplitudes in each process grow with energy but almost cancel out together
- Excellent place to search for anomalous interactions at high energy

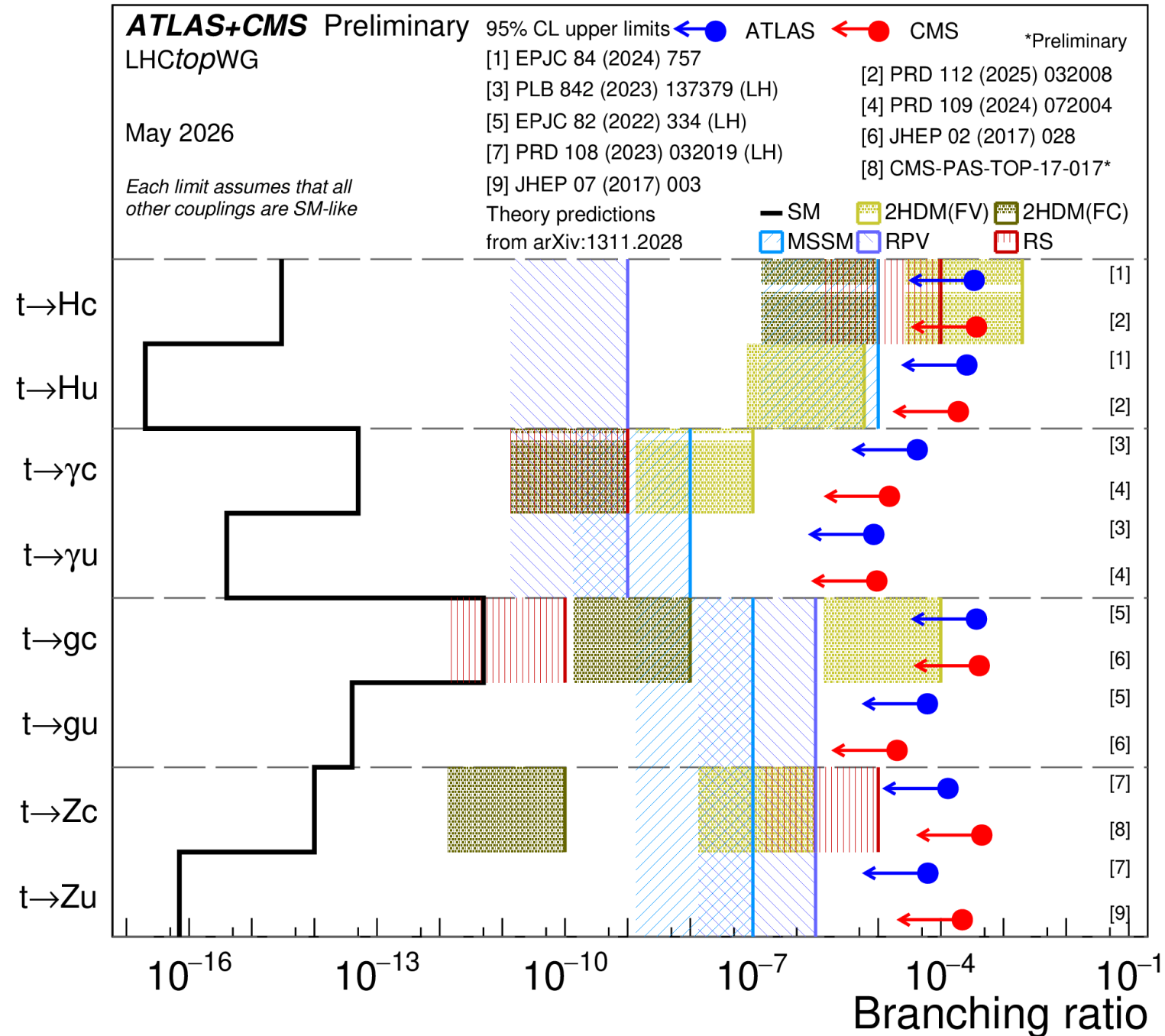


Flavor-changing neutral currents



LHCtopWG Summary Plots

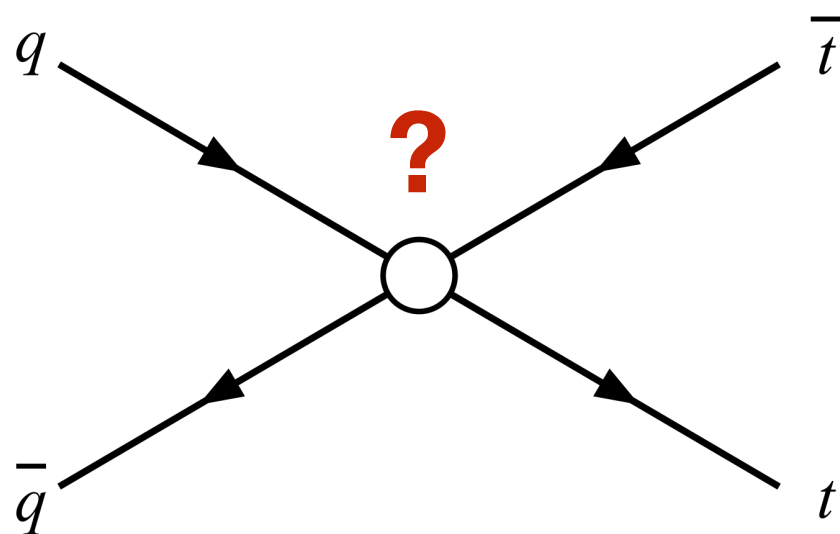
- **Forbidden** at tree level in SM
- Significantly suppressed in higher orders
- New physics can open it up
- Similar signatures as in single top + X processes



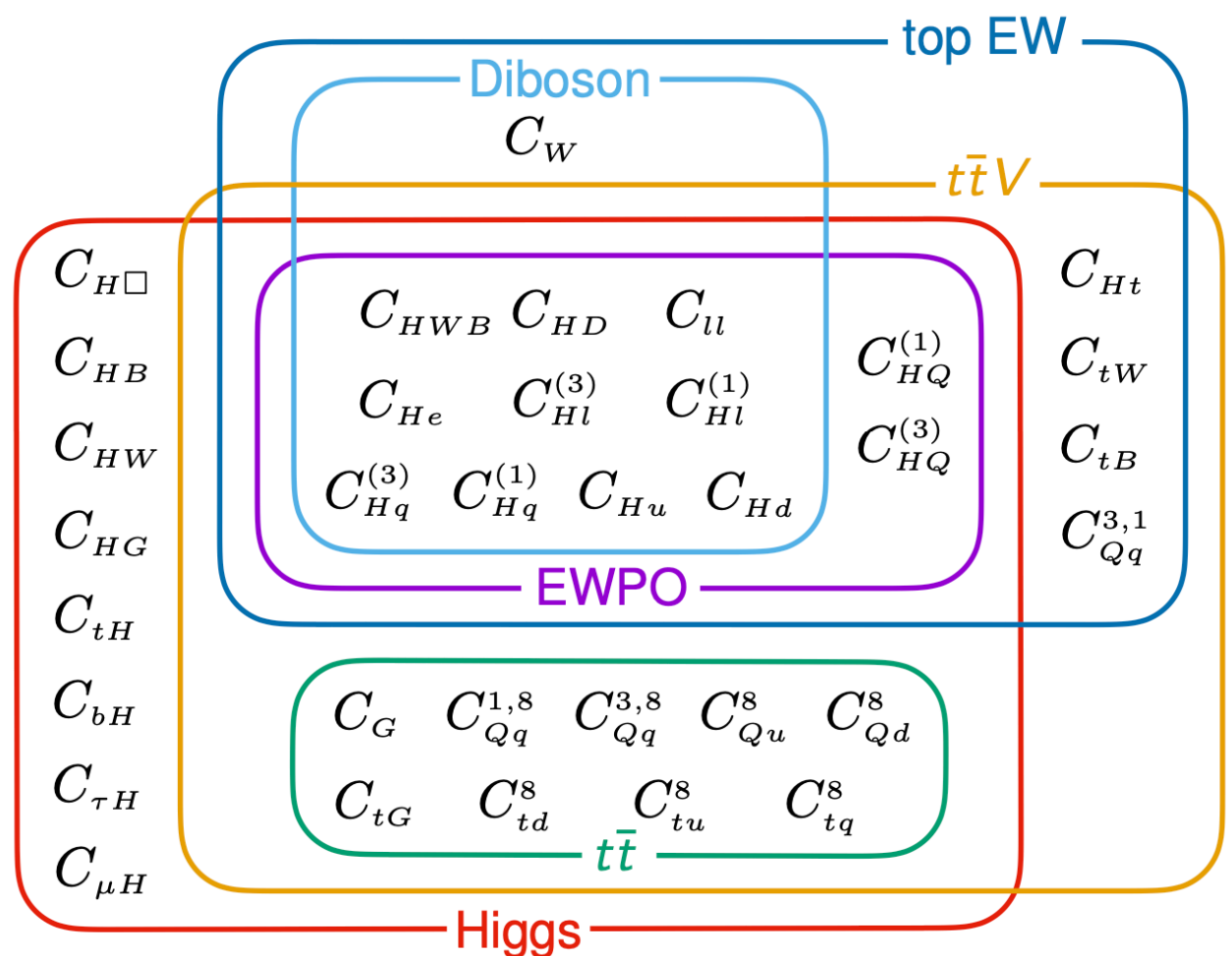
Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d,j} \frac{c_j^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_j^{(d)}$$

- A **generalized approach** to search for new physics
- Extend the SM Lagrangian with terms suppressed by the new physics energy scale (Λ)
- A common interpretation framework across different physics sectors

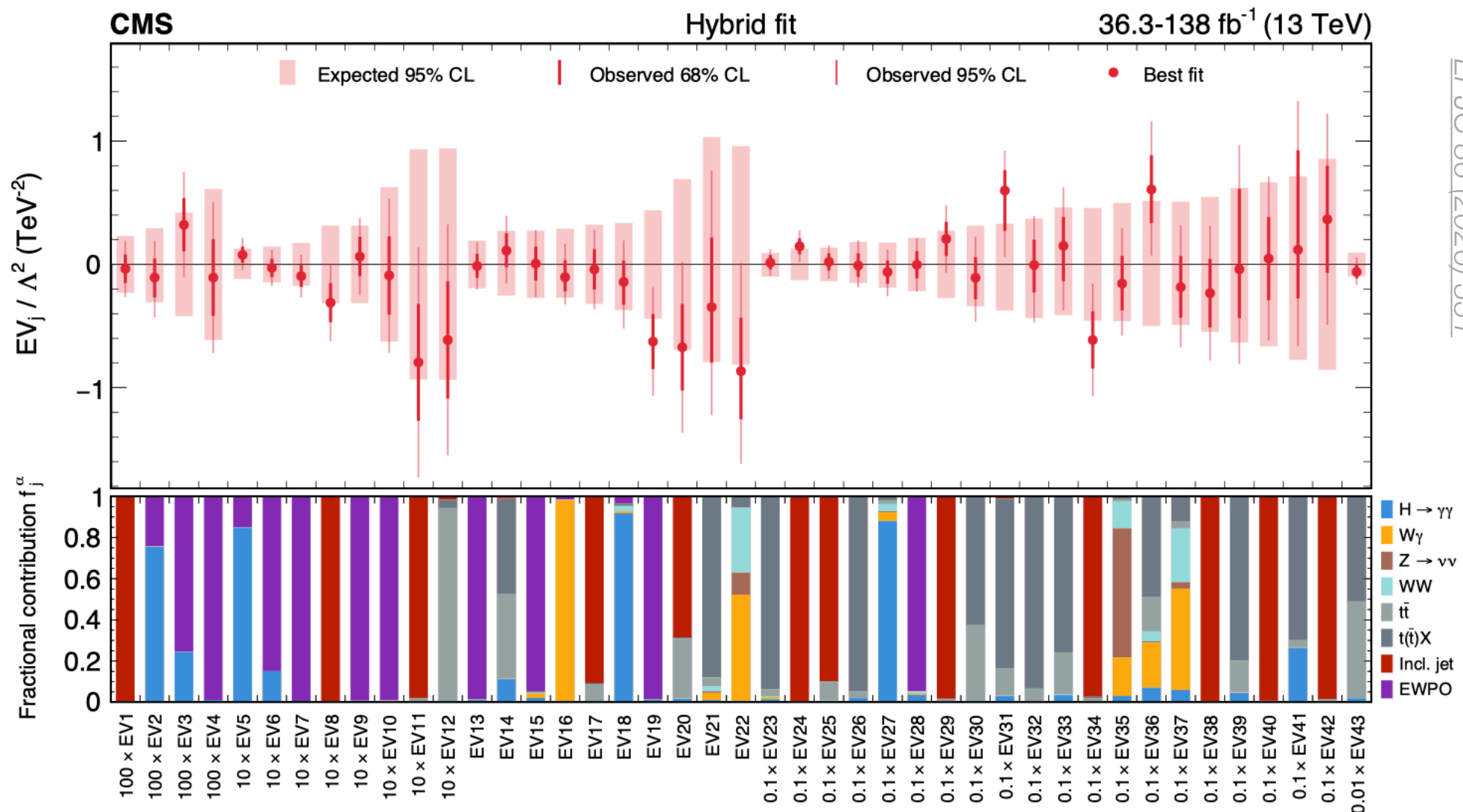


JHEP 04 (2021) 279



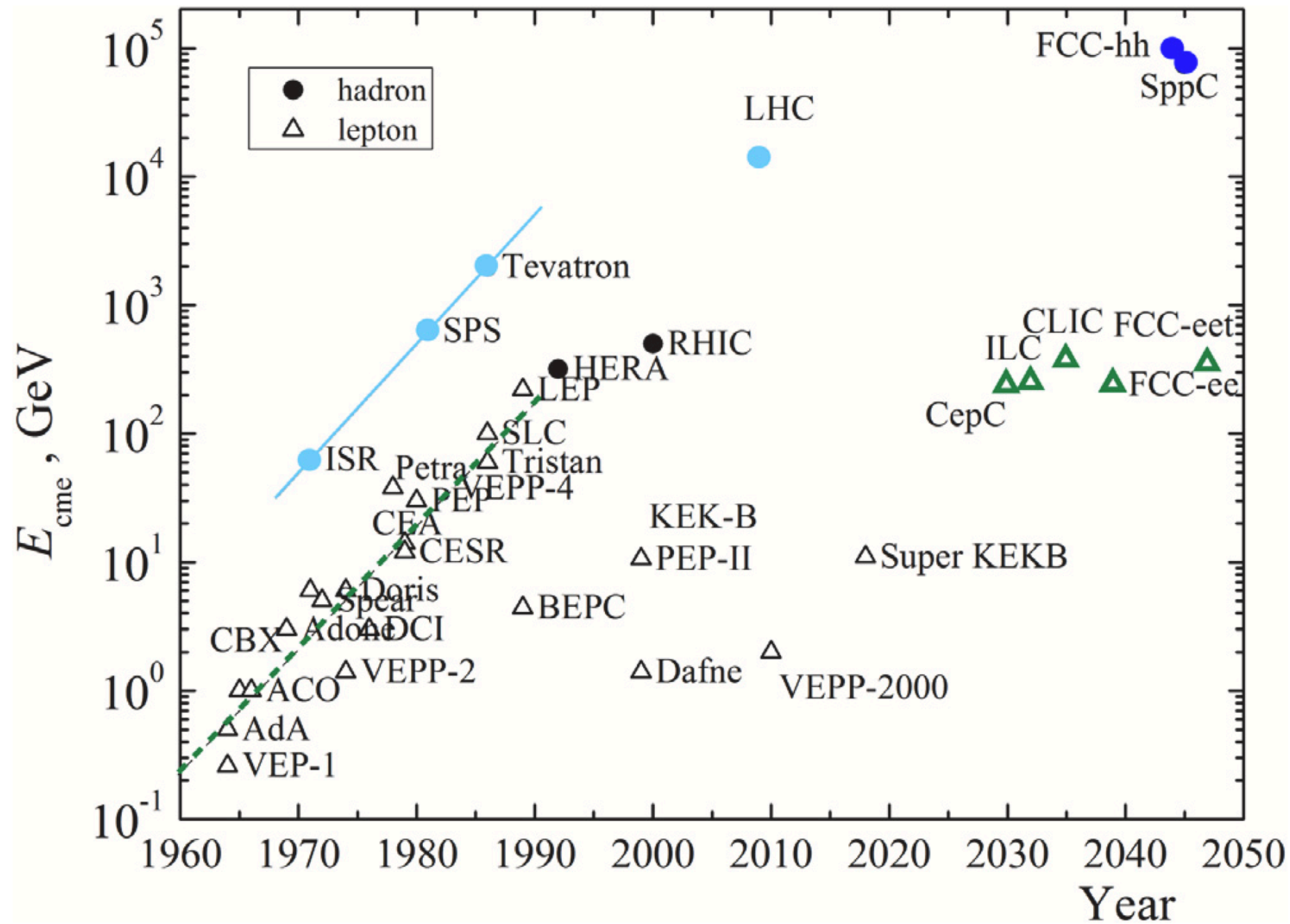
Top EFT legacy

- Many top results are included in global EFT combinations
- Interplay among various sensitivities from different observables
- **EFT fits** became standard in many experimental studies

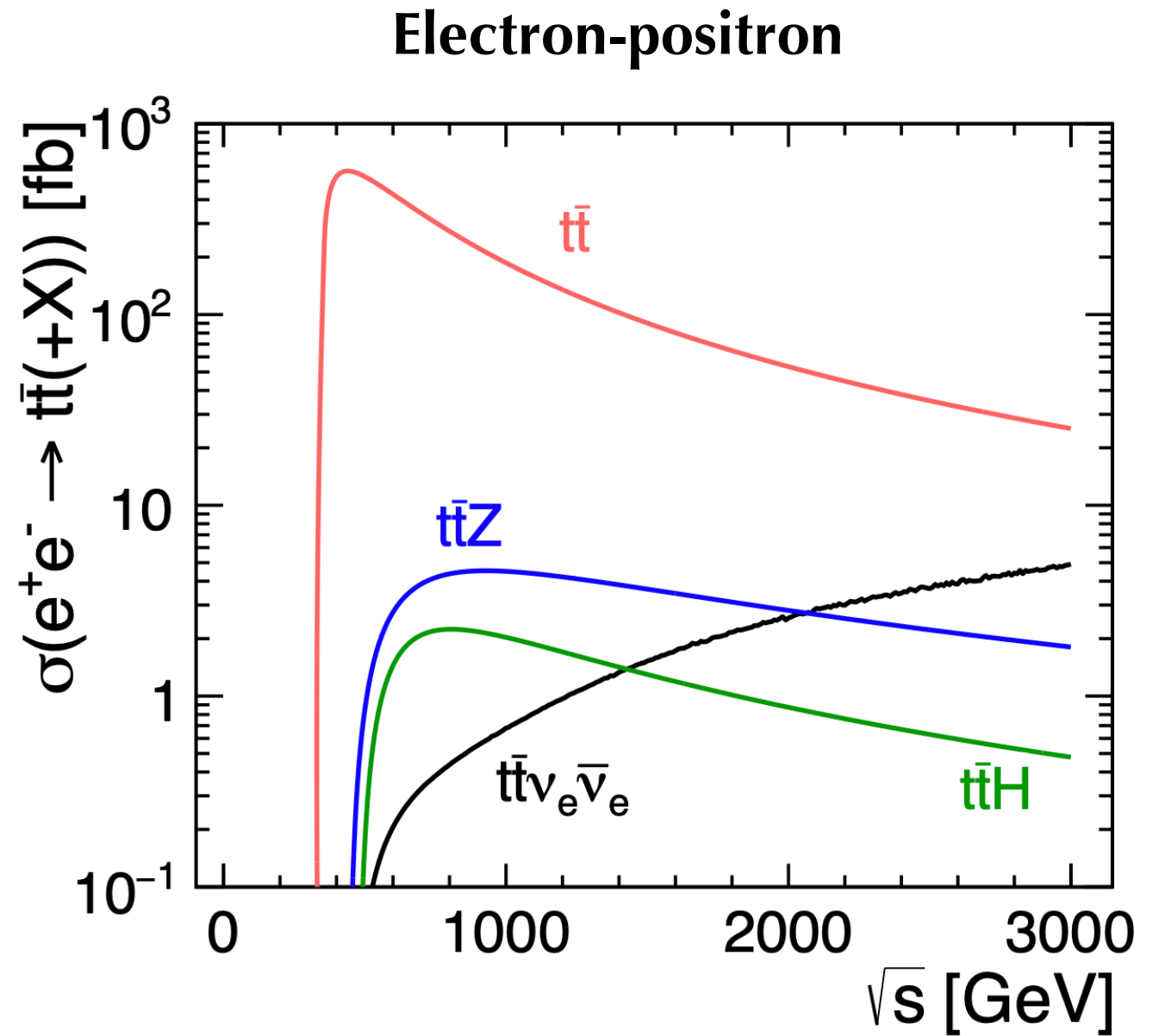
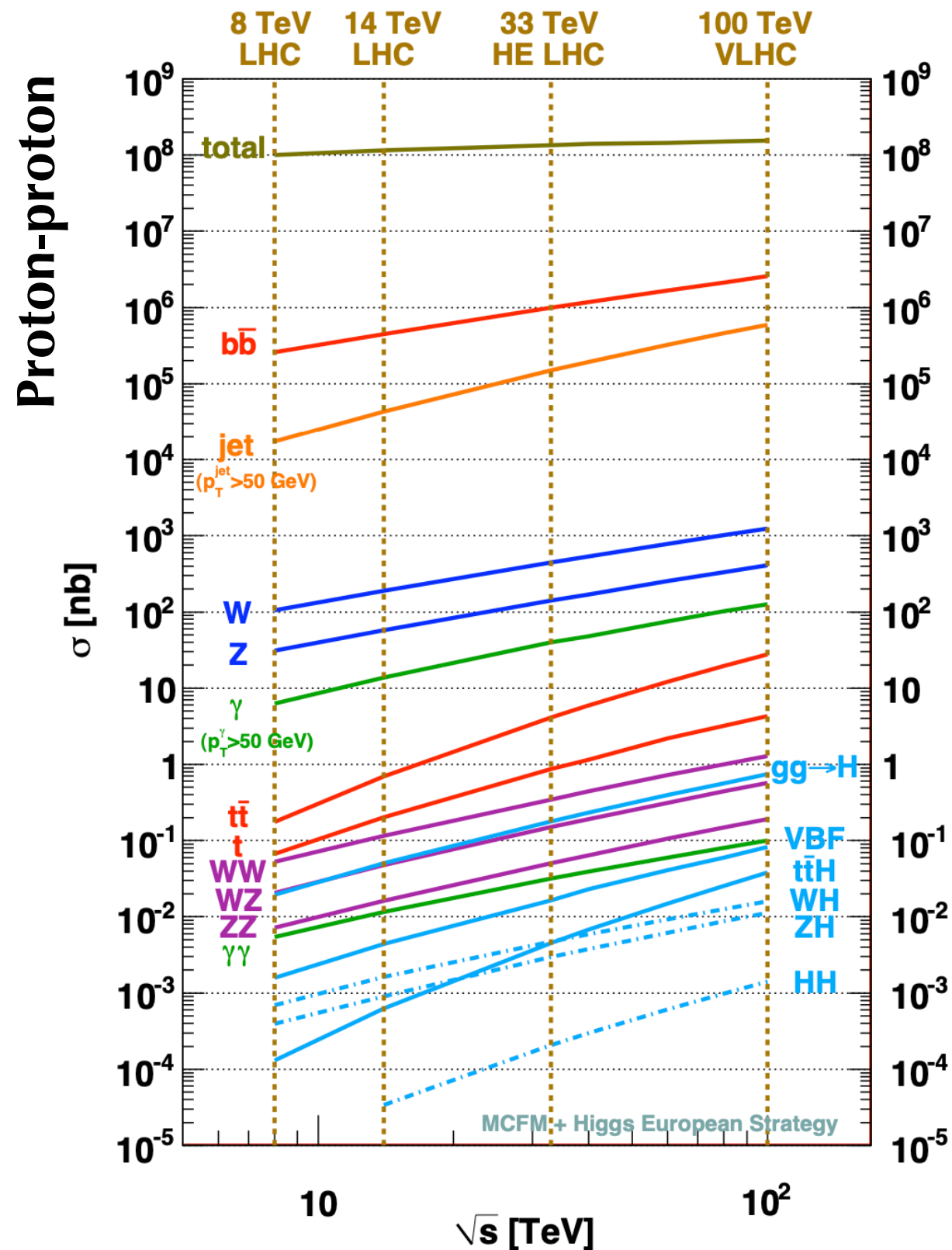


EPJC 86 (2026) 331

Towards the future

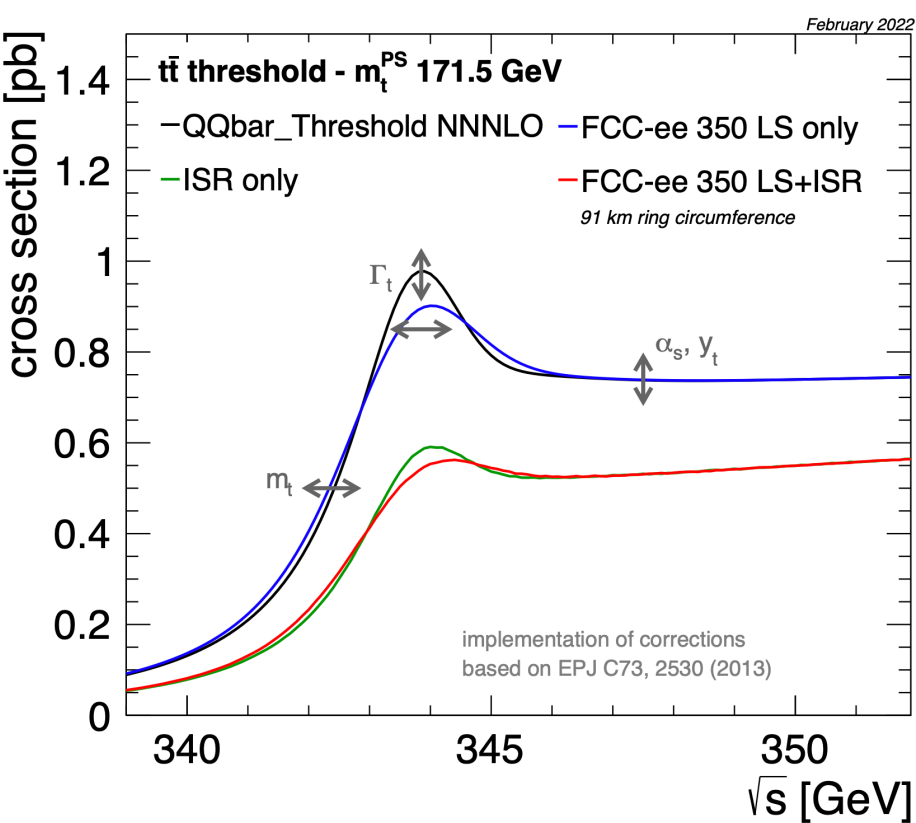
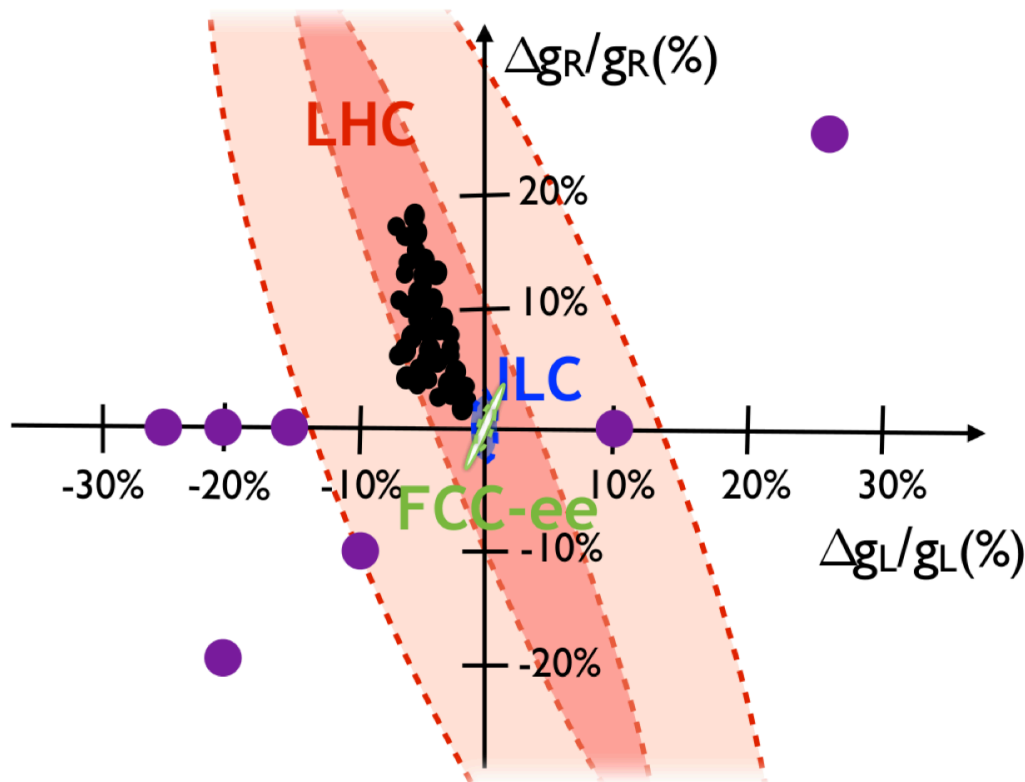


Hadrons vs leptons

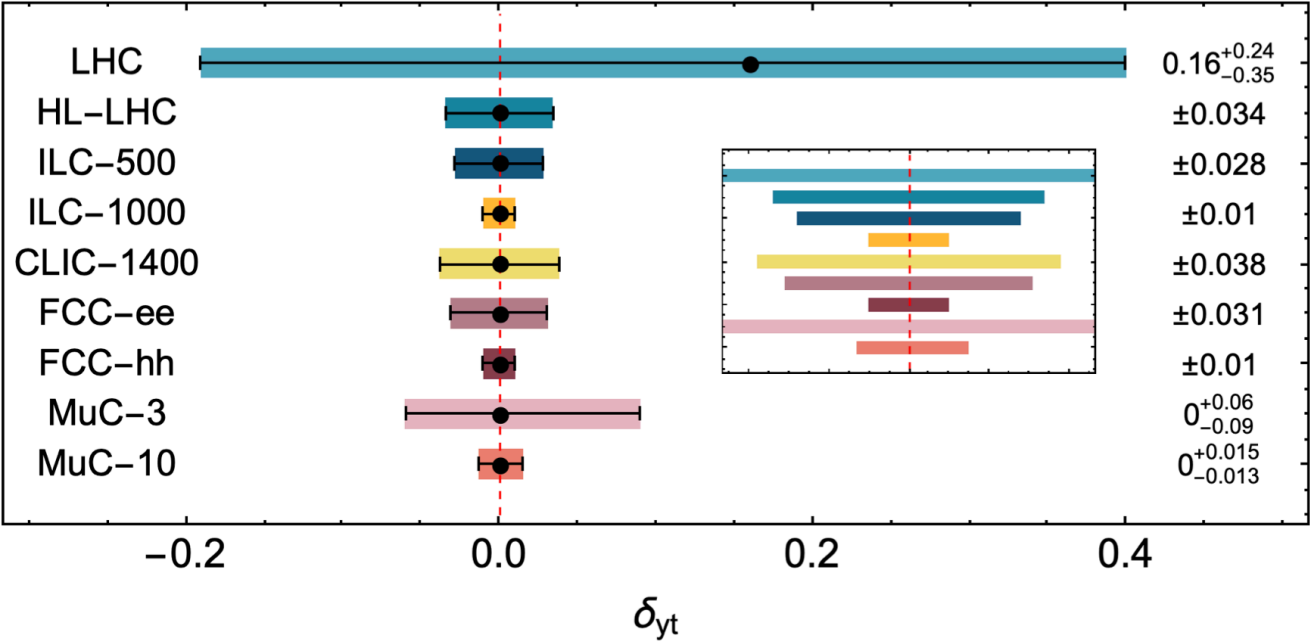


What to expect

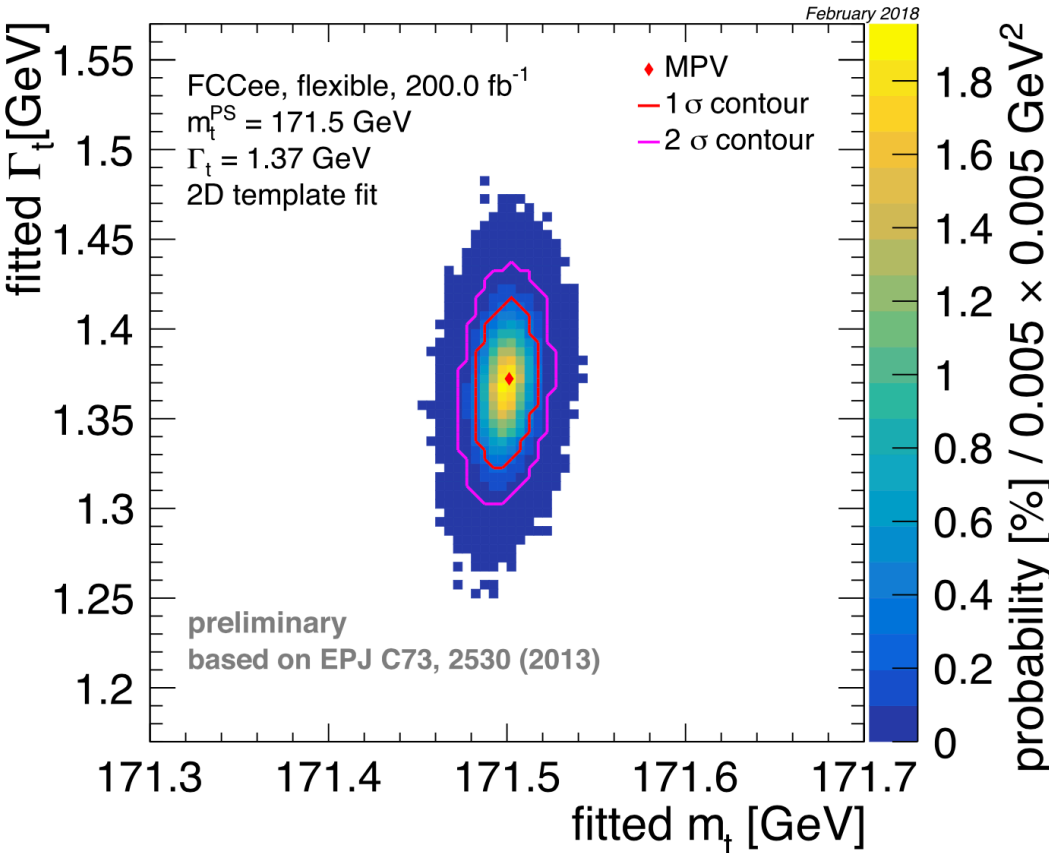
JHEP 08 (2015) 127



arXiv:2203.06520



PRD 109 (2024) 035021



EPJC 79 (2019) 474