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Top Quark Physics — part 2

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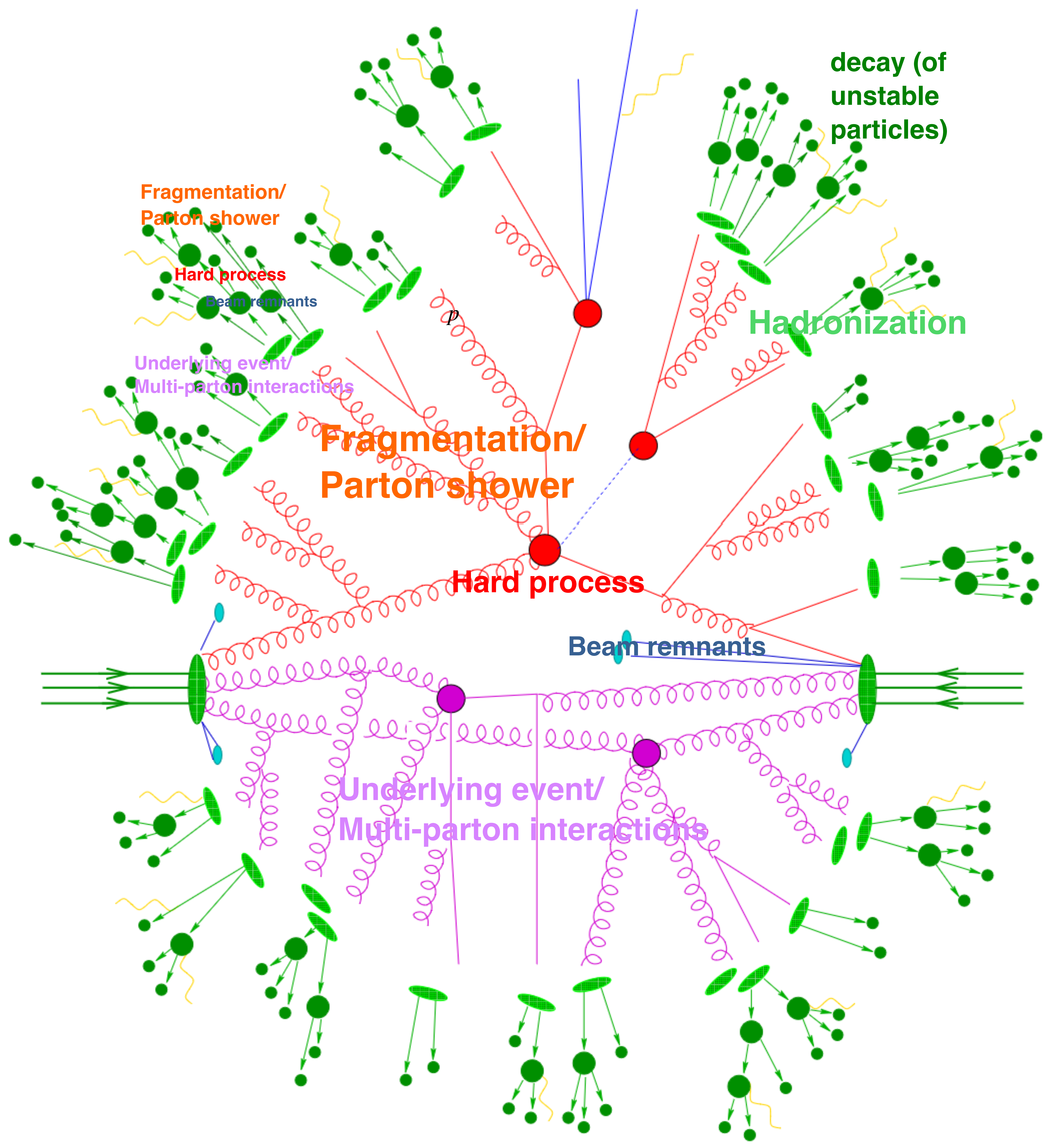
Outline — part 2

* Partially covered
    * Top quark modelling and differential measurements
    * Spin correlation/Quantum entanglement/Quantum Magic
    * Toponium
    * Top quark mass
    * Two examples of new physics searches

Simplified structure of a simulated pp event

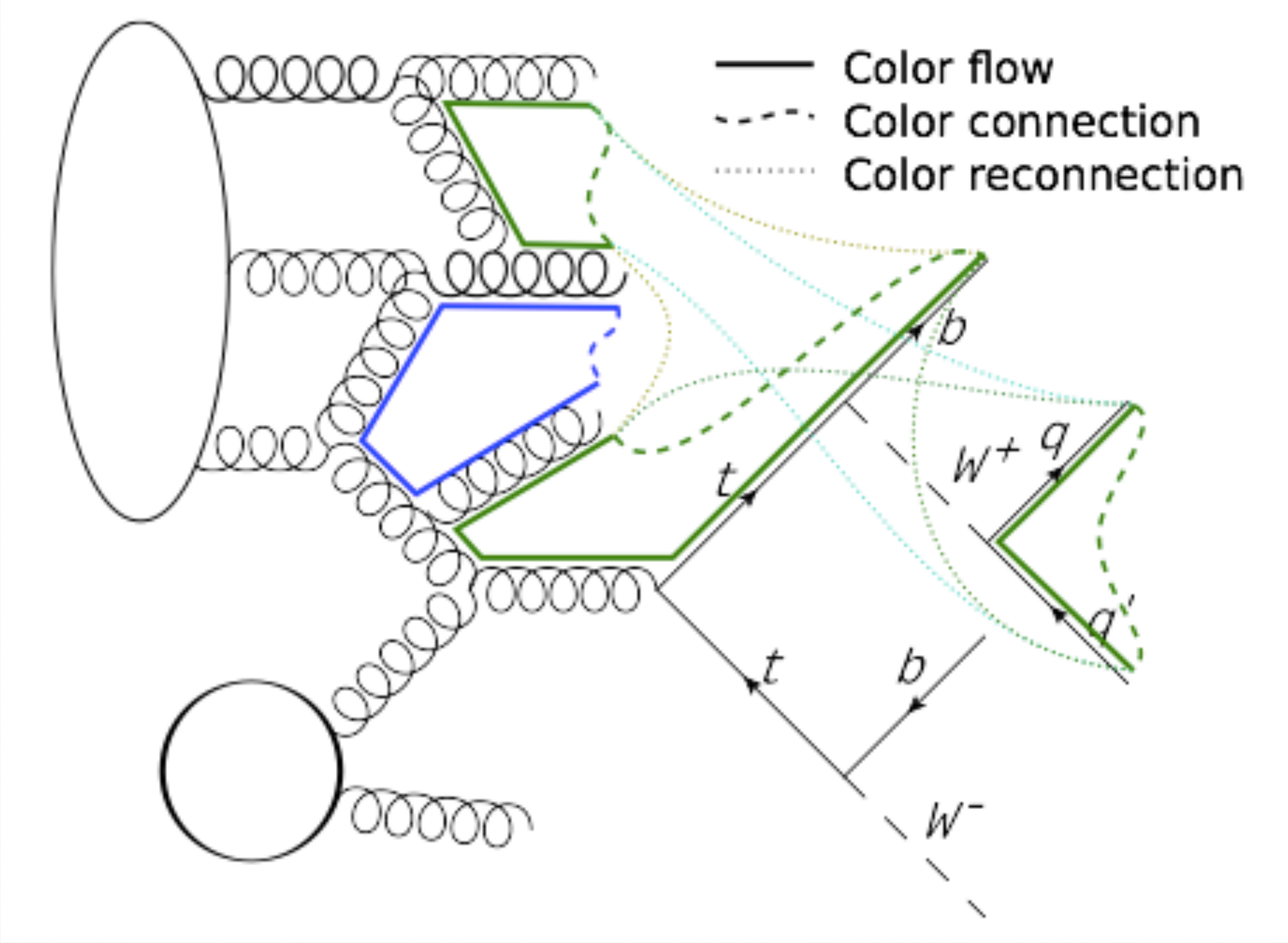


Tanju Gleisberg et al. JHEP02(2004)056

- Many pieces, approximations, parameters, settings to compare to data and tune.
  - Matrix element generation: Sherpa, MG5_aMC, Powheg, Pythia, Herwig, ...
  - Hadronization and parton shower: Pythia, Herwig ... and underlying event tunes.
  - Depending on the process/generator Multi-leg LO and (N)NLO consistently matched to parton shower with N number of jets with different matching prescriptions.
  - Particle decays and QED corrections: EvtGen, Photos, ...
  - Other essential tools with diverse scopes: Rivet, Professor/ Apprentice, HepMC, ...

A relatively recent review and for references: Valassi, Yazgan, McFayden et al. CSBS 5 (2021) 12

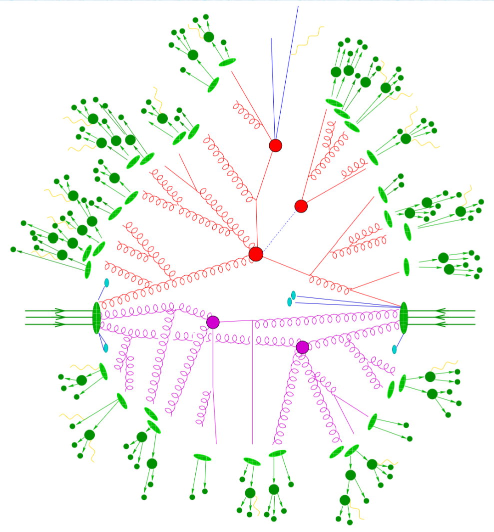
Simplified structure of a simulated $pp \rightarrow t\bar{t}$ event

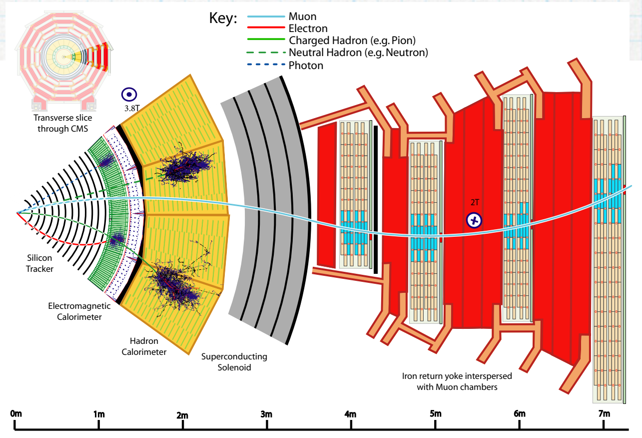


* Underlying event: any hadronic activity that can't be attributed to particles from the hard process.
* Underlying event constitutes the recoil against the hard process.
* Main contribution to underlying event from color exchanges between beam particles.
* Modelled in terms of multiparton interactions, color reconnection, and beam-beam remnants.
* Color reconnection mainly occurs between one of the fragmentation products of the b quark and the proton remnants —> **induces ambiguity in the origin of some of the final states present in a b quark jet.**

A comprehensive guide to the physics and usage of PYTHIA8.3
https://arxiv.org/abs/2203.11601

(Top quark) Event modelling: from pp to observables

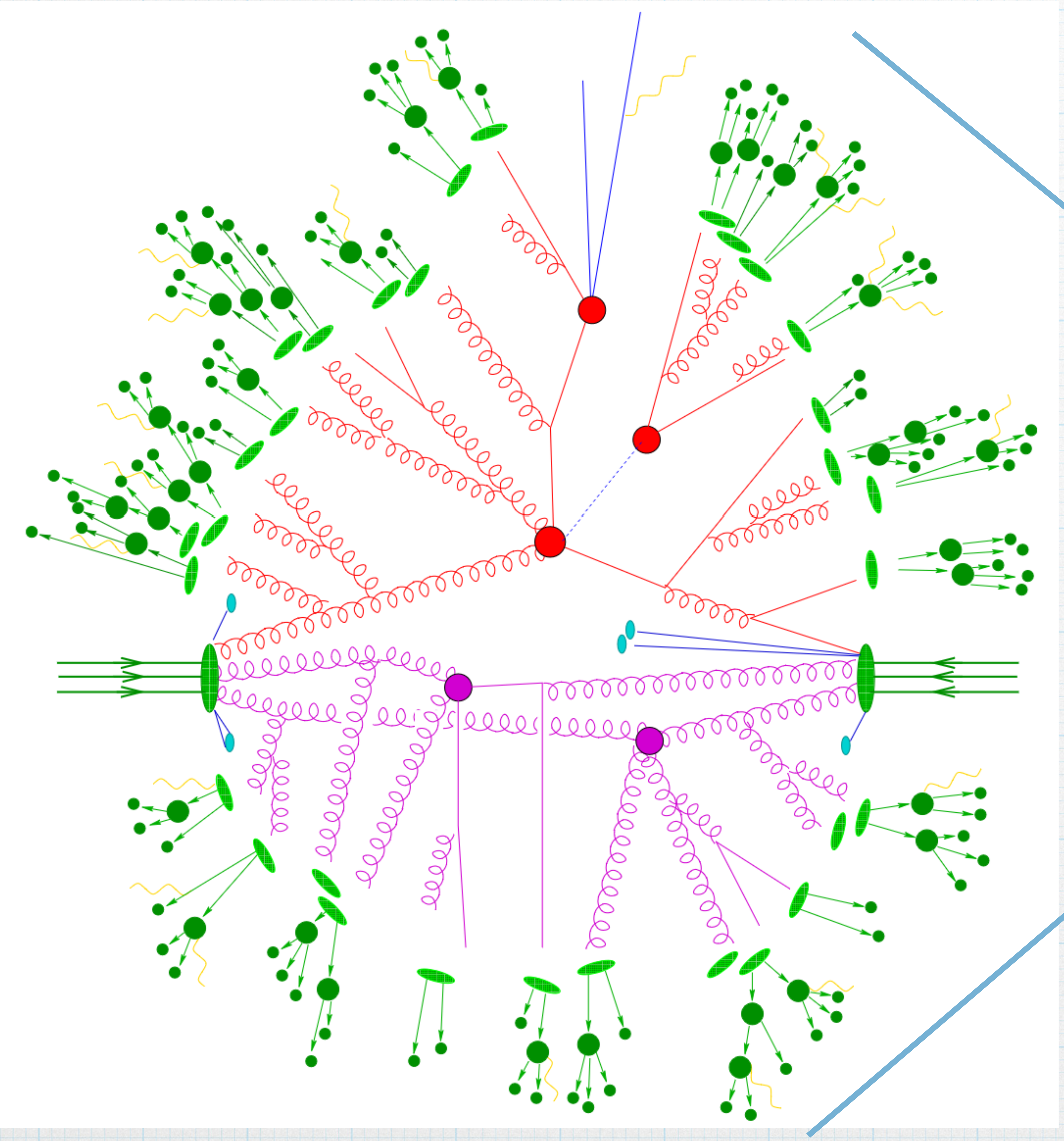




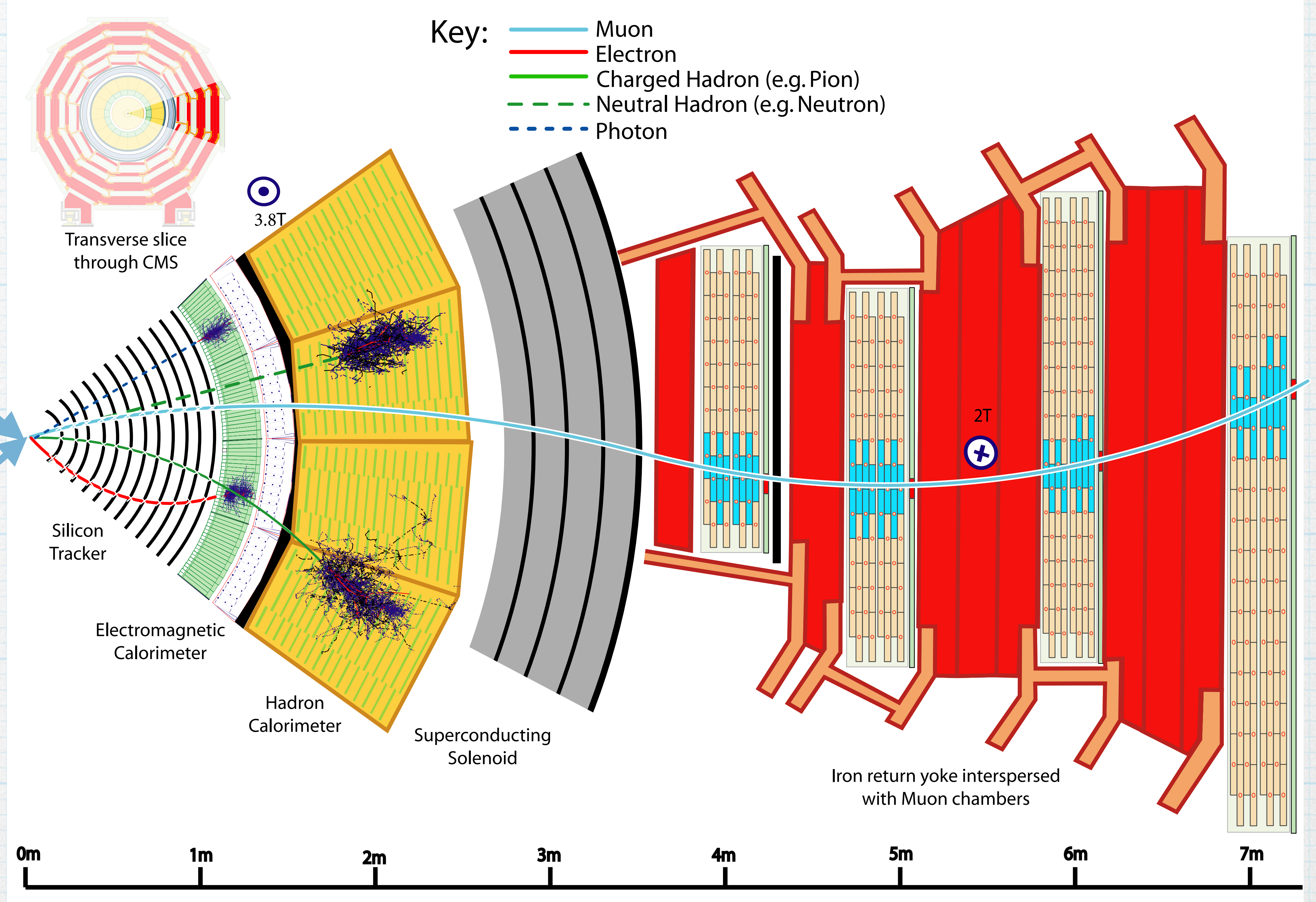
Proton/ (anti-)proton		Colliding partons		Final state		Stable particles		Measured event
P	PDF	q	Processes	Lepton	Hadronization	Lepton	detector	Lepton
$P/\bar{P}$		q	$t\bar{t}$	neutrino	showering	Neutrino		MET
			...	b	Underlying event	Gen-Jet		Jet
				b		Gen-jet		Jet
				u		Gen-Jet		Jet
				d		Gen-jet		Jet

$$\sigma_{pp\to t\bar{t}}\left(s,m_t\right)=\sum_{i,j=partons}\int dx_1\,dx_2\,f_i^{pdf}\left(x_1,\mu_f^2\right)f_j^{pdf}\left(x_2,\mu_f^2\right)\hat{\sigma}_{ij\to t\bar{t}}\left(\hat{s},m_t,\mu_f,\mu_r,\alpha_s\left(\mu_r\right)\right)$$

Top Quark Physics (Production and Mass), E. Yazgan, Lectures in Hadron Collider School - HASCO 2015, Gottingen, Germany, 19-24 July 2015.



Physics event generation/parton shower/hadronization/decay

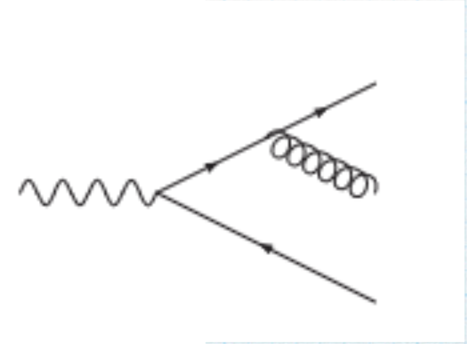


Detector simulation (Geant4)

Top Quark Event Modeling

$$\sigma_{pp\to t\bar{t}}(s,m_t) = \sum_{i,j=partons} \int dx_1\, dx_2\, f_i^{pdf}(x_1,\mu_f^2)\, f_j^{pdf}(x_2,\mu_f^2)\, \hat{\sigma}_{ij\to t\bar{t}}(\hat{s},m_t,\mu_f,\mu_r,\alpha_s(\mu_r))$$

$\oplus$ showering/ & hadronization



e.g. see basics of parton showers: https://indico.cern.ch/event/829653/contributions/3568527/attachments/1946887/3230236/ps.pdf

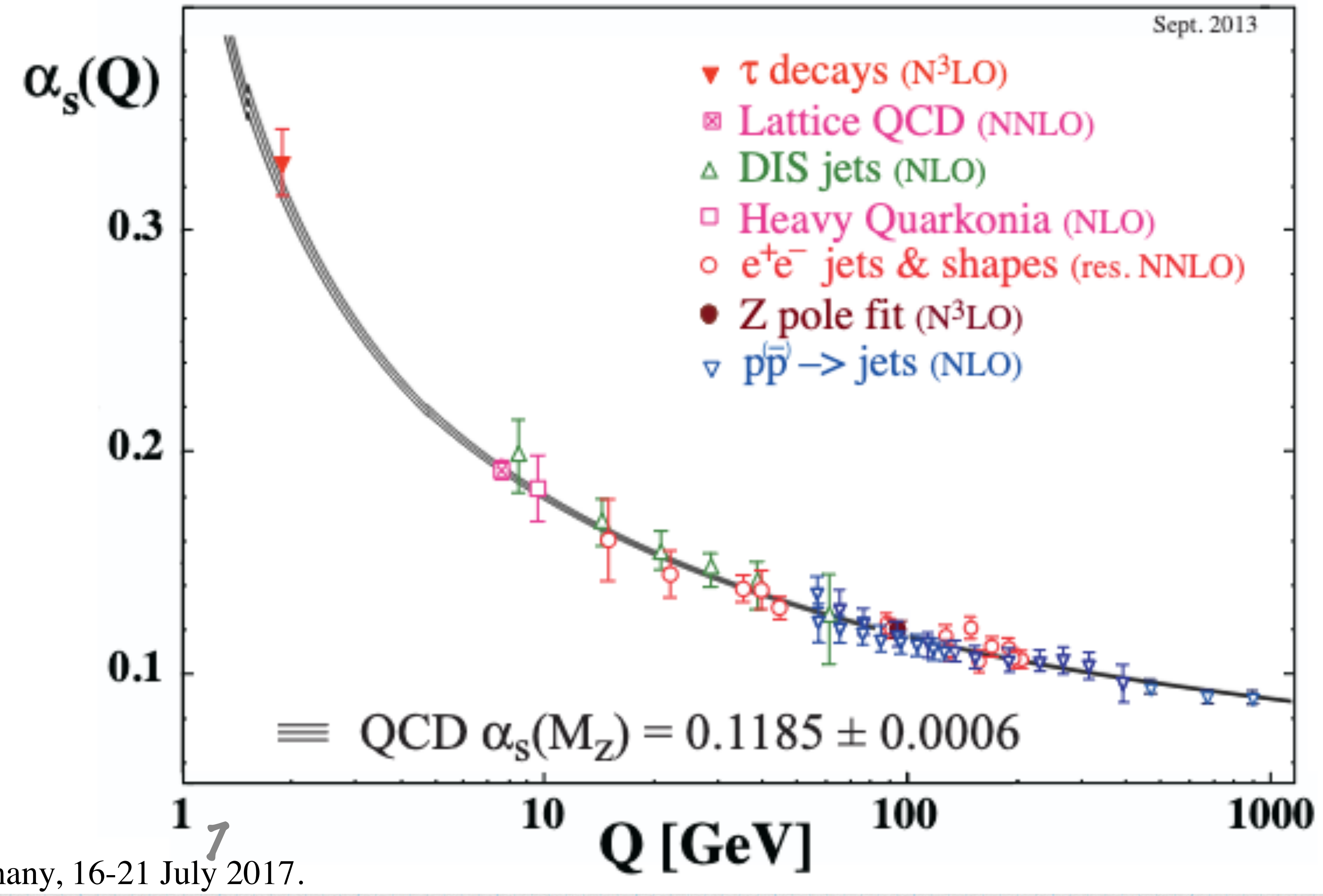
Non-perturbative | *Perturbative in α_s*

factorization➔ $PDFs(x,\mu_f^2) \otimes \hat{\sigma}(\hat{s},m_t,\mu_f,\mu_r,\alpha_s(\mu_r))$

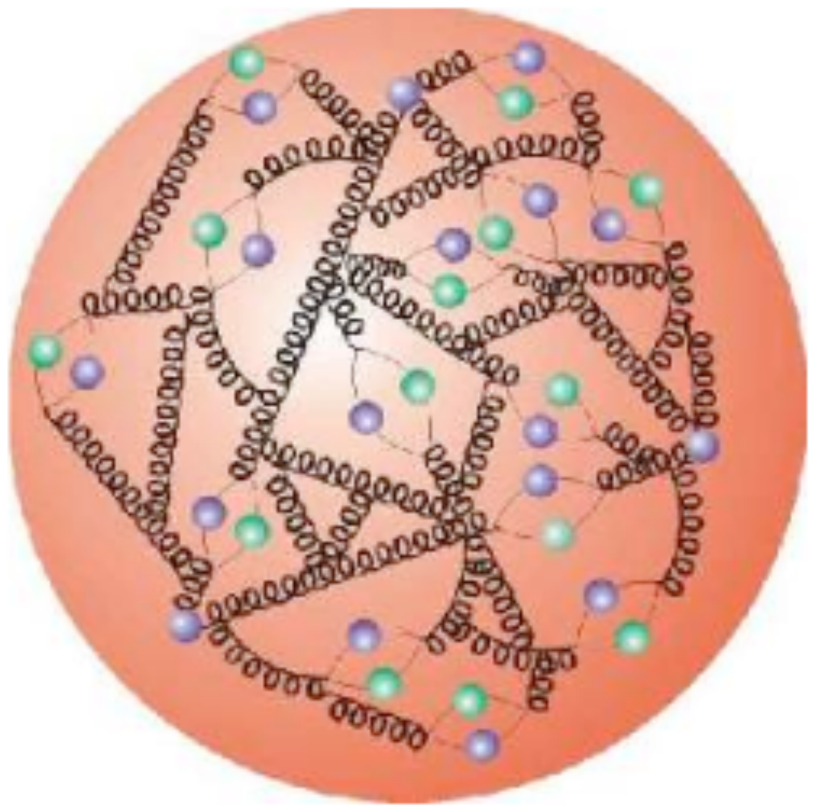
$p_T^{parton} < \mu_F$ | $p_T^{parton} > \mu_F$

$\mu_f \sim Q \sim \sqrt{\hat{s}} \sim \sqrt{x_1 x_2 s}$ *(Q: energy scale of the hard process)*

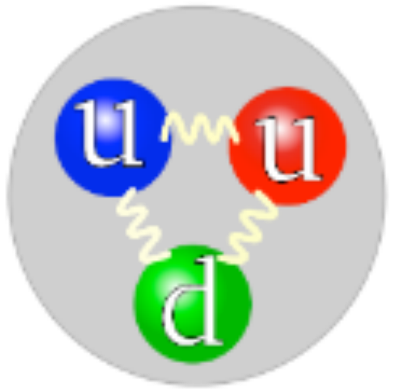
→ *inputs: m_t, α_s, and PDFs*



Nucleon Structure

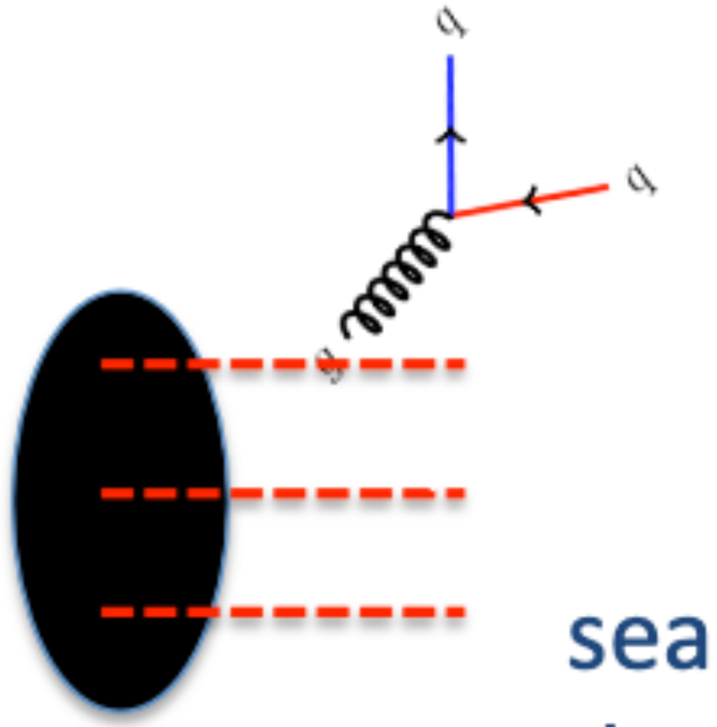


- Hadron collider = parton collider
- $f_i(x,Q^2)$ probability to find a parton to carry the fraction x of the longitudinal hadron momentum at the energy scale Q^2.
  - Intrinsic property of the nucleon → process independent.
  - Parametrized by PDF sets.

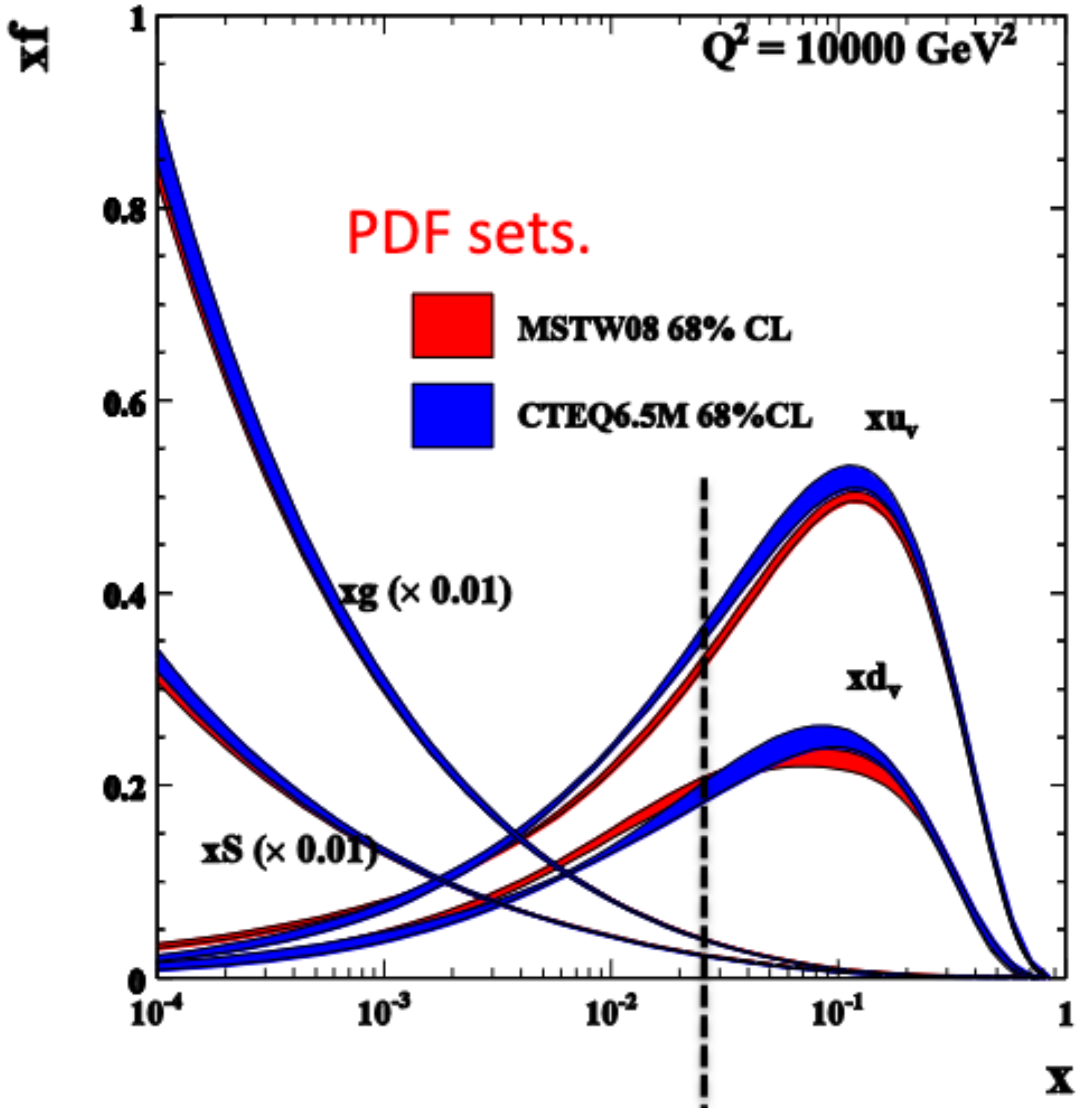


The quark sea:

~ Valence quarks emit gluons that in turn split into quark-antiquark pairs.



sea quarks dominate.



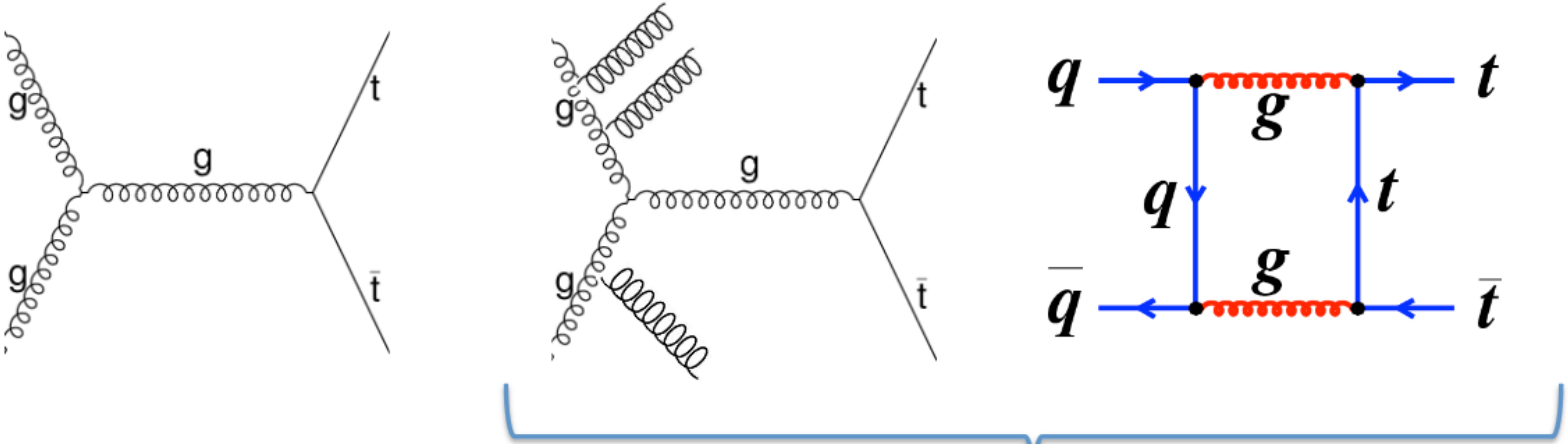
determine the quantum numbers of the hadron.

Valence quarks dominate.

Top Physics, E. Yazgan, Lectures in Hadron Collider School - HASCO 2017, Gottingen, Germany, 16-21 July 2017.

Hard Process

- Calculation in perturbative QCD
  - LO → LO ME + Radiation from parton shower.
  - Multi-leg LO → LO + Additional partons in the hard process but no loops + radiation from parton shower.
  - NLO → LO + Additional partons in the hard process including loops (+ parton shower).



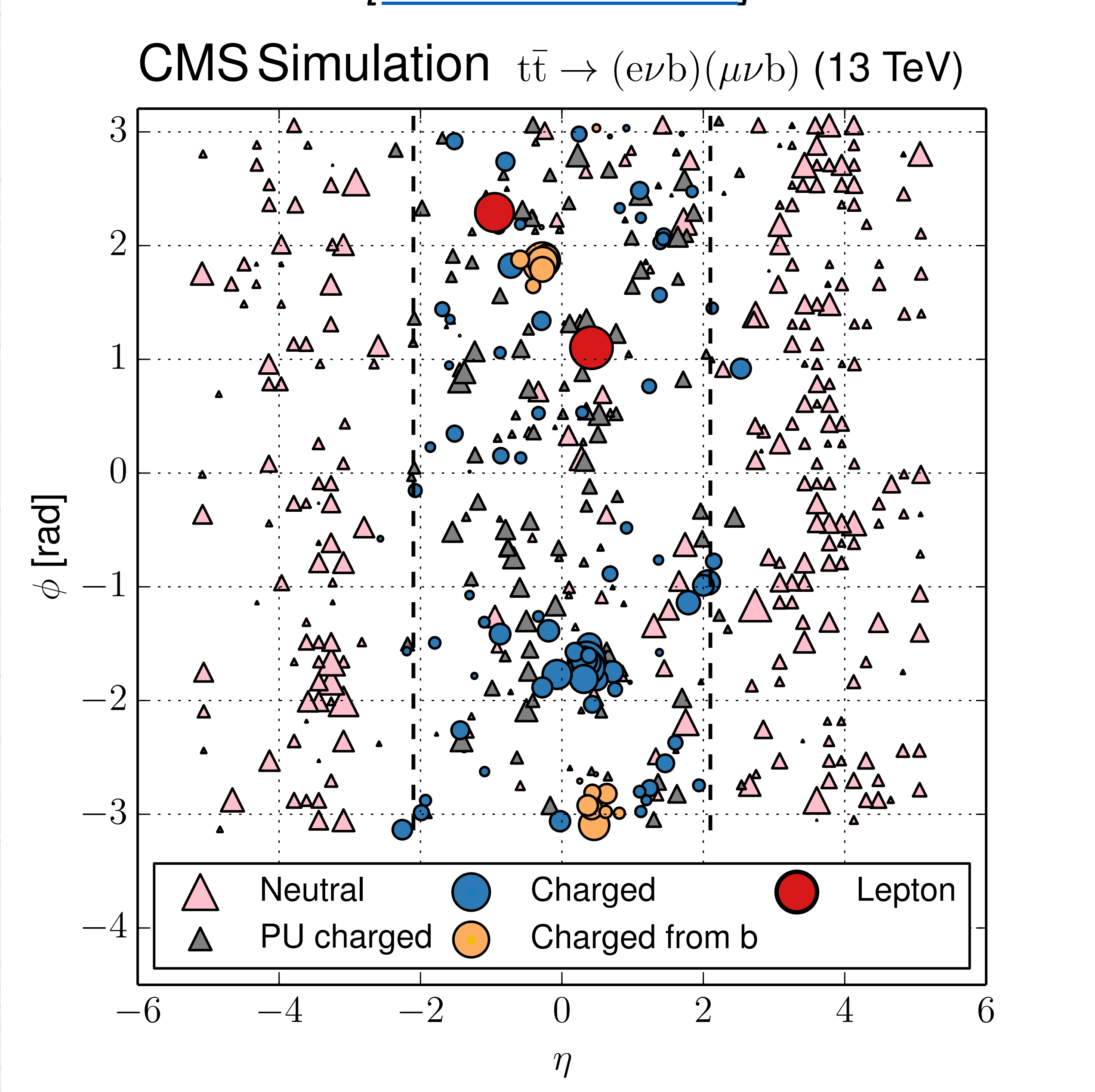
NLO and multi-leg LO need matching/merging to the parton shower.

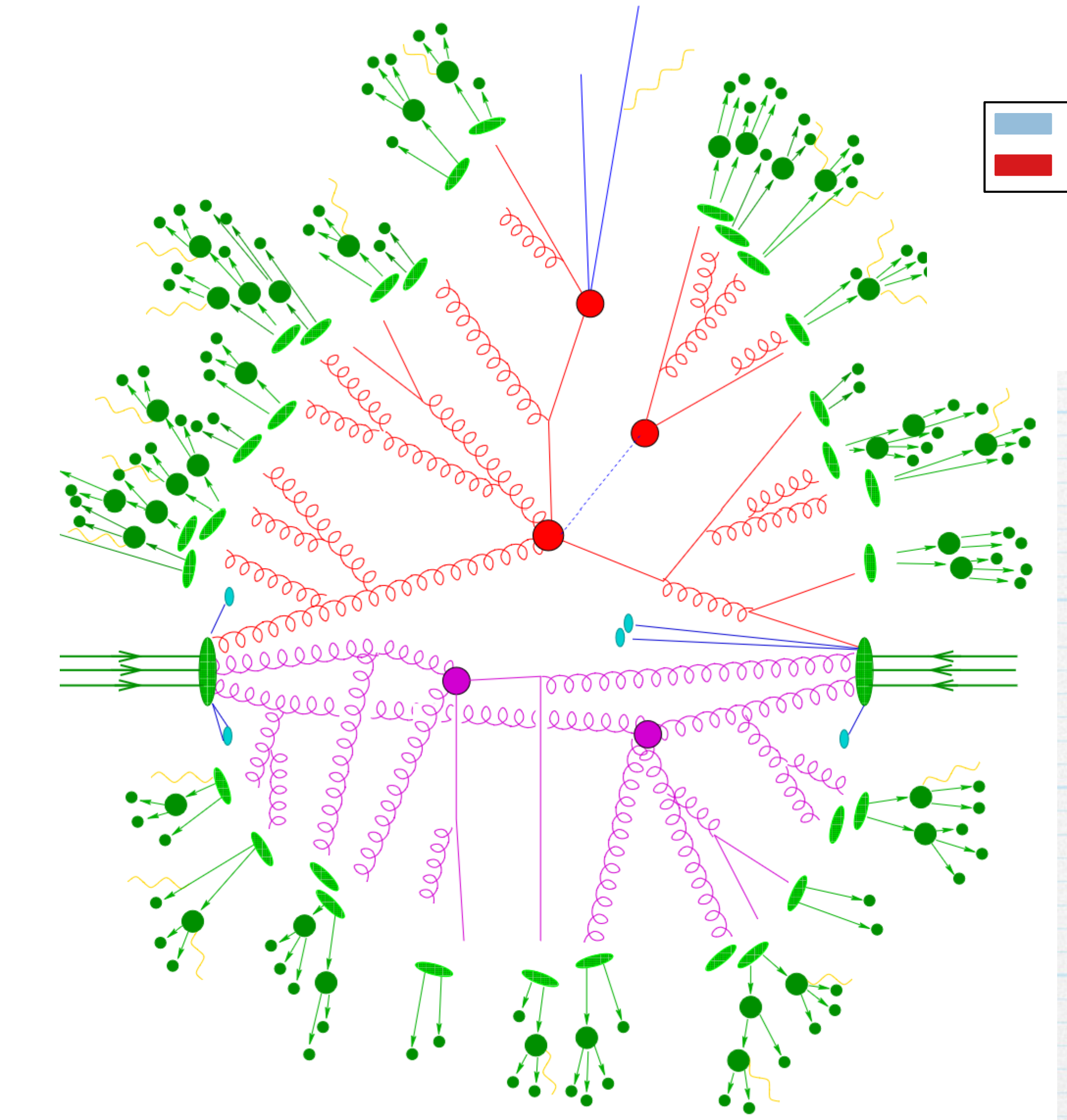
Top Physics, E. Yazgan, Lectures in Hadron Collider School - HASCO 2017, Gottingen, Germany, 16-21 July 2017.

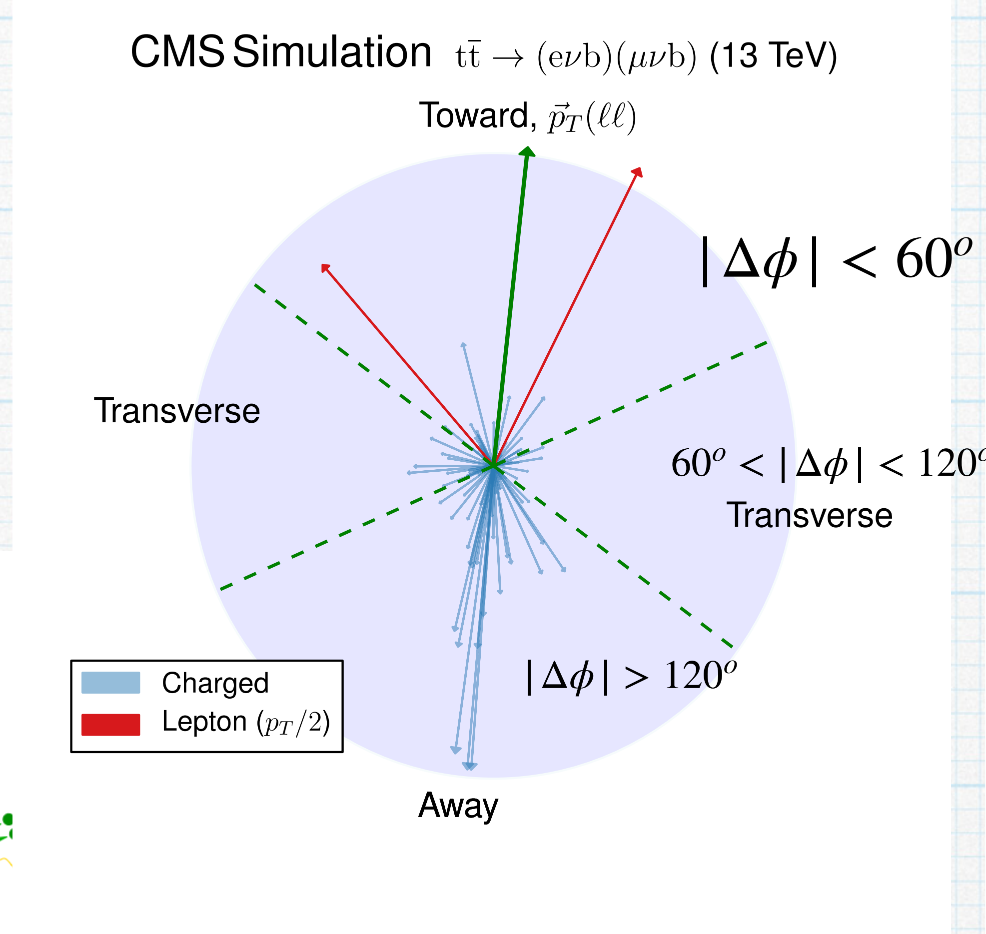
Top modelling: Underlying event in $pp \to t\bar{t}$ events

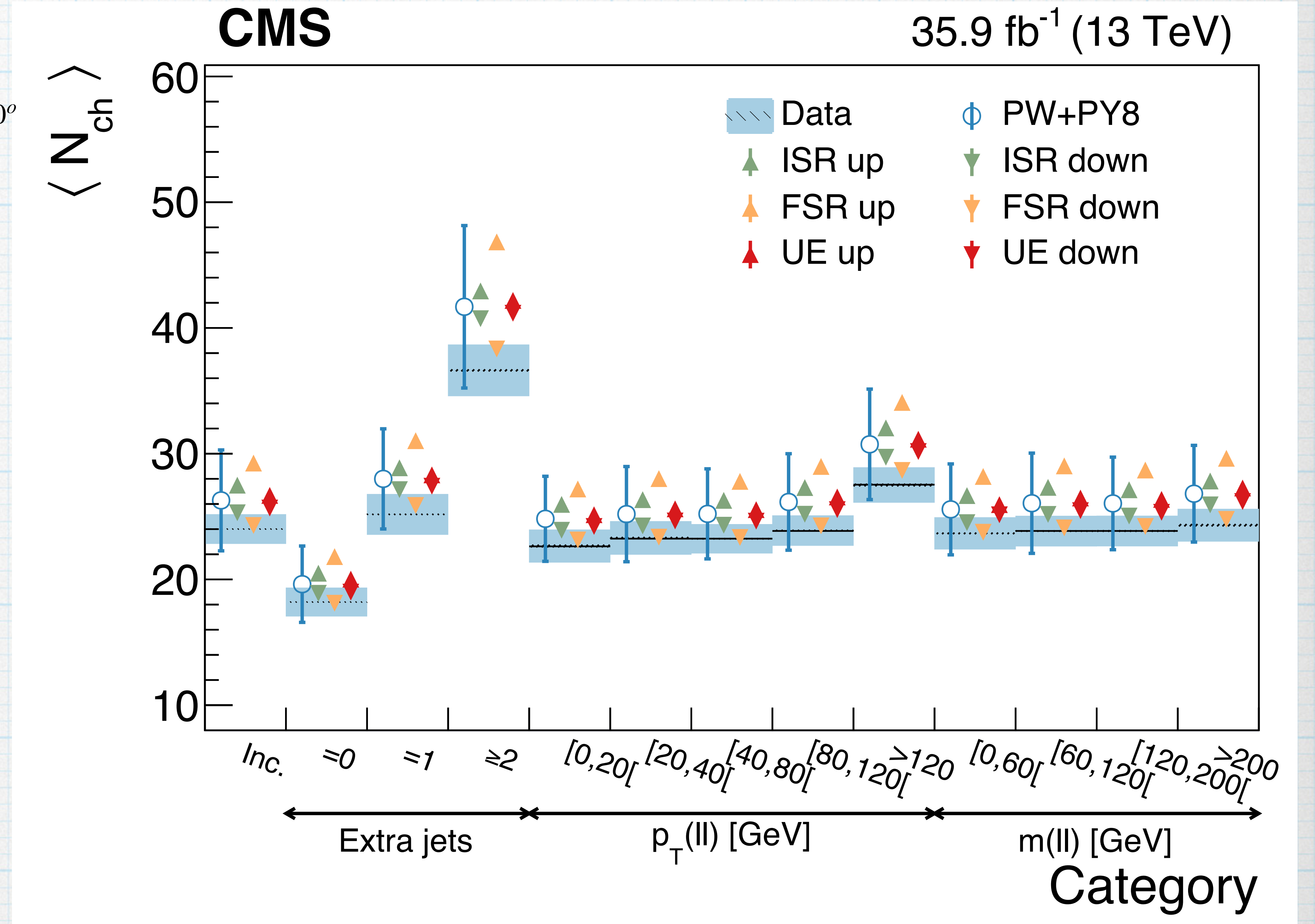
Particle flow (PF) candidates
POWHEG+PYTHIA8 [CUET8M2T4 tune]

CMS EPJC79(2019)123



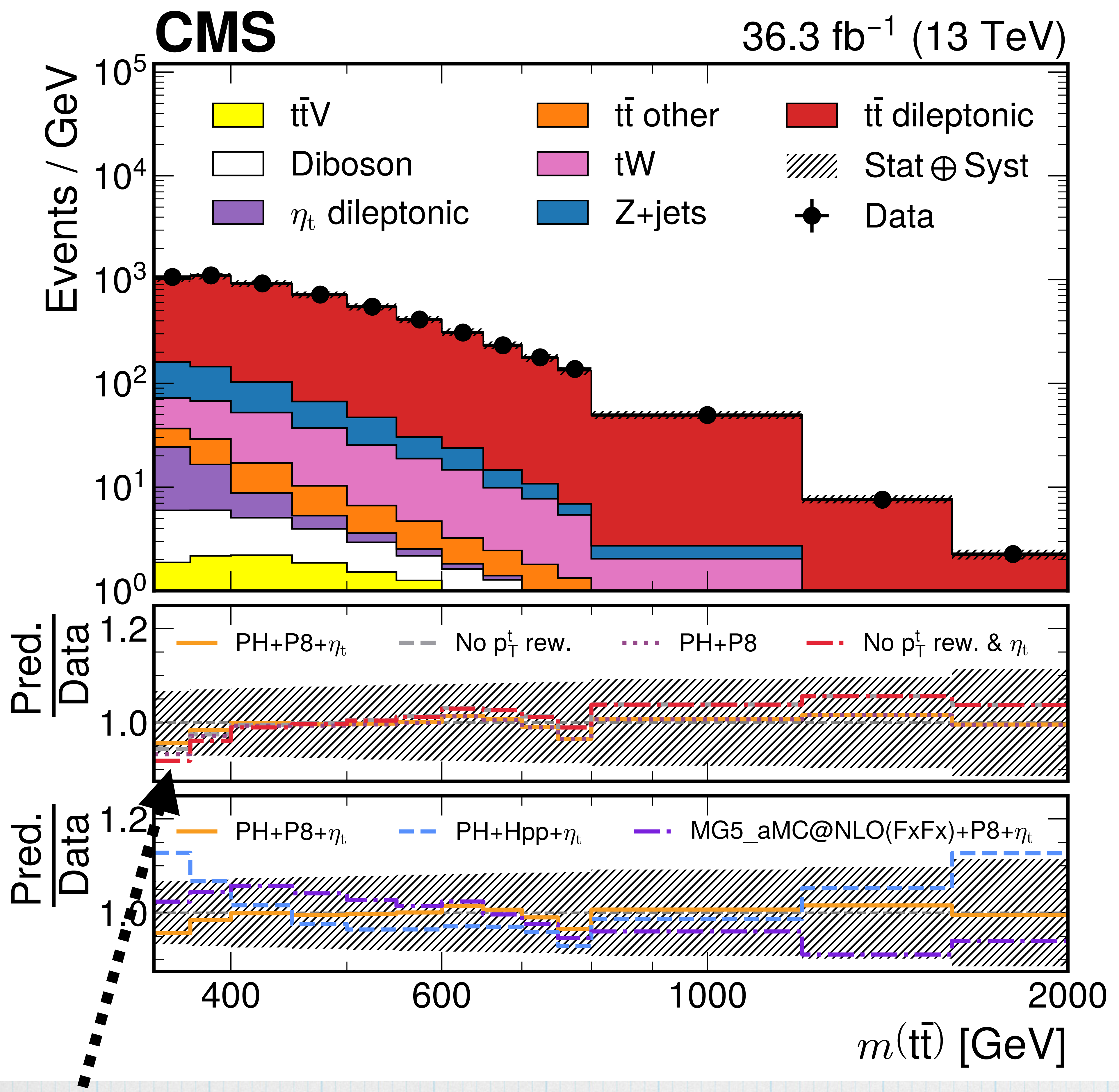






- Average ≈ 25 charged particles.
- $< N_{ch} >$ depends strongly on N(extra jets) and weakly on $m(\ell\ell)$.
- High $< N_{ch} >$ events –> collective/quark-gluon plasma effects?
  - Weak dependence on $m(\ell\ell)$ (also of other variables) shows that underlying event is « universal » but more precise measurements and characterization of underlying event in top quark events ==> more precise top mass measurements with better understood systematics.

Differential measurements



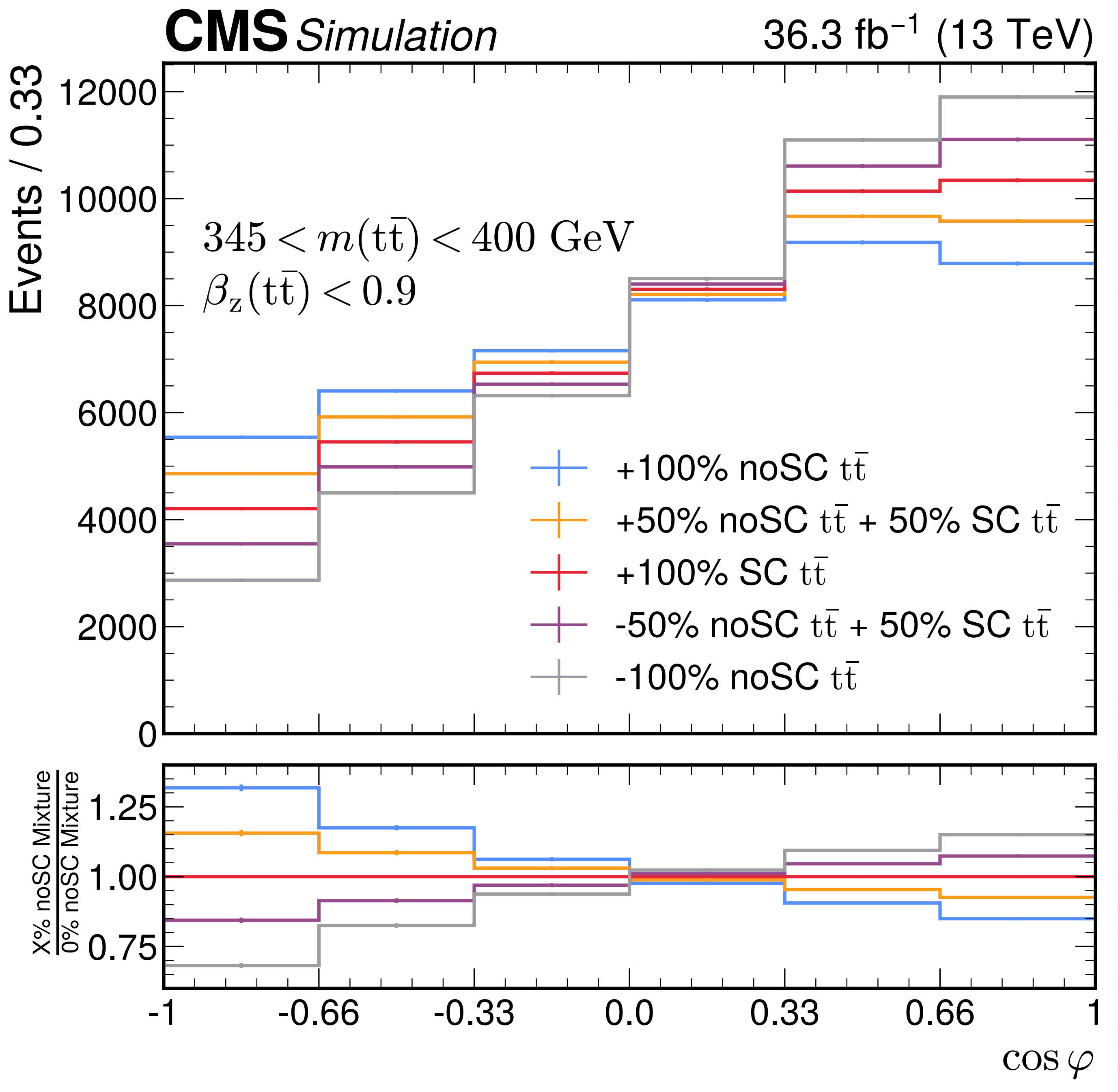
* Reconstructed invariant mass of the $t\bar{t}$ system compared to different MC configurations (also with and without « toponium ».
* Different parts of the phase space sensitive to different physics.
* $t\bar{t}$ production threshold: $m_{t\bar{t}} \approx 2m_t \simeq 345$ GeV
  * $t\bar{t}$ spin correlation depends on $m_{t\bar{t}}$ — BSM effects significant in $t\bar{t}$ spin correlations for high $m_{t\bar{t}}$.
  * Just below this threshold, recently discovered bound state of a top quark and top antiquark: « toponium ». — Recall: predicted in SM long before top quark discovery following the observations of b-quark and c-quark bound states.
  * Sensitive to quantum entanglement (an intrinsic property of quantum mechanics) — test predictions of quantum mechanics at highest energies currently possible.
  * Quantum magic — quantifies computational advantage of quantum over classical states.
  * $t\bar{t}$ production cross section sensitive to top-quark mass and top Yukawa coupling.

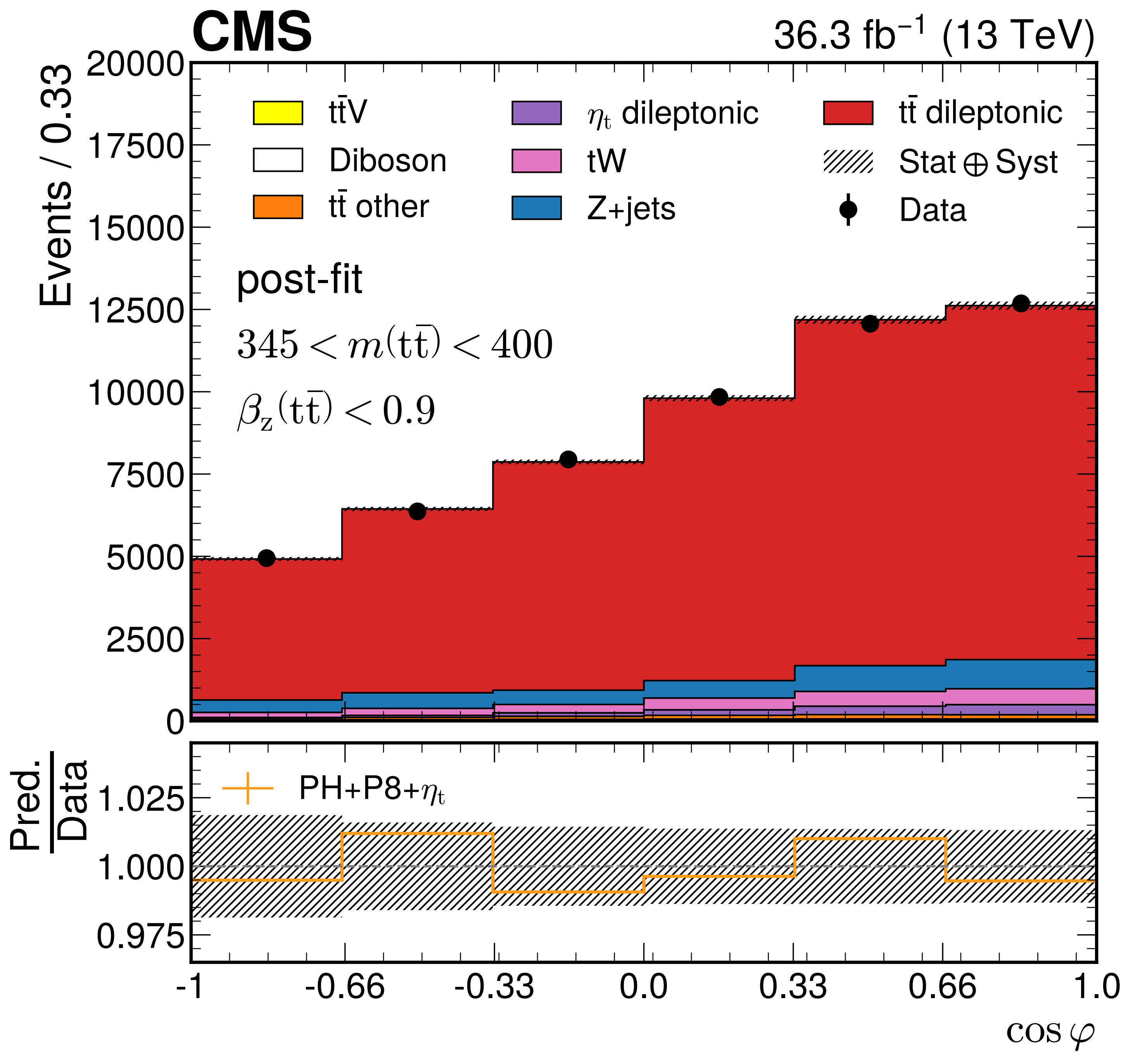
Spin correlation in dilepton channel

* At $m(t\bar{t}) \sim 350$ GeV: $D = -\frac{1}{3}\Delta_E$, $\frac{d\sigma}{d\cos\varphi} = \sigma_{norm}(1 - D\cos\varphi)$
* $D = 0 \leftrightarrow$ no spin correlation.

Helicity angle: $\cos\varphi = \hat{\ell}^+ \cdot \hat{\ell}^-$

* Top reconstruction
* D variations from samples w/ different degrees of SM and no-spin correlation assumptions.
* D measurement from binned-profile likelihood fit of $\cos\varphi$.
* Fits including (and not) a ground state « **toponium** » (η_t):
  * Non-relativistic QCD quasi-bound state model at 343 GeV, cross section=6.4 pb.





$$t\bar{t} + \eta_t$$

Rep. Prog. Phys. 87 (2024) 117801

Full Spin density matrix

* Differential cross section

$$\Sigma_{tot}(\phi_{p(\bar{p})}, \theta_{p(\bar{p})}) = \frac{d^4\sigma}{d_{\phi_p} dcos(\theta_p) d_{\phi_{\bar{p}}} dcos(\theta_{\bar{p}})}$$

$$= \sigma_{norm}(1 + \kappa \mathbf{P} \cdot \mathbf{\Omega} + \bar{\kappa} \bar{\mathbf{P}} \cdot \bar{\mathbf{\Omega}} - \kappa\bar{\kappa} \mathbf{\Omega} \cdot (C \bar{\mathbf{\Omega}}))$$

$$= \Sigma_0 + \sum_{m=1}^{15} Q_m \Sigma_m$$

Ω: unit vector in helicity basis.
P: polarization vector.
C: 3x3 spin correlation matrix
κ: spin analyzing power

Lepton and d-type quark (from W) for max top quark spin transfer to decay products: $\kappa \to 1$.

* $t\bar{t}$ spin dependence fully characterised by 15 coefficients
  $Q_m = \{P_n, P_r, P_k, \bar{P}_n, \ldots, C_{nn}, C_{nr}, \ldots, C_{kk}\}$ all probed by angular distributions
  $\Sigma_m = \sigma_{norm}\{\kappa \sin\theta_p \cos\phi_p, \ldots, \kappa\bar{\kappa} \cos\theta_p \cos\theta_{\bar{p}}\}$

PhysRevD 110 (2024) 112016

Quantum entanglement from $t\bar{t}$ spin density matrix

* Peres-Horodecki criterion [Afik, De Nova, EPJPlus 136 (2021) 907] provides sufficient condition for entanglement

$$\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$$

* Spin-singlet state (expected from $gg \to t\bar{t}$ at production threshold)

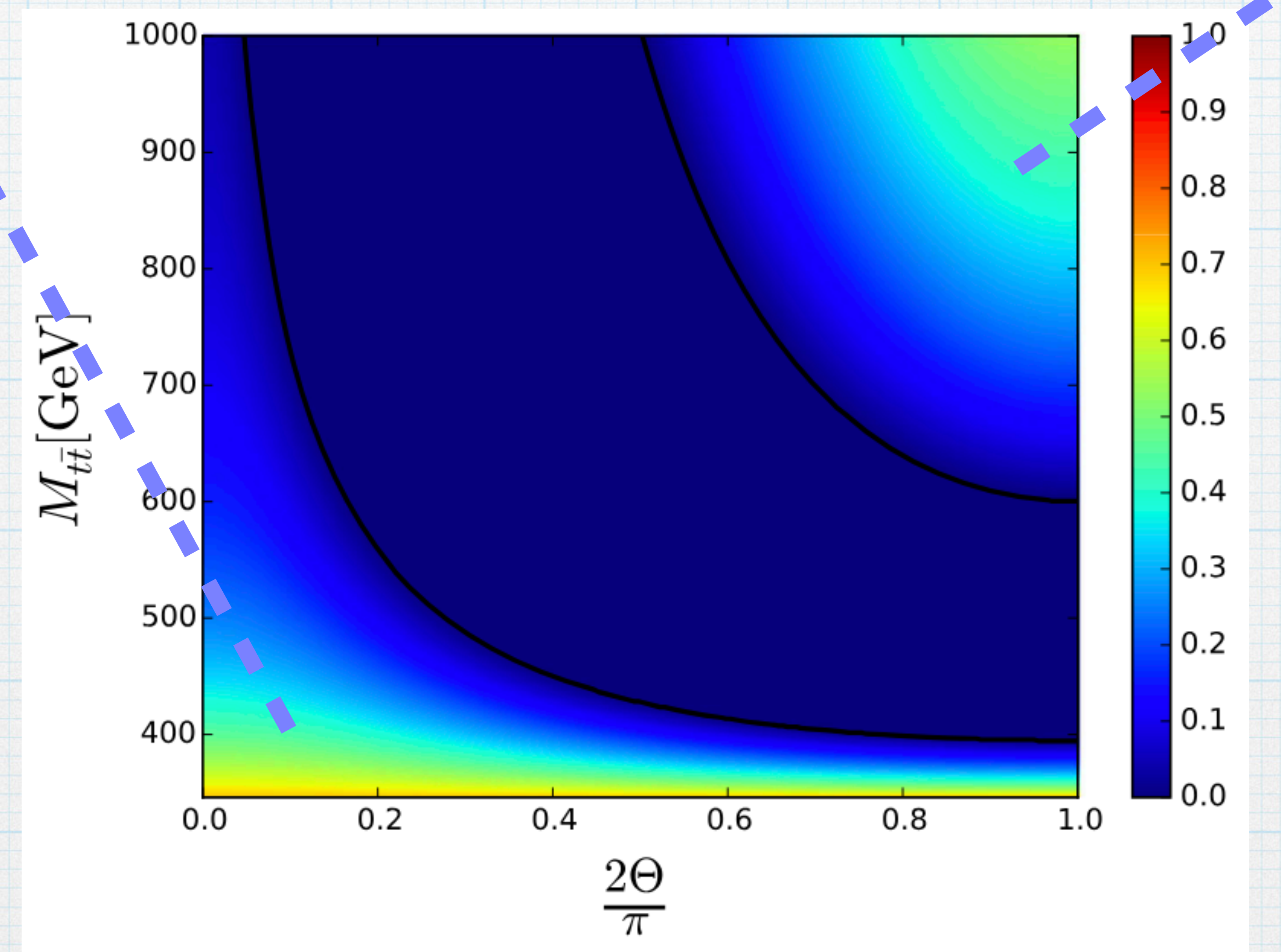
$$\frac{d\sigma}{d\cos(\chi)} = \sigma_{norm}(1 + D\kappa\bar{\kappa}\cos(\chi))$$

where $D = -\frac{1}{3}Tr(C)$

$$C_{rr}, C_{kk} > 0$$

$$\Delta_E = -3D = Tr(C) > 1$$

Extract D using χ: opening angle between two decay products in the helicity basis, $\cos\chi = \Omega \cdot \bar{\Omega}$



Afik, De Nova, EPJPlus 136 (2021) 907

* Spin-triplet state (expected from both $q\bar{q}, gg \to t\bar{t}$ at high $m(t\bar{t})$ and low $|\cos\theta|$)

$$\tilde{D} = \frac{1}{3}(C_{nn} - C_{rr} - C_{kk})$$

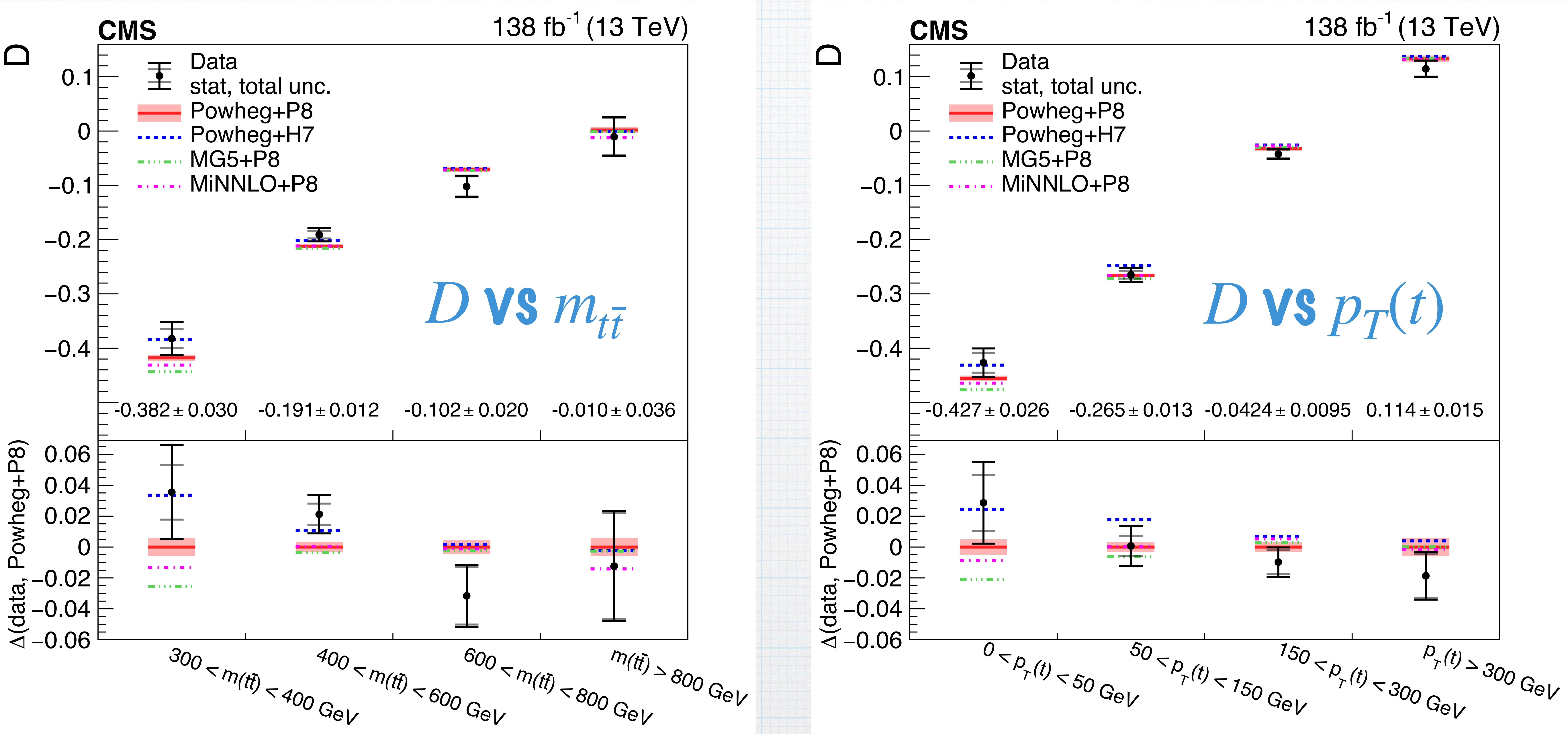
When $p_T(t) \sim m_t$,

$$C_{rr}, C_{kk} < 0$$

$$\Delta_E = 3\tilde{D} > 1$$

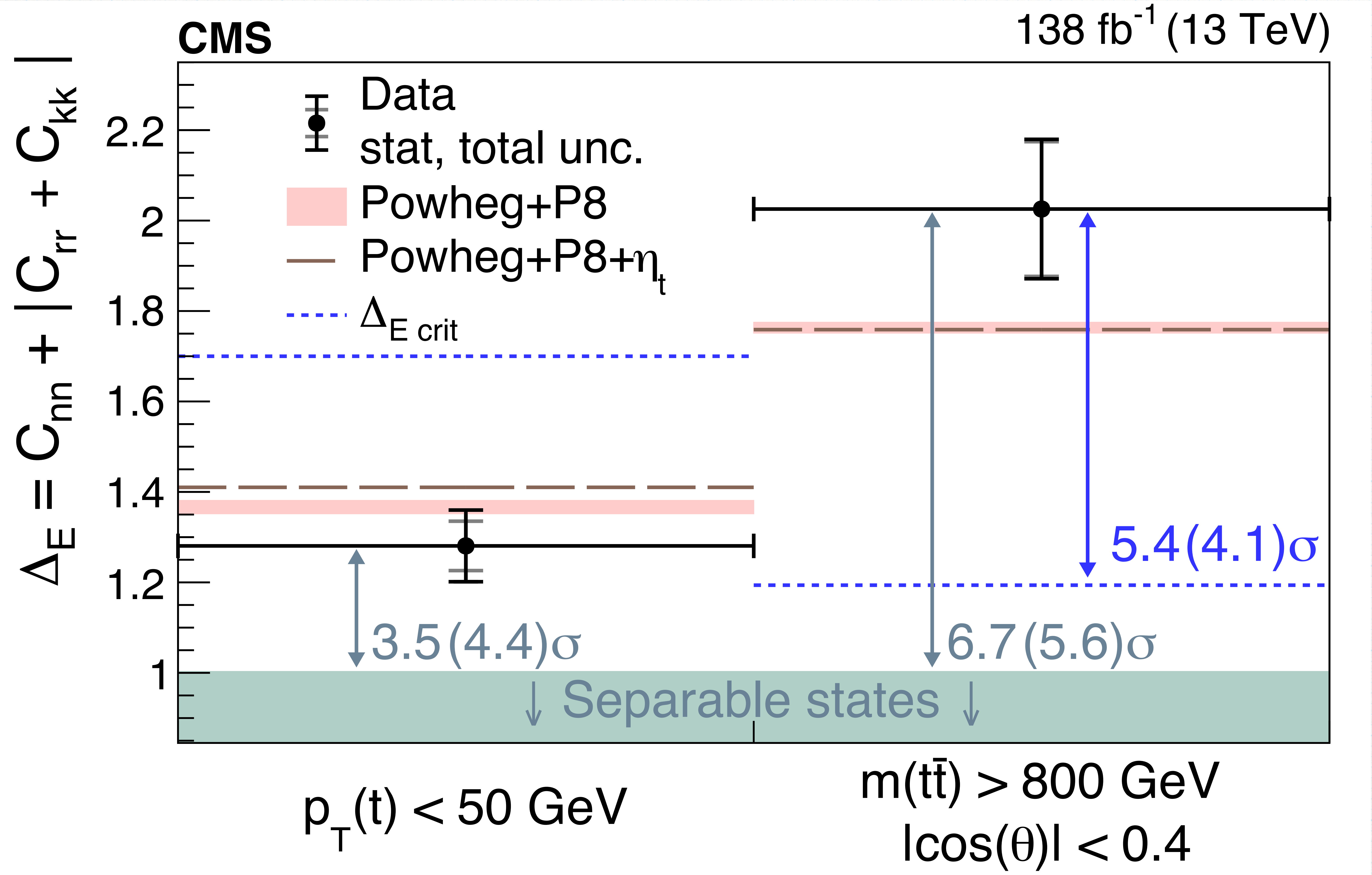
Extract $\tilde{D}$ using $\tilde{\chi} = -\Omega_n\bar{\Omega}_n + \Omega_r\bar{\Omega}_r + \Omega_k\bar{\Omega}_k$

Quantum entanglement from $t\bar{t}$ spin density matrix



* Good agreement with predictions.

Quantum entanglement from $t\bar{t}$ spin density matrix



* First observation of entanglement at high $m(t\bar{t})$ where ~90% of observed $t\bar{t}$ are space-like separated.

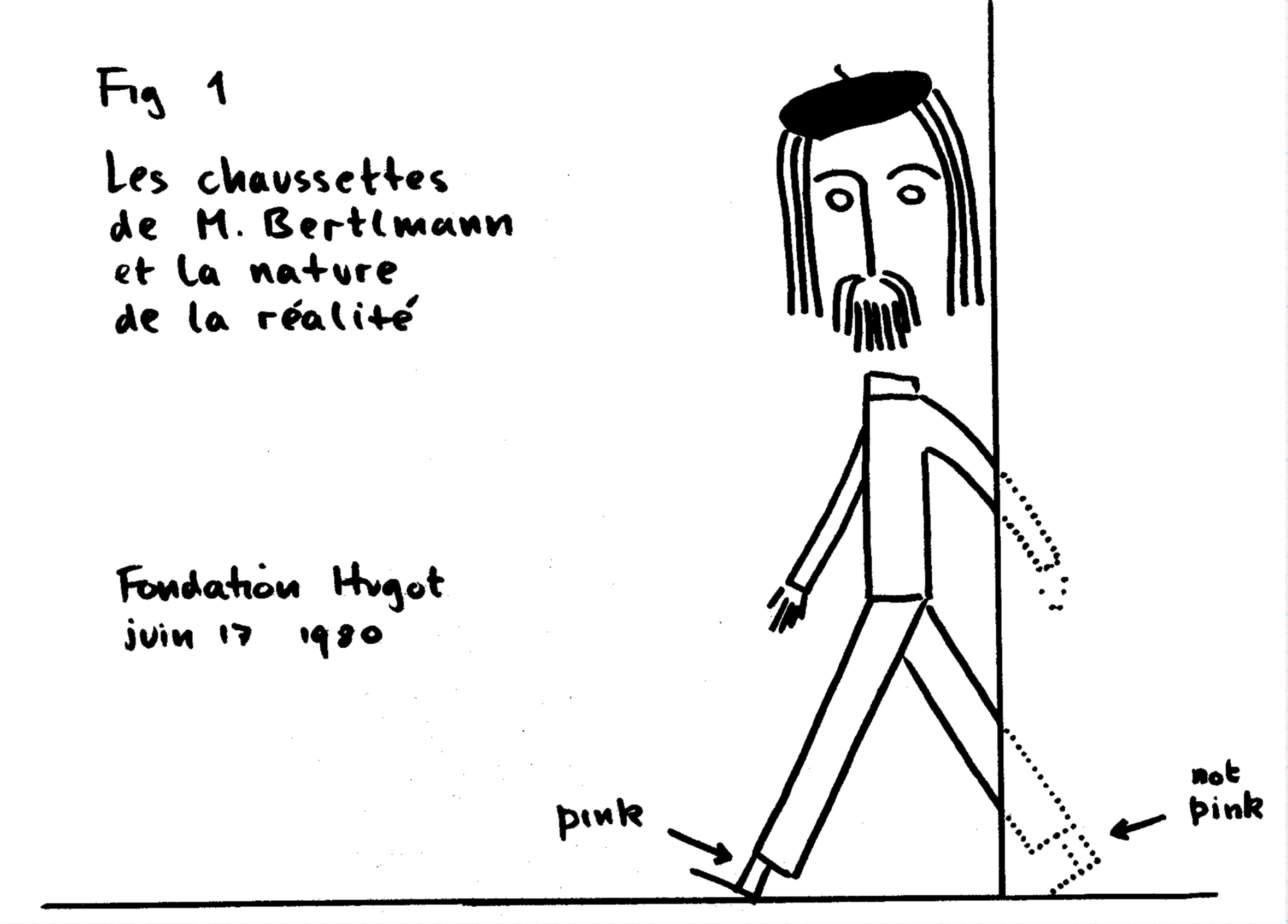
PhysRevD 110 (2024) 112016

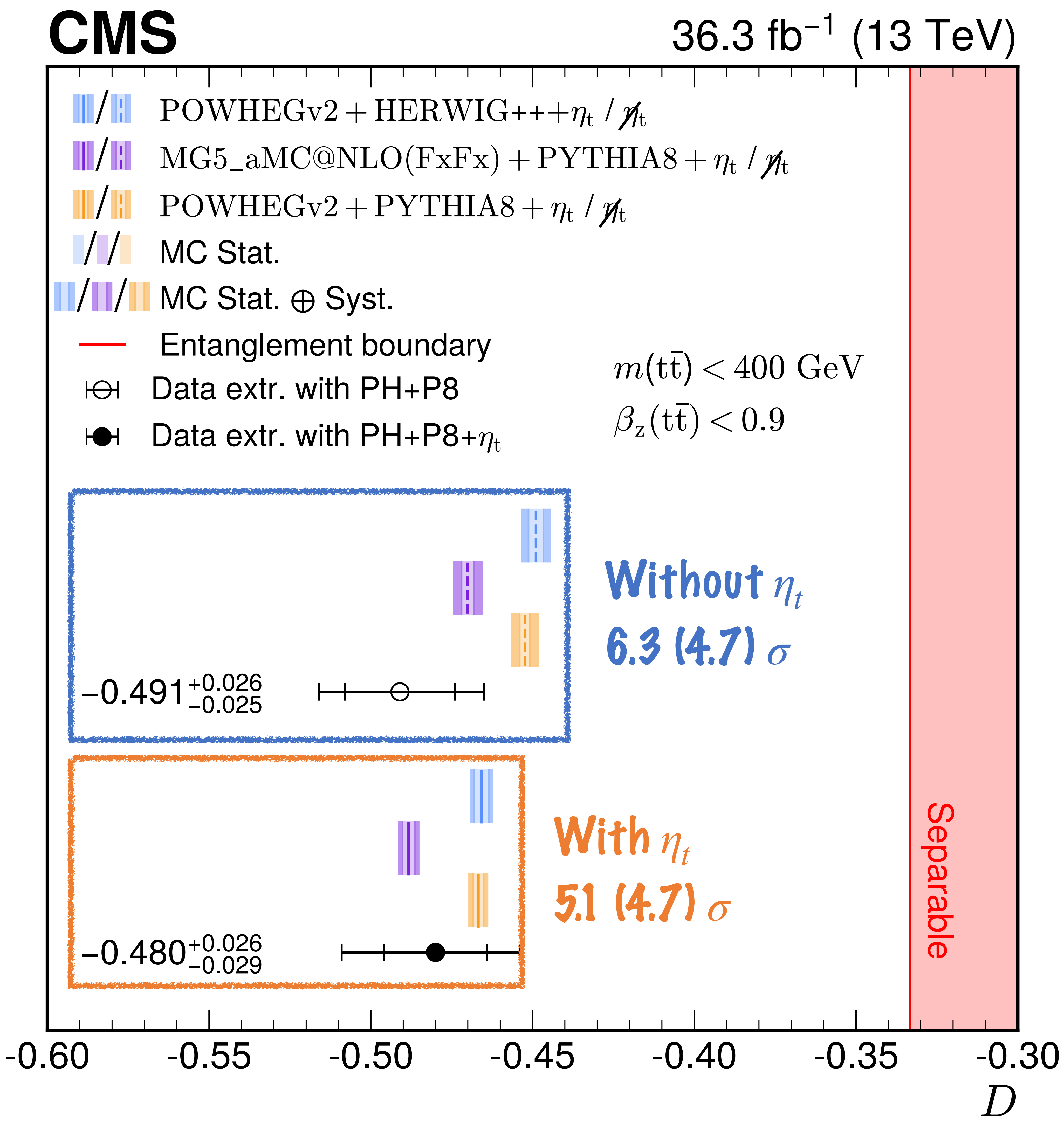
Quantum entanglement: dilepton channel

Rep. Prog. Phys. 87 (2024) 117801

* > 5σ observation of entanglement irrespective of η_t.
* Including η_t improves the data/simulation agreement.

J.S. Bell, CERN-TH-2926





Quantum « magic »

* Quantum Magic quantifies the computational advantage of quantum over classical states.
    * **Entanglement by itself doesn't guarantee this.**

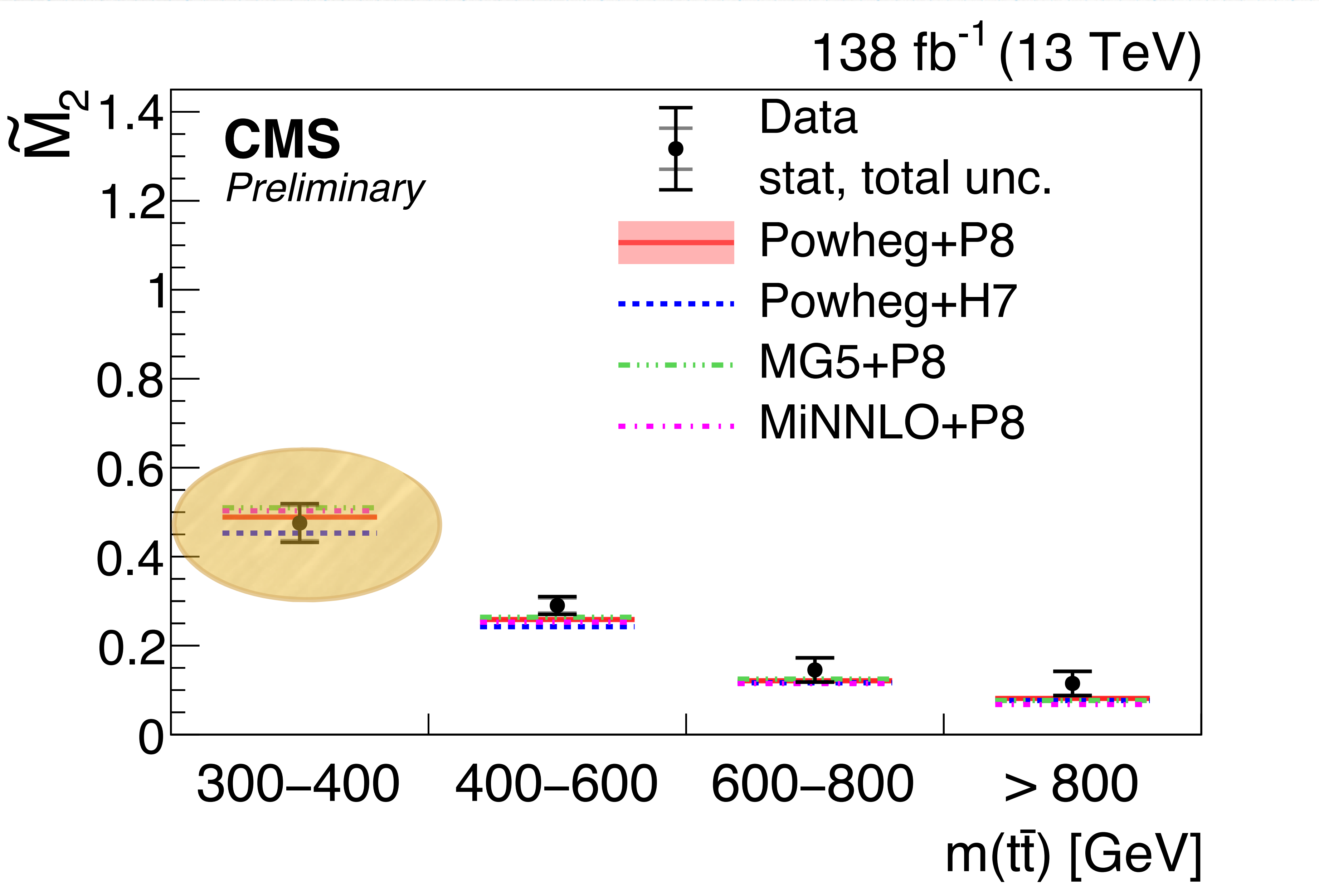
For mixed states **(e.g. two-qubit $t\bar{t}$ system):**

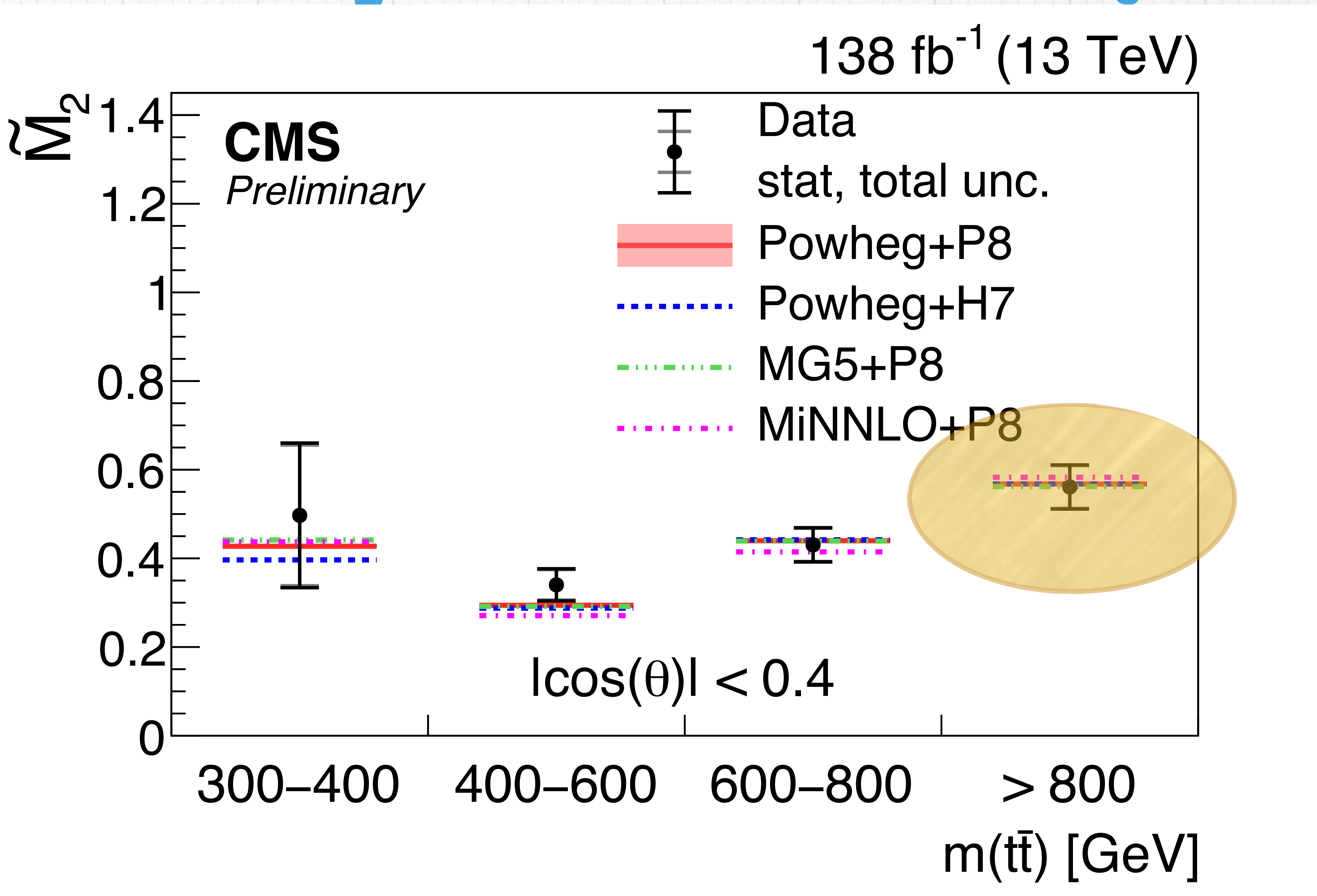
$$\tilde{M}_2 = -\,log_2\left(\frac{1+\Sigma_{i\in n,k,r}[(P_i^4+\bar{P}_i^4)]+\Sigma_{i,j\in n,k,r}C_{ij}^4}{1+\Sigma_{i\in n,k,r}[(P_i^2+\bar{P}_i^2)]+\Sigma_{i,j\in n,k,r}C_{ij}^2}\right)$$

* Zero magic $\leftrightarrow$ classical computer.
* **$\tilde{M}_2$ is nonlinear and phase-space dependent: nonzero magic from $pp \to t\bar{t}$ doesn't mean the same thing for individual processes $qq \to t\bar{t}$ and $gg \to t\bar{t}$ b/c.**

CMS-PAS-TOP-25-001

Quantum « magic » from $t\bar{t}$ spin density matrix

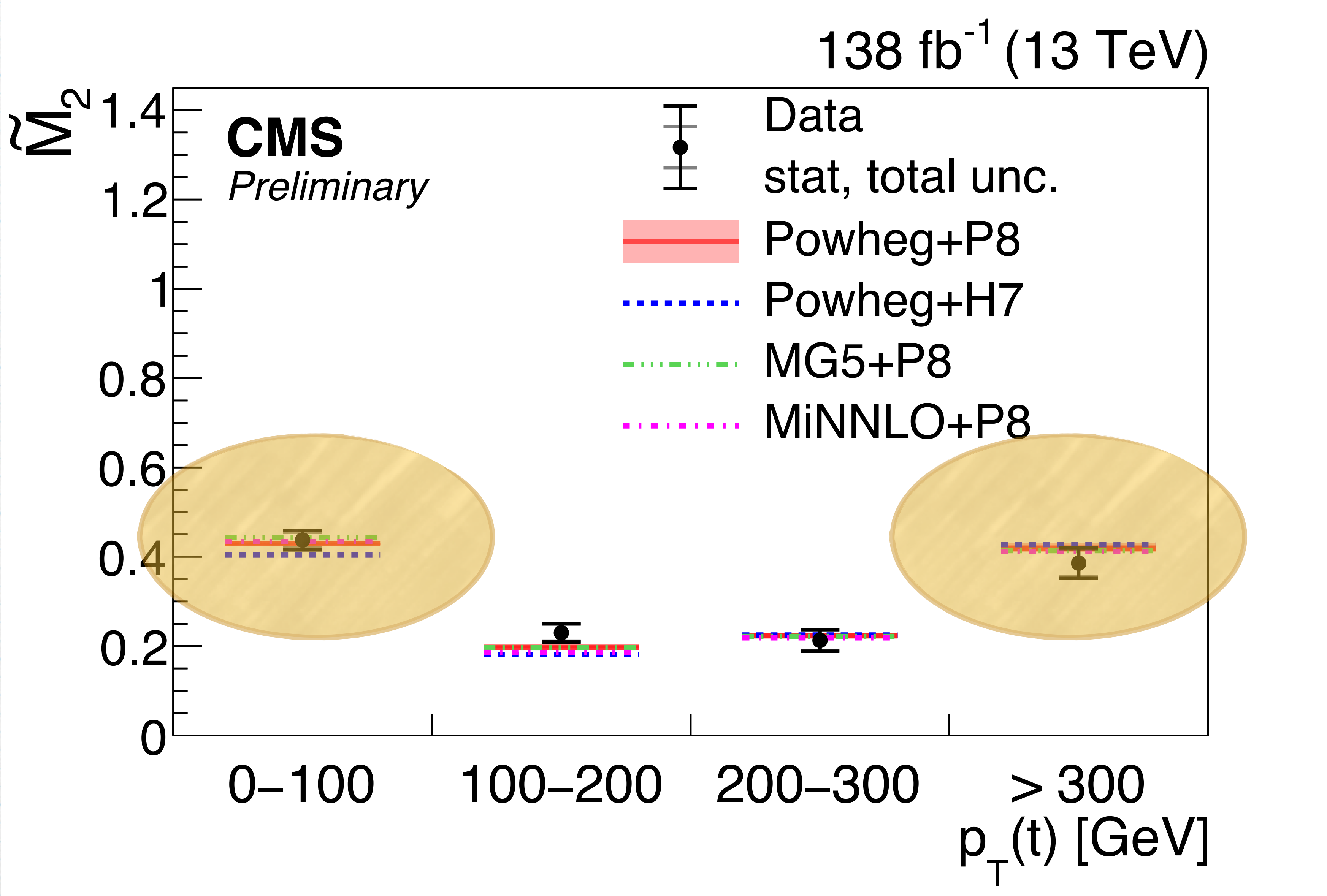




- Calculation uses the spin density matrix measurement from the lepton+jets channel [PhysRevD 110 (2024) 112016]
- First magic measurement from $t\bar{t}$ spin density matrix → $\tilde{M}_2 > 0$

CMS-PAS-TOP-25-001

- Depends on phase space region/Good agreement with predictions./Statistical uncertainties dominant.
  - one of the first connections between **quantum information science** and **particle physics**.
  - shows the potential of **collider experiments for investigating foundations of quantum mechanics.**



The top quark — toponium formation

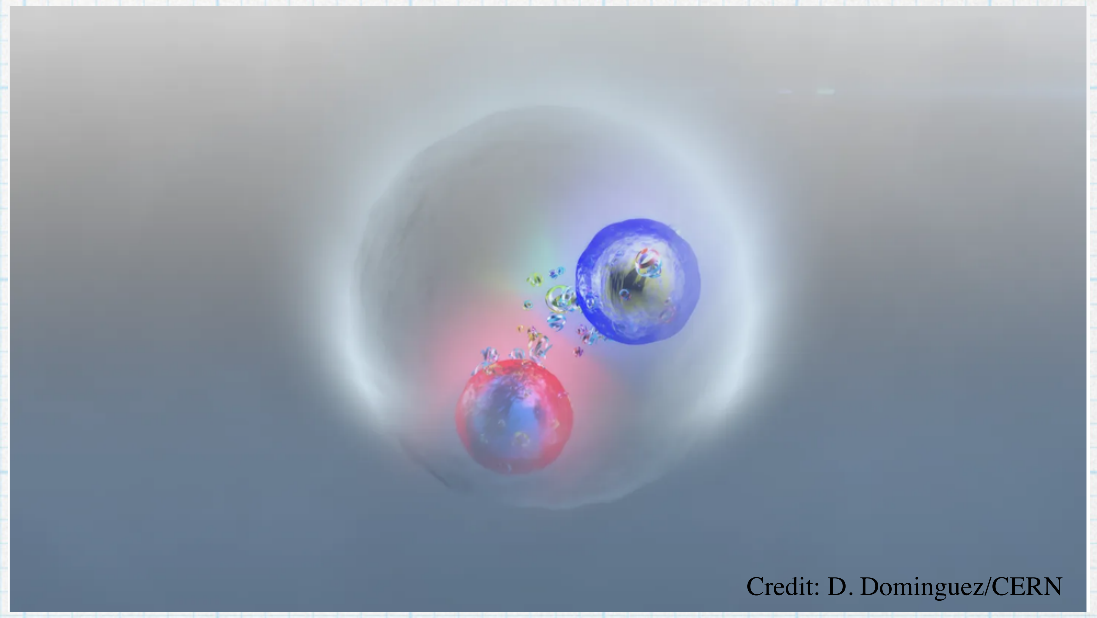
* **Most massive** elementary particle known since **'96**— **very short lifetime.**

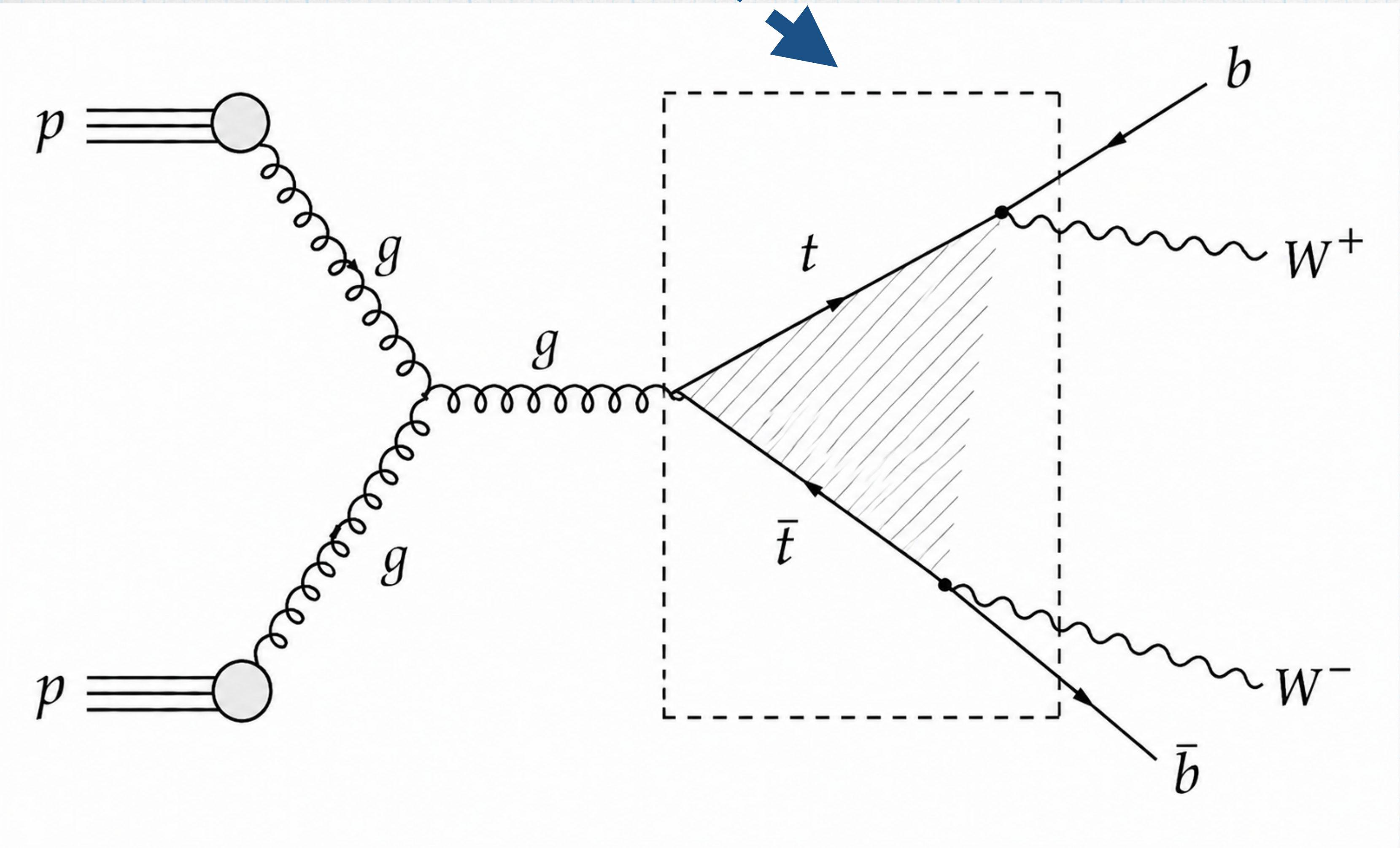
$$\frac{1}{m_t} < \frac{1}{\Gamma_t} < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda^2_{QCD}}$$

production 10^{-27} s | lifetime 10^{-25} s | hadronization 10^{-24} s | spin-decorrelation 10^{-21} s

Λ_{QCD}: scale at which α_s becomes very strong
$\sim$ 1 fm scale of a hadron (proton radius)

Bigi et al. PLB181(1986)157





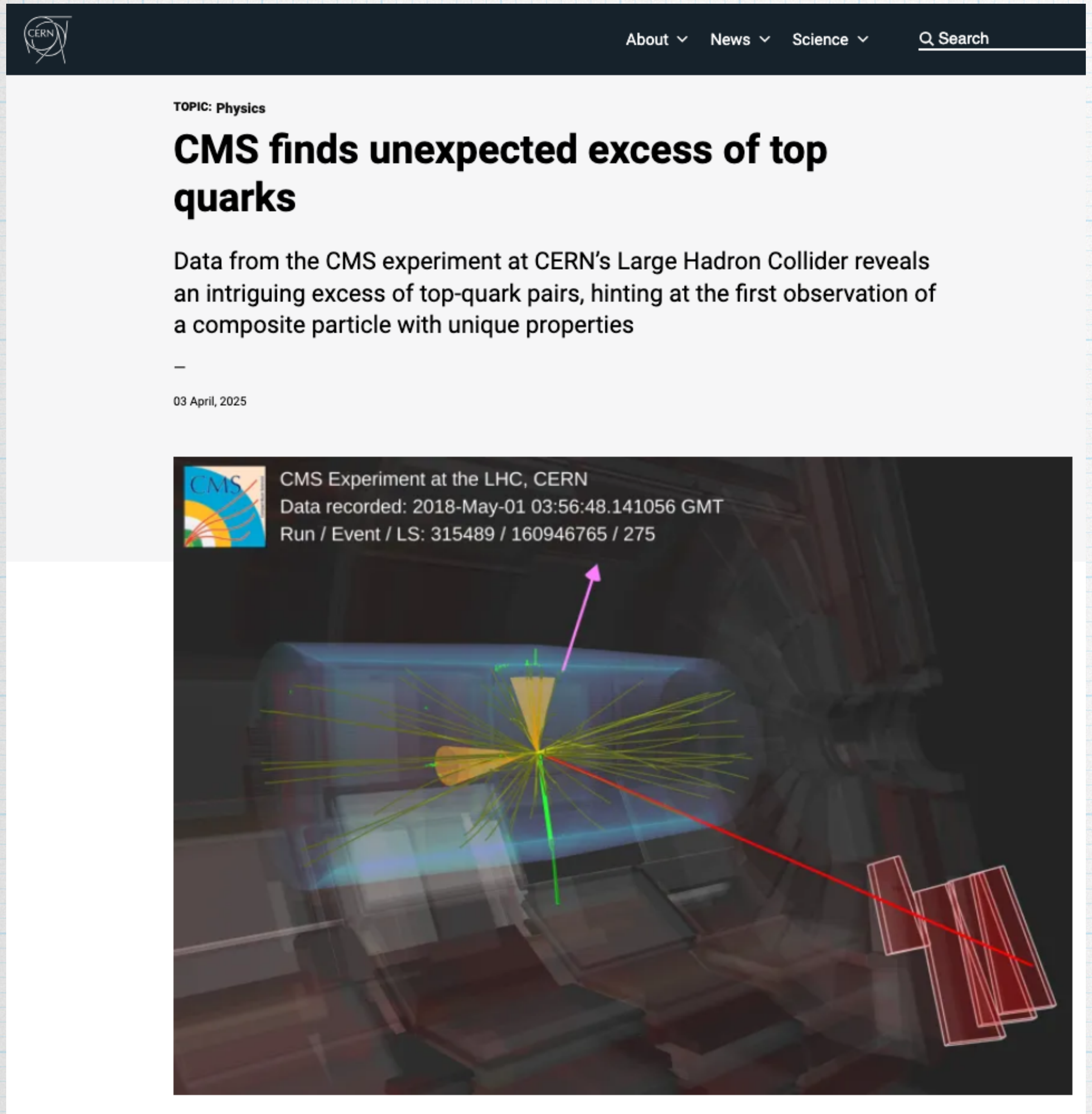
Adapted from Sumino et al. PRD47(1993)56

* Toponium: quasi-bound Coulombic system (it can be classified using the spectroscopic notation: ${}^1S_0^{[1]}, {}^3P_0^{[1]}$ etc.).
* Top has small speed in $t\bar{t}$ system: $p \approx \alpha_s m_t \rightarrow v = \frac{p}{l} m_t \approx \alpha_s$
* Rotation period or toponium formation time: $\sim \frac{r}{v} \approx \frac{1}{\alpha_s^2 m_t} \sim 3.3 \times 10^{-25}$ s

similar to top quark lifetime —> Only a small portion of t and $\bar{t}$ will survive a complete rotation to have an observable effect.

==> The smallest hadron in the SM
==> The heaviest known bound state! (more massive than the most massive atomic nucleus).

Toponium observation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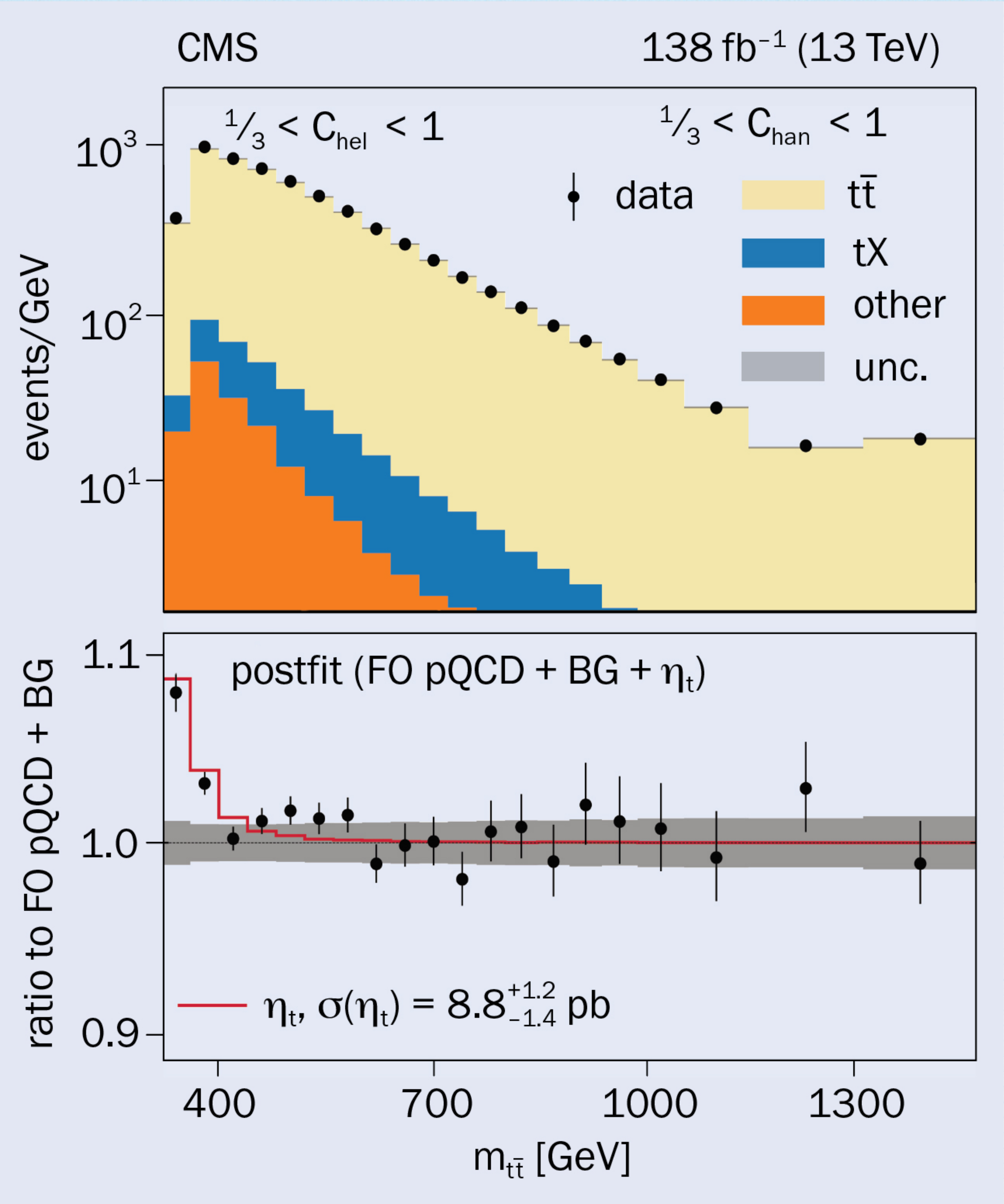
TOPIC: Physics

CMS finds unexpected excess of top quarks

Data from the CMS experiment at CERN's Large Hadron Collider reveals an intriguing excess of top-quark pairs, hinting at the first observation of a composite particle with unique properties

03 April, 2025

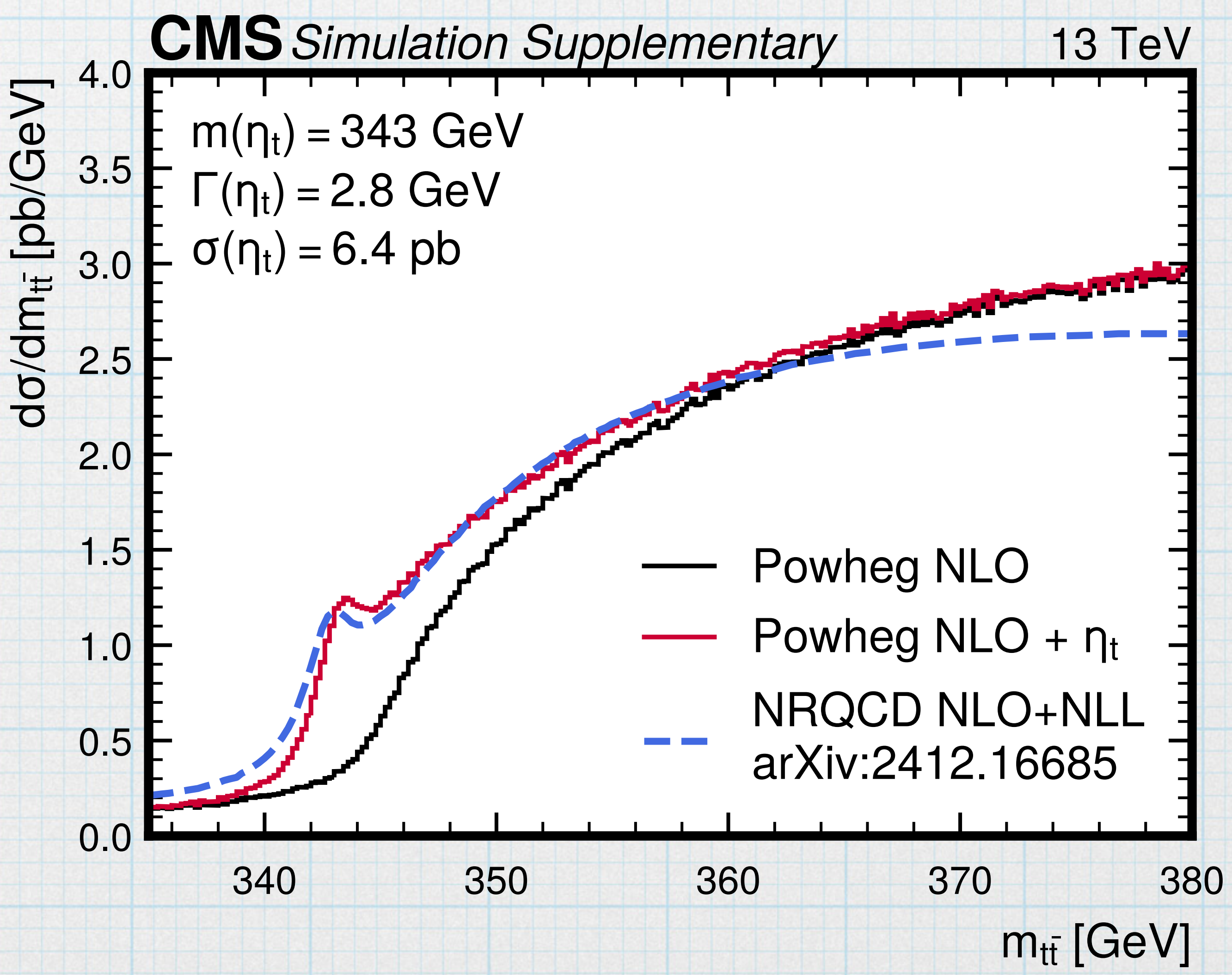
https://home.cern/cms-finds-unexpected-excess-top-quarks/



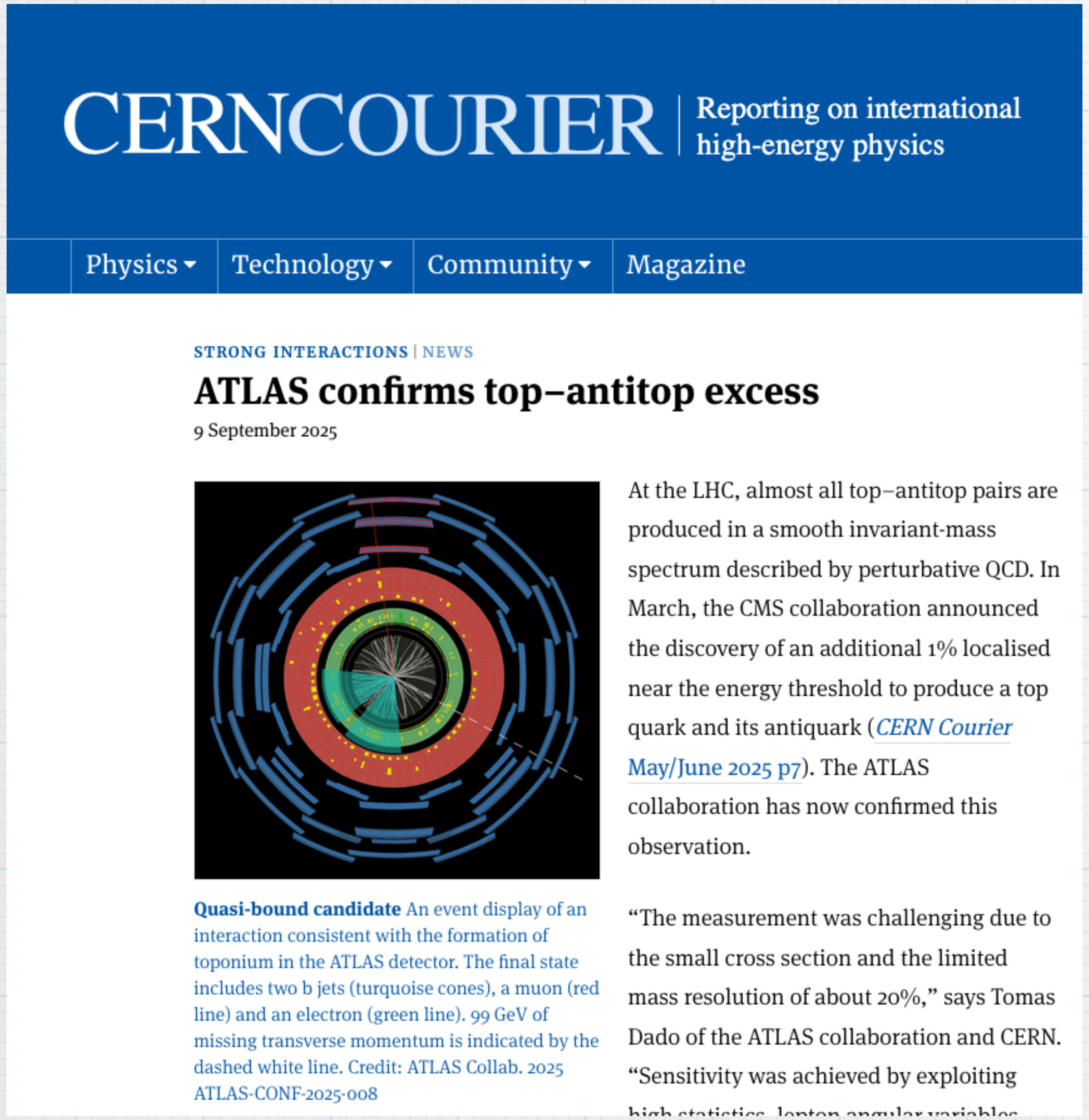
https://arxiv.org/abs/2503.22382

https://cerncourier.com/a/cms-observes-top-antitop-excess-2/

* Invariant mass of top quark-antiquark pairs in certain regions defined by spin-correlation observables.
* Excess can be modelled by a new top-antitop bound state: « toponium »



Toponium observation



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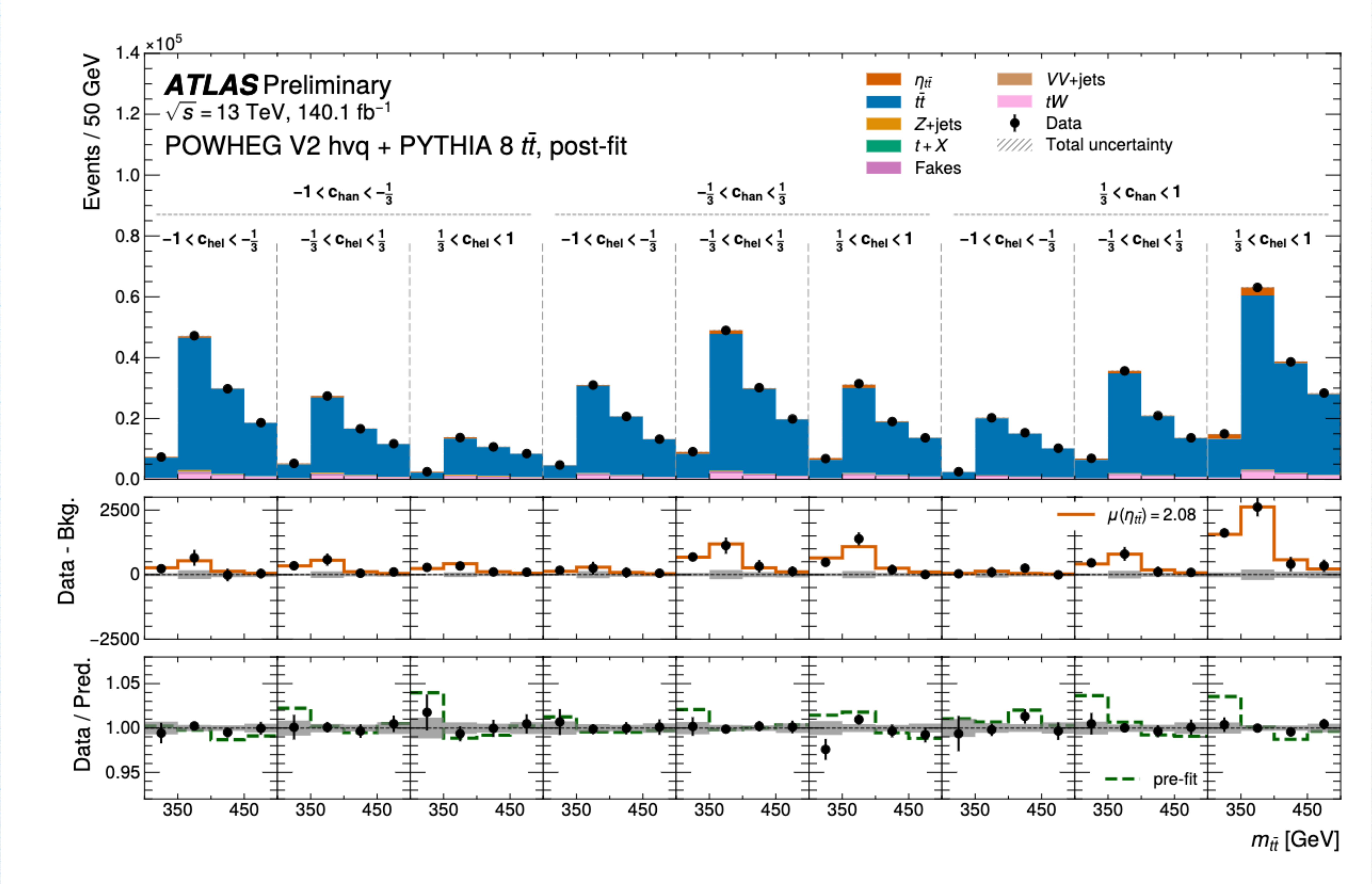
ATLAS confirms top–antitop excess

9 September 2025

At the LHC, almost all top–antitop pairs are produced in a smooth invariant-mass spectrum described by perturbative QCD. In March, the CMS collaboration announced the discovery of an additional 1% localised near the energy threshold to produce a top quark and its antiquark (*CERN Courier* May/June 2025 p7). The ATLAS collaboration has now confirmed this observation.

Quasi-bound candidate An event display of an interaction consistent with the formation of toponium in the ATLAS detector. The final state includes two b jets (turquoise cones), a muon (red line) and an electron (green line). 99 GeV of missing transverse momentum is indicated by the dashed white line. Credit: ATLAS Collab. 2025 ATLAS-CONF-2025-008

"The measurement was challenging due to the small cross section and the limited mass resolution of about 20%," says Tomas Dado of the ATLAS collaboration and CERN. "Sensitivity was achieved by exploiting

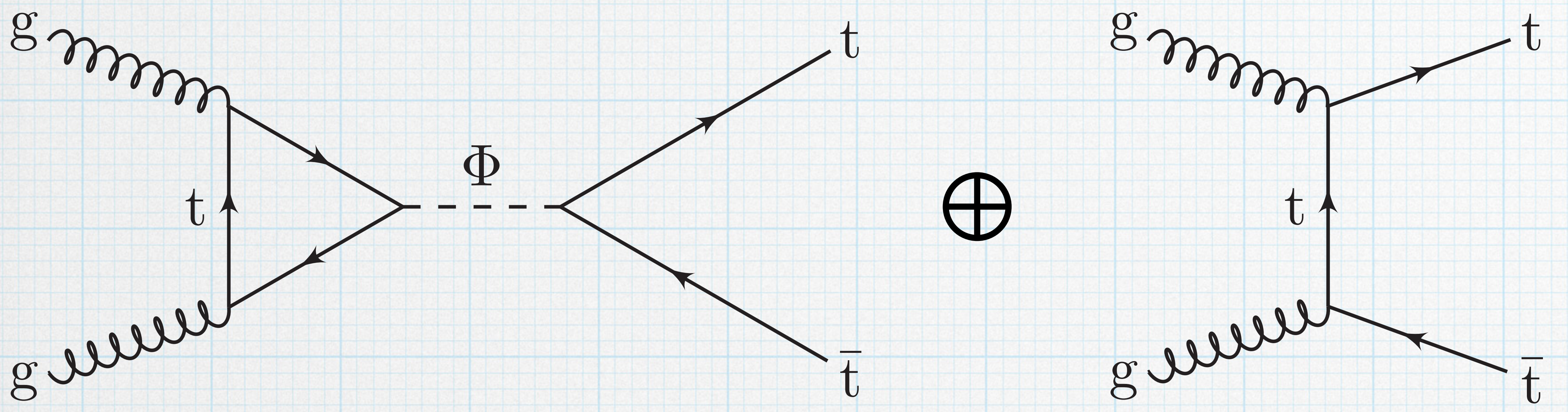


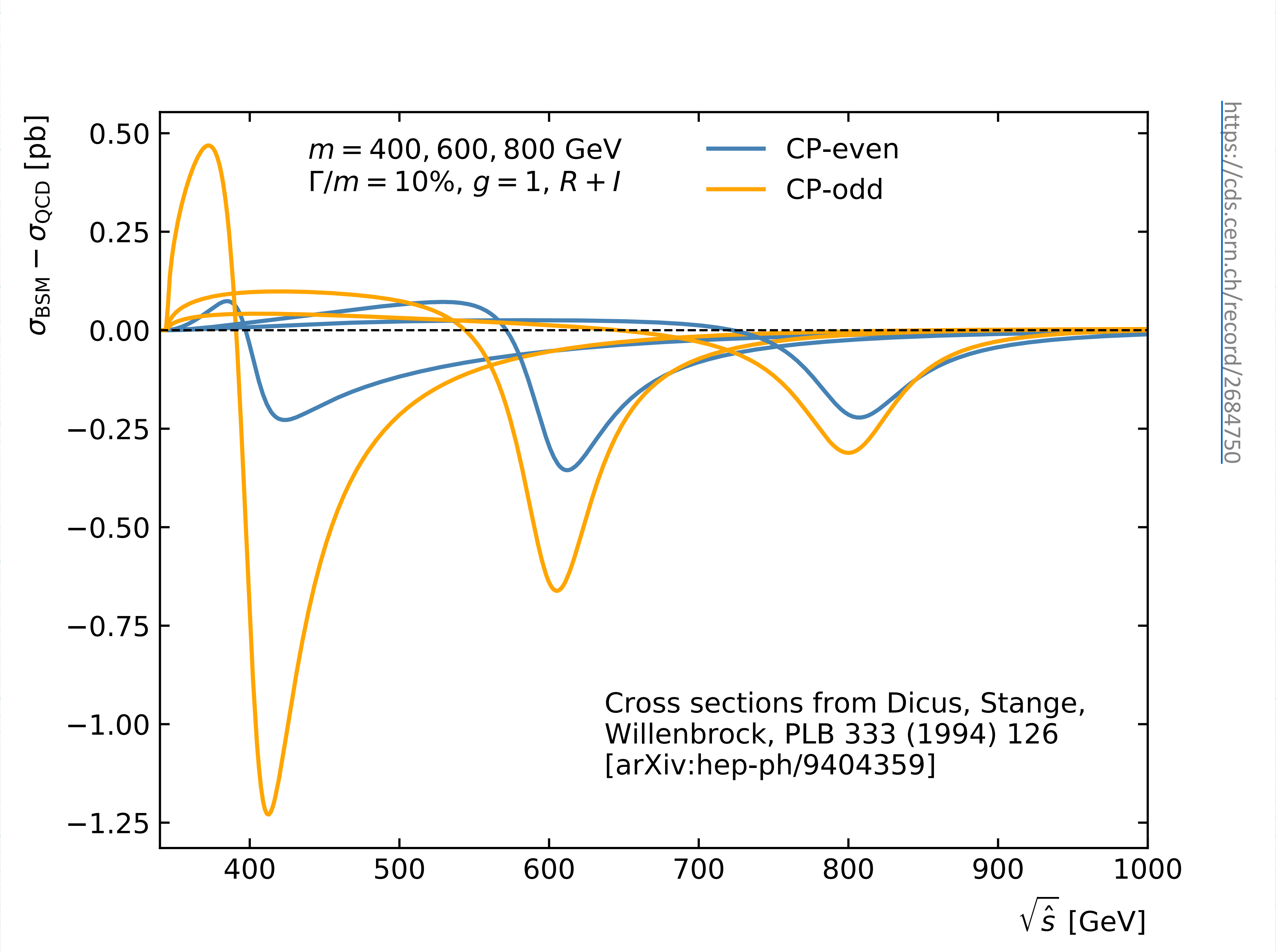
https://cds.cern.ch/record/2937636/files/ATLAS-CONF-2025-008.pdf

* At least one of Okun's criteria satisfied...

$A/H \rightarrow t\bar{t}$

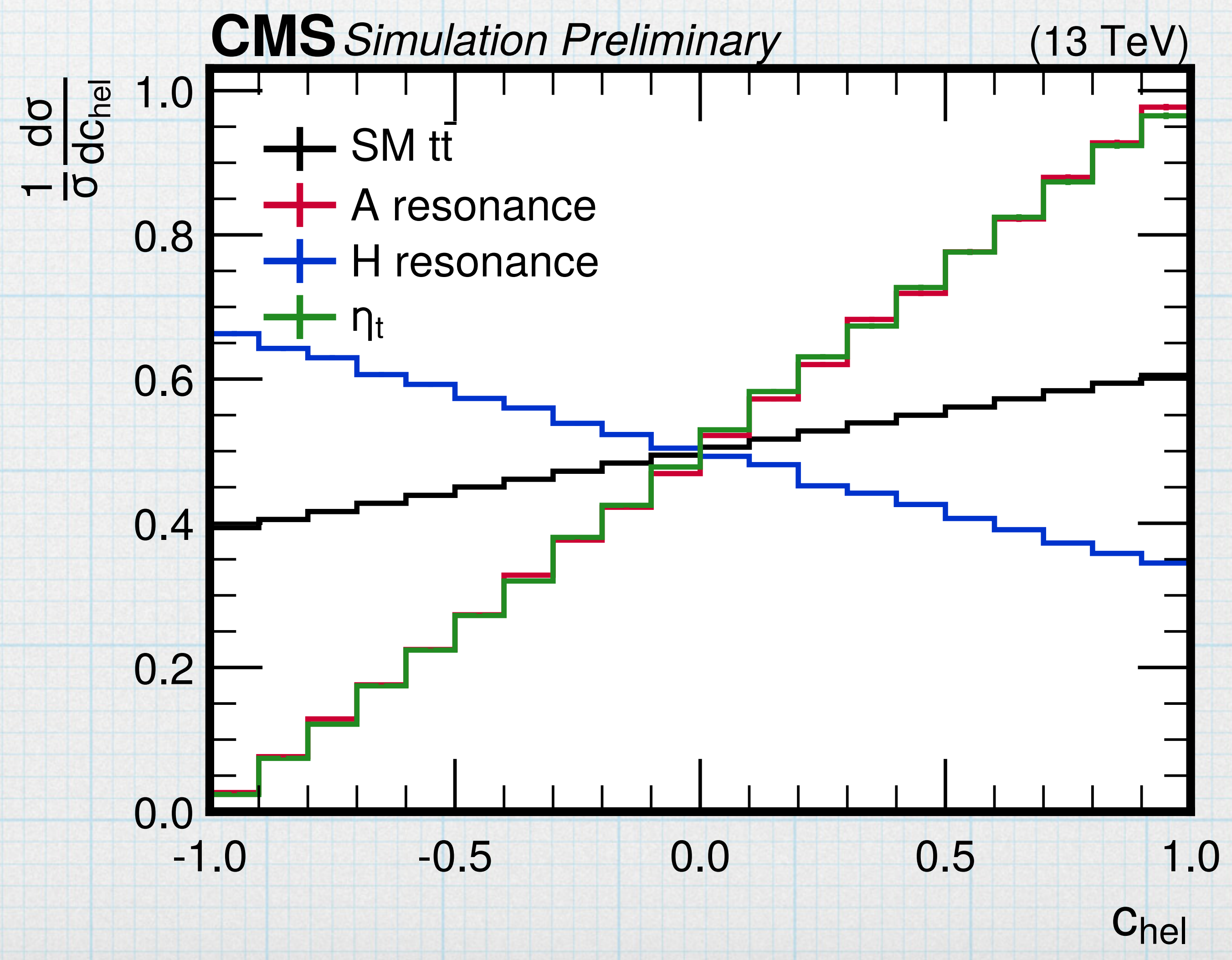
CMS-PAS-HIG-22-013





https://cds.cern.ch/record/2684750

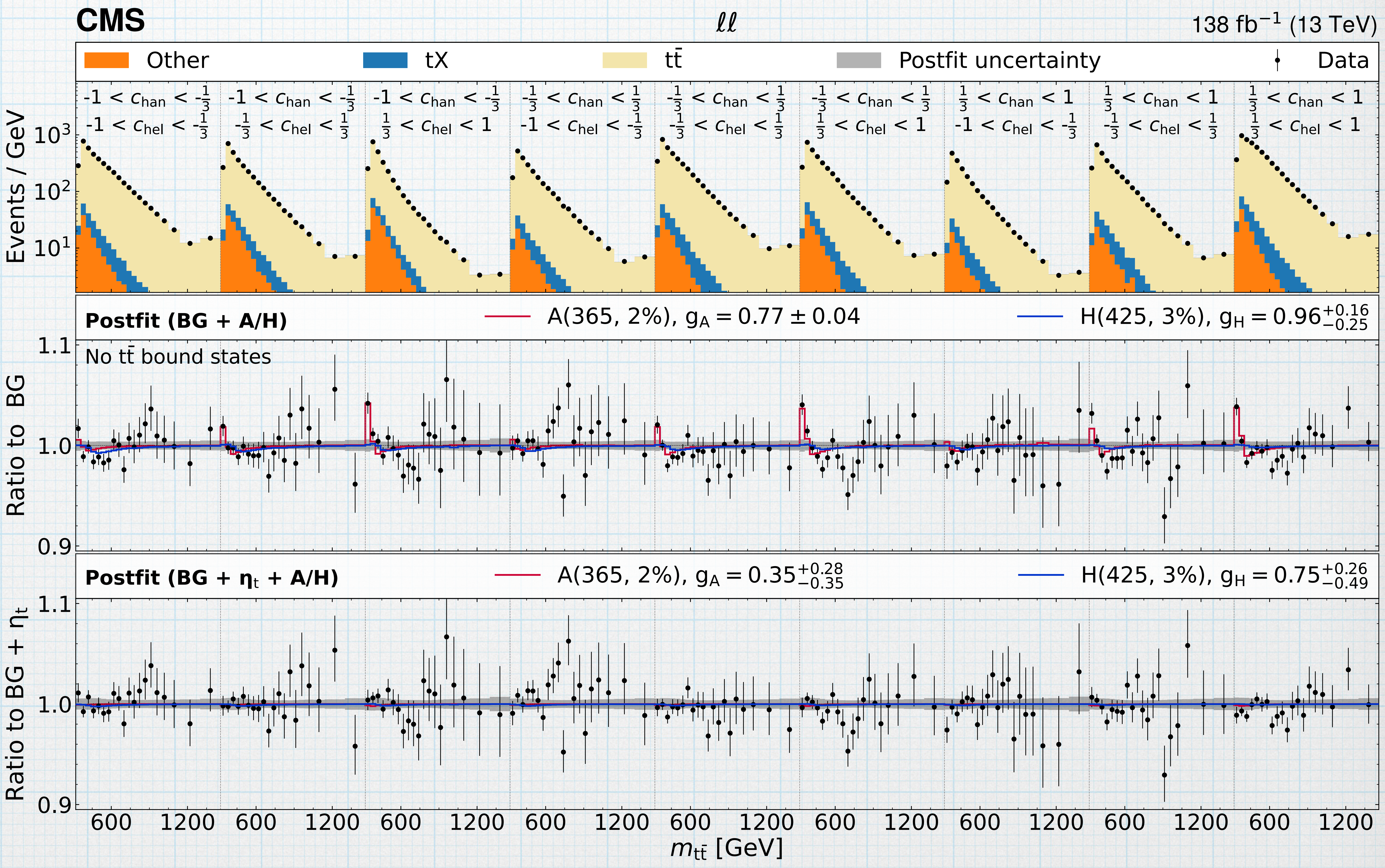
- Signal extraction using $m_{t\bar{t}}$ and spin correlation observables (in dilepton and lepton+jets channels).
- Interpretations with
  - Pseudoscalar colour-singlet $t\bar{t}$ bound state (η_t) from a simplified model of non relativistic QCD (NRQCD) [Fuks et al. arrive:2102.11281] (« toponium »)
  - A and/or H including interference with SM $t\bar{t}$ with or without « toponium ».
    - No interference between A and H.



$A/H \to t\bar{t}$ or toponium

* Colour-singlet ${}^1S_0^{[1]}$ $t\bar{t}$ quasi-bound state, η_t, within a simplified non relativistic QCD model, with an unconstrained normalisation to the background —> agreement with the observed data —> no need for additional exotic (pseudo)scalar or scalar boson production?

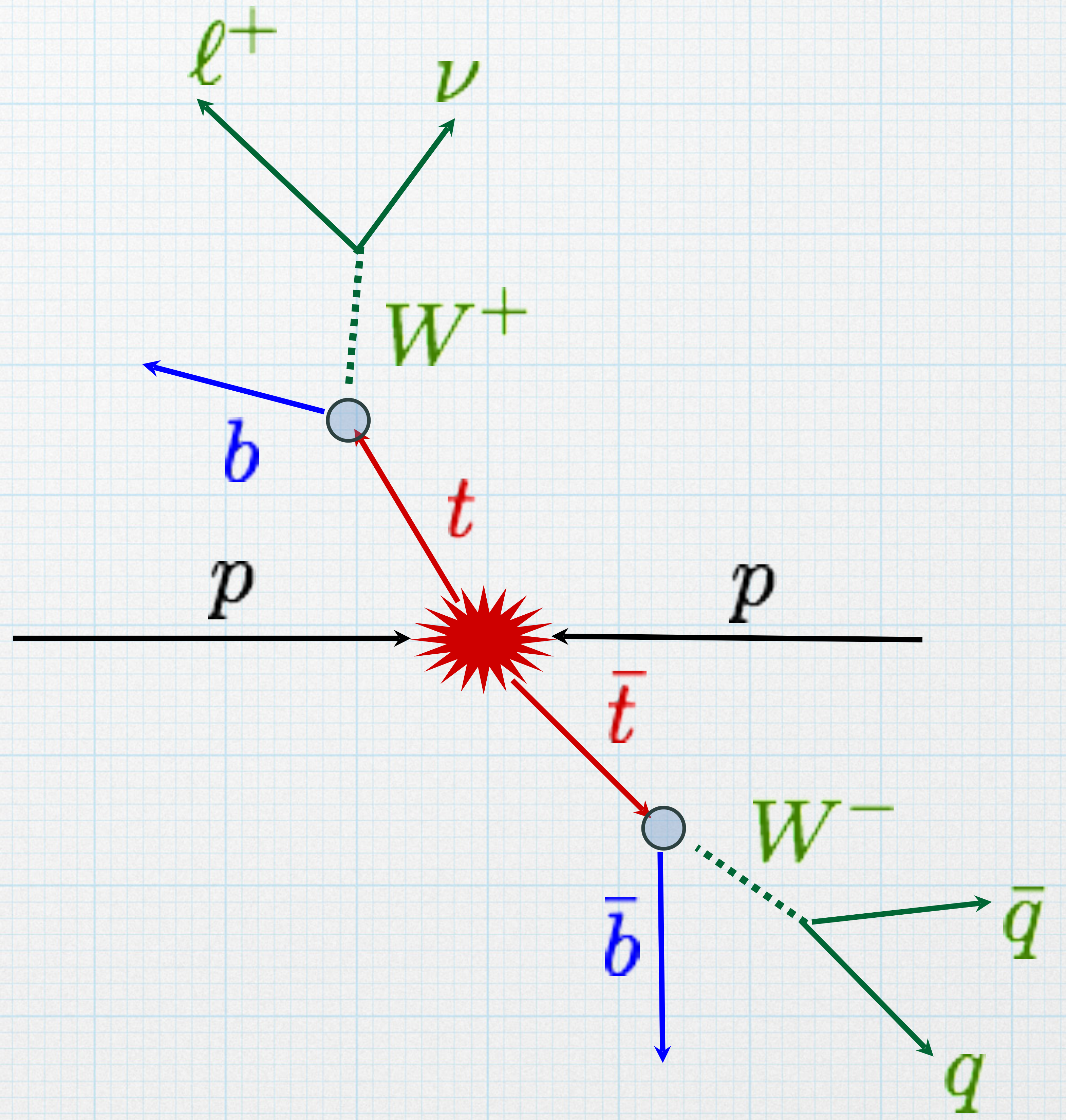
* However, precision not yet enough to conclude if toponium by itself or a new A boson, or a mixture of the two is required.



Rep. Prog. Phys. 88 (2025) 127801

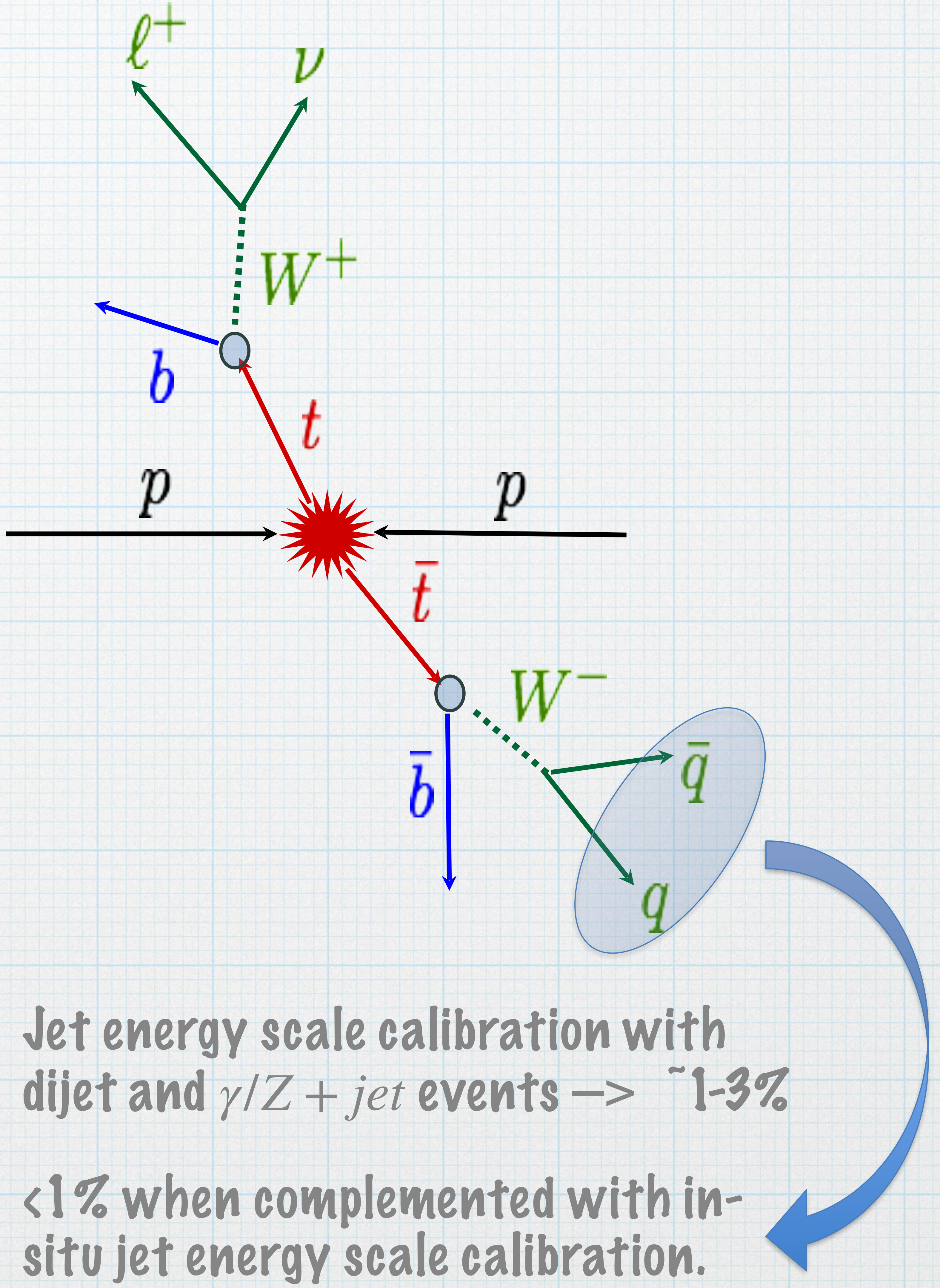
Top mass measurements

* Basic methods
  * Full invariant mass reconstruction: The most powerful and standard.
  * Partial reconstruction using a variable correlated to top mass: less powerful but different systematic uncertainties.
  * Indirect measurements through various cross section measurements: top quark pole mass.

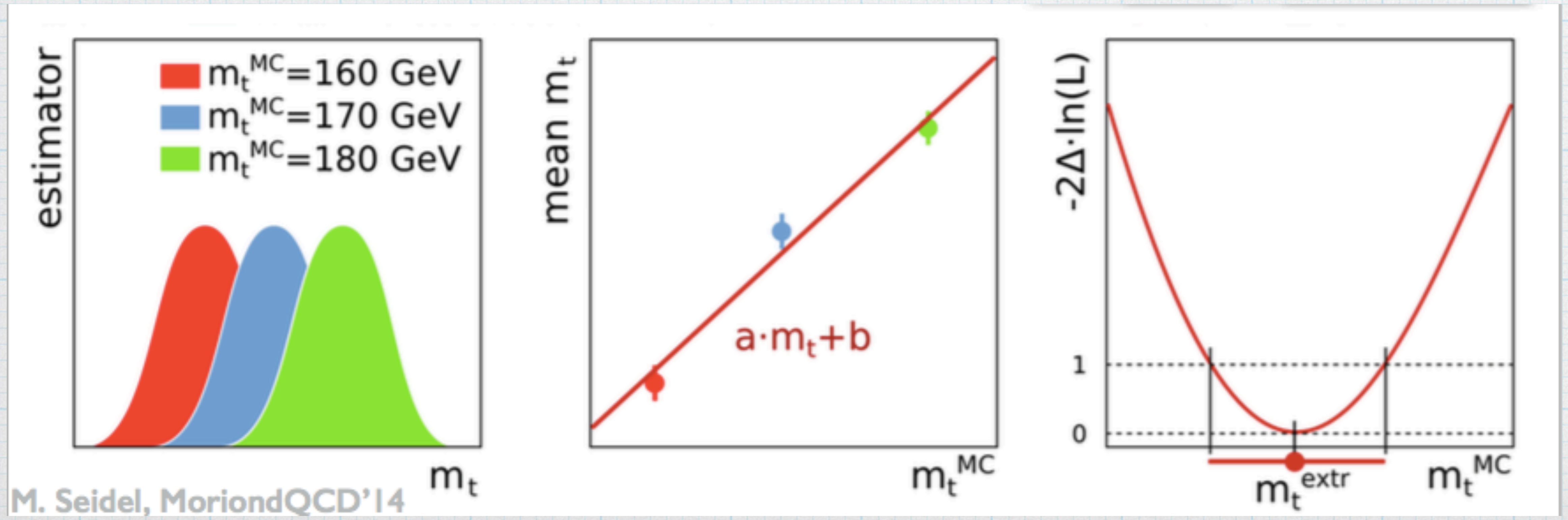


Full mass reconstruction

- General features:
  - Assign each jet to a top decay product (constrained kinematic fits)
  - Fit to templates.
  - Calibration of the method based on $m_t^{MC} = m_t^{measured}$
  - Determination of m_t^{MC} and jet energy scale simultaneously from data.



Main challenges: jet reconstruction, jet energy scale uncertainties, and modelling.

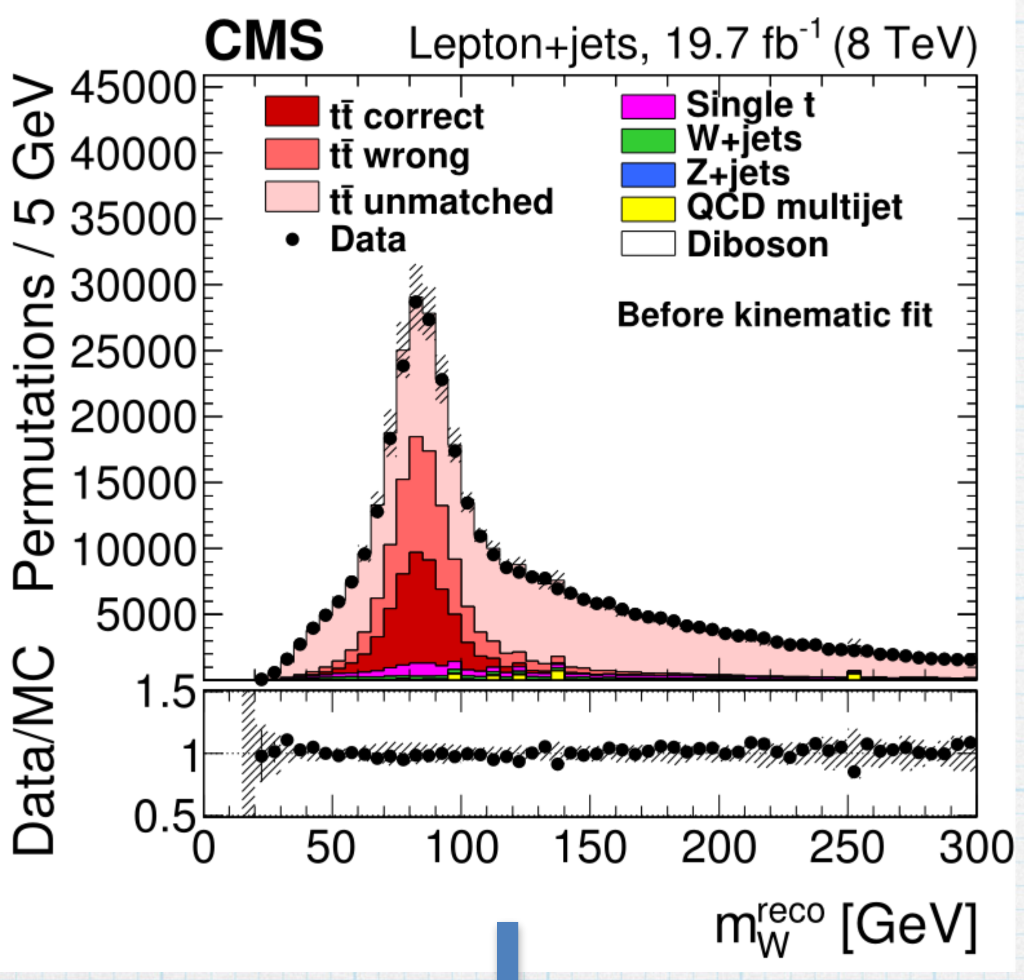


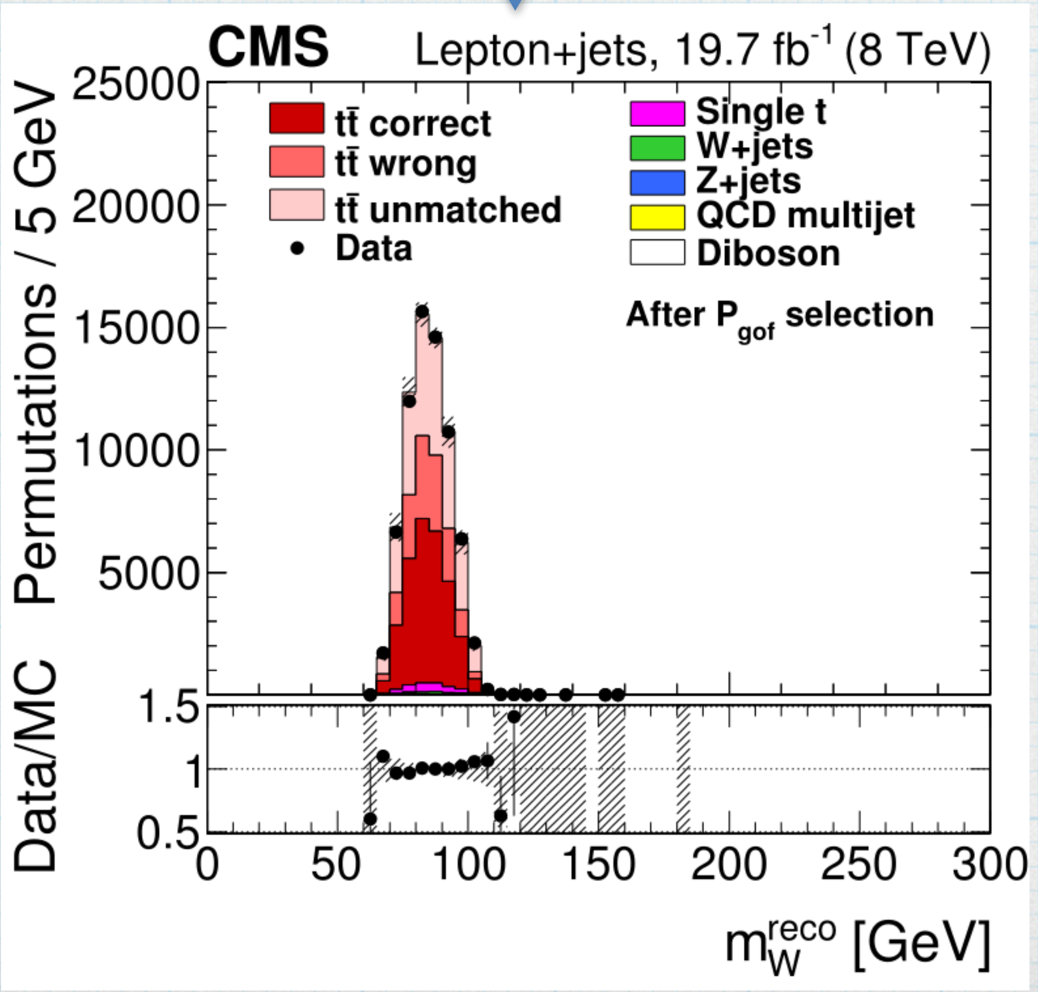
- Jet energy scale calibration with dijet and $\gamma/Z + jet$ events –> ~1-3%
- <1% when complemented with in-situ jet energy scale calibration.

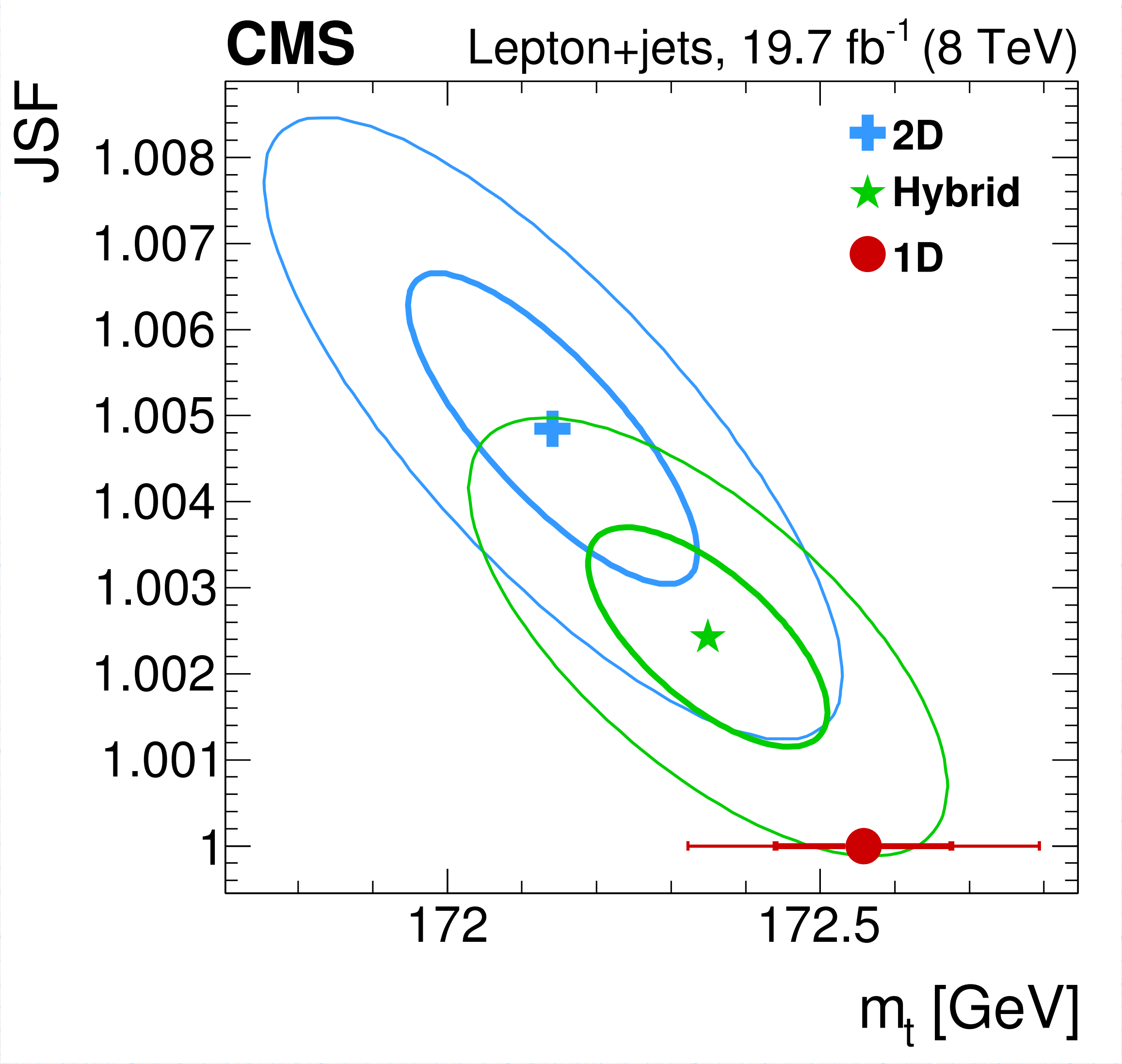
Full mass reconstruction — e.g.

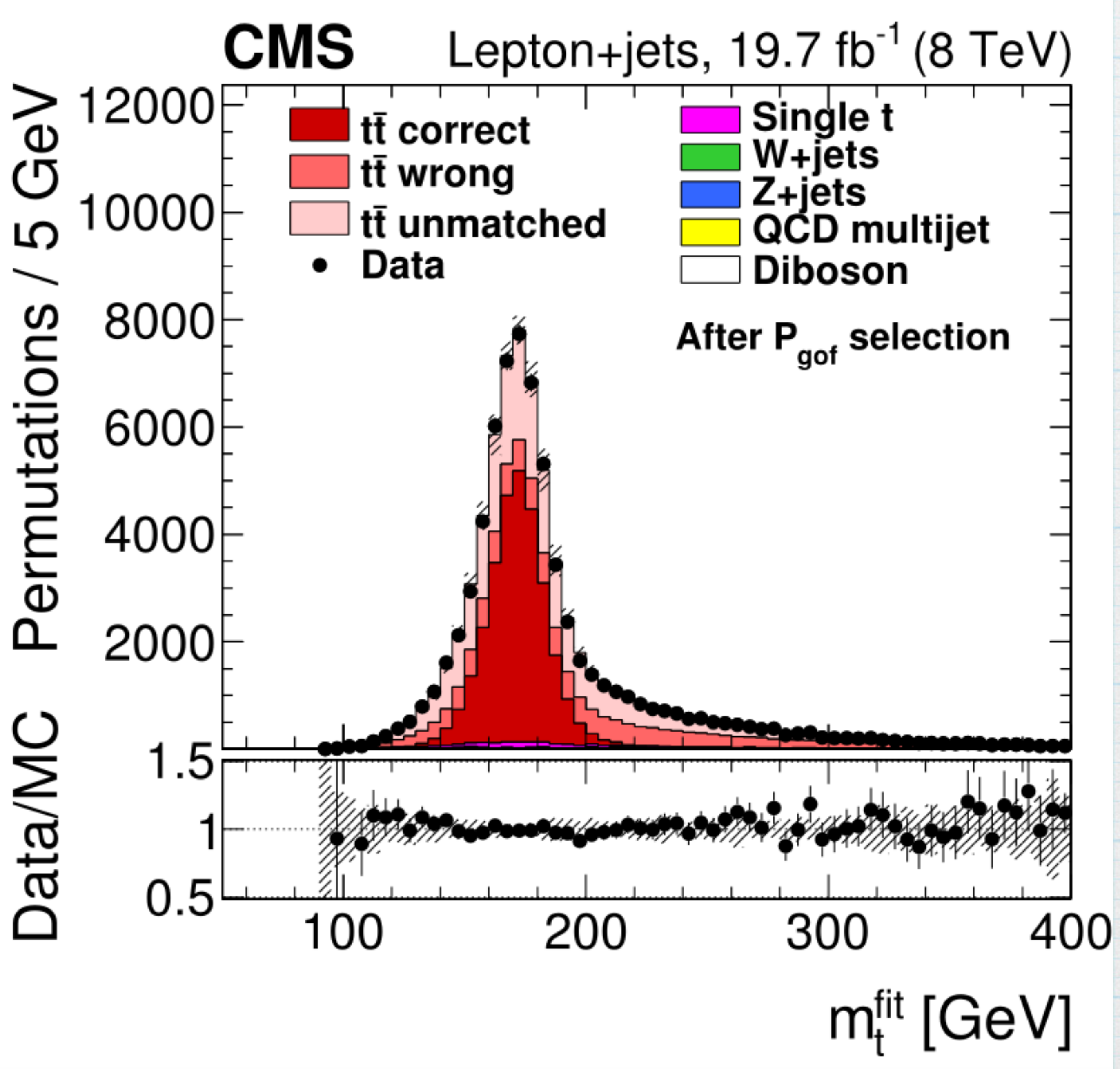
* Template method with multiple permutations (correct, wrong, unmatched) per event.
* All different permutations taken into account.
* Kinematic fit improves mass reconstruction.

arXiv: 1509.04044

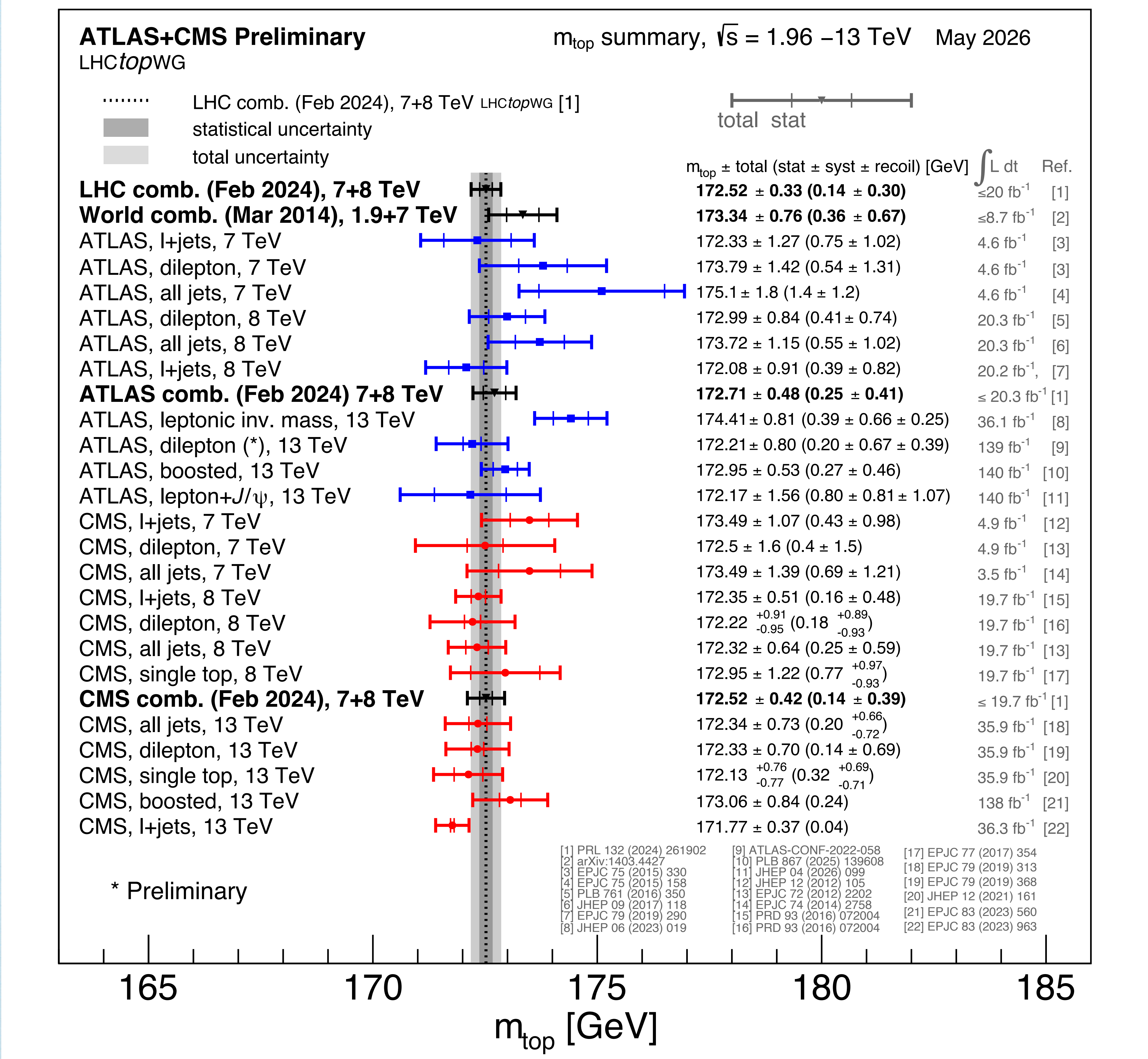








Summary of top mass measurements



* Improving top mass measurements
  * Dedicated measurements, theory and modelling studies.
  * Alternative measurements displaying different aspects of systematics.
  * Use observables with a well-defined mass definition in perturbative QCD: $\sigma(t\bar{t}), m_{\ell b}, m_{t\bar{t},jet}, \ldots$
  * And alternative topologies.
  * All should point to same value within uncertainties.

* LHC combination precision (7+8 TeV) = 0.19% $\approx \Lambda_{QCD}$
* Dominant systematic uncertainties: jet energy scales, and modelling (e.g. underlying event).

Top quark mass definitions

* Free quarks not observable (confining property of QCD)
* All quarks except the top quark hadronize –> Top quark mass theoretical framework dependent.
* Two common definitions
  * Pole mass
    * Perturbatively defined
    * Position of the pole in the renormalised quark propagator.
    * « Intuitive mass » (directly related to the production rate of $t\bar{t}$ pairs.
    * Suffers from ambiguities due to nonperturbative corrections of order $\Lambda_{QCD} \sim 200\mathrm{MeV}$.
  * Running (or short distance mass) $m_t^{\overline{MS}}$
    * Perturbatively defined
    * Renormalization scale dependent
    * More difficult to compare to experiment
  * The two definitions can be related analytically with an uncertainty $\lesssim \Lambda_{QCD}$

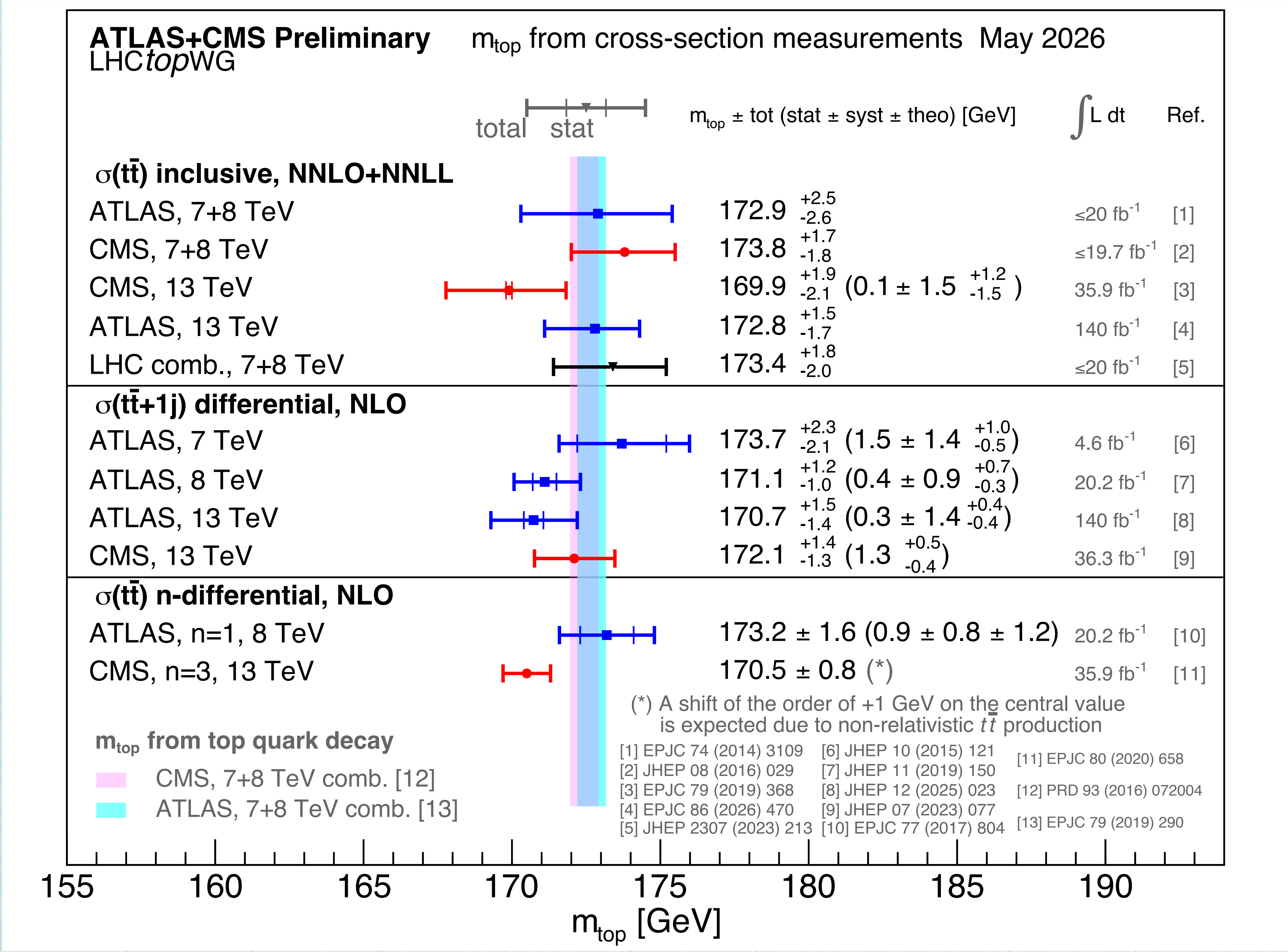
e.g. see Marquard et al. PRL 114 (2015) 142002

* Energy levels of mesons and baryons can be measured very precisely –> quark masses can be extracted using QCD.
* Different hadronic systems provide independent measurements.
* Hadrons are physical, i.e. observable, even though constituent quark masses are scheme dependent.
* For top, no hadron spectroscopy to constrain the mass. Mass reconstructed from decay products.
* Numerical value depends on theoretical framework to translate from experiment to fundamental parameter.

Top quark mass definitions

* Monte Carlo mass
    * No straightforward definition in standard top mass measurements.
    * Direct top quark measurements rely on the complicated relation between the experimental observable and m_t.
    * Matrix elements are at fixed order (LO,NLO,NNLO) QCD + parton showers

$$m_t^{MC} \neq m_t^{pole} \neq m_t^{MS} \neq m_t^{XX}$$



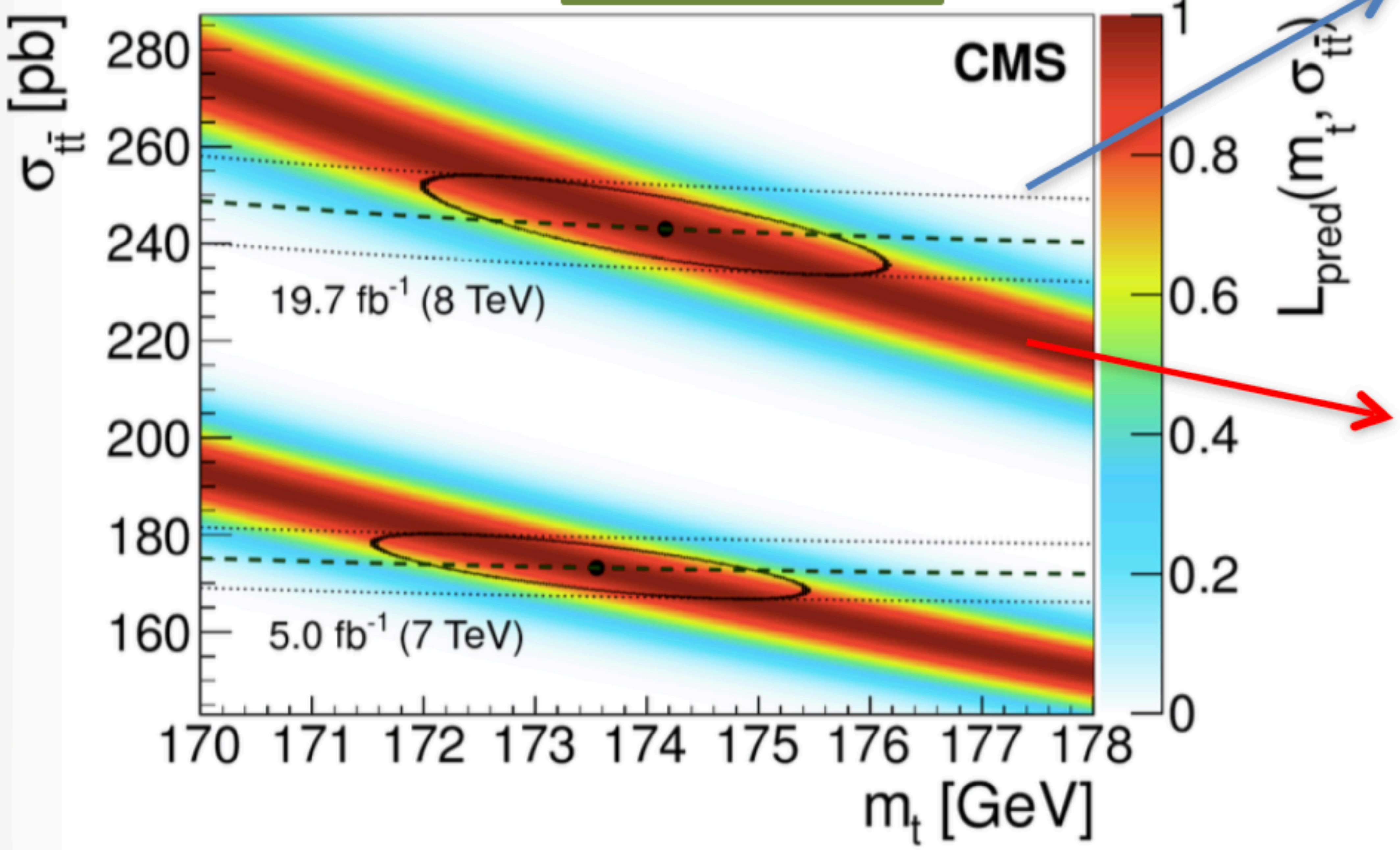
* With the current precision top-quark pole mass measurements consistent with the standard measurements.

Top Quark Pole Mass from ttbar Production Cross Section: Fix $\alpha_s(m_Z)$ and PDF → Determine m_t^{pole}

$$\sigma_{pp\to t\bar{t}}(s, m_t) = \sum_{i,j=partons} \int dx_1\, dx_2\, f_i^{pdf}(x_1, \mu_f^2)\, f_j^{pdf}(x_2, \mu_f^2)\, \hat{\sigma}_{ij\to t\bar{t}}(\hat{s}, m_t, \mu_f, \mu_r, \alpha_s(\mu_r))$$

- Full phase space cross sections at parton level with full Run-I data at 7 and 8 TeV in the most precise channel (eμ).
- Minimize theory x experimental likelihoods.

arXiv:1603.02303



Dependence due to efficiency and acceptance depending weakly on m_t.

Recall: $\sigma = \dfrac{N_{obs} - N_{bkg}}{(A\times\varepsilon)\times B\times L}$

It is harder to produce heavier particles.

	m_t [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$

Dominant uncertainties: Luminosity, beam energy

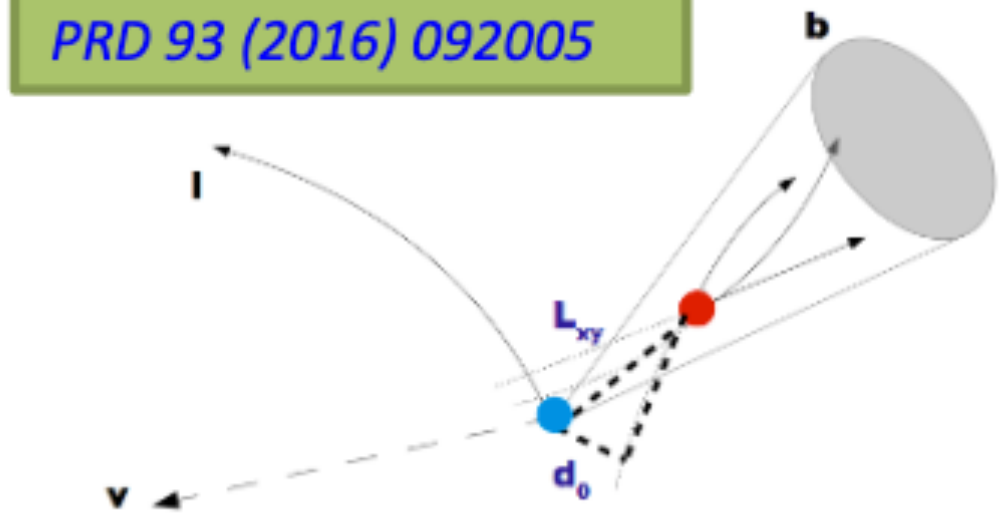
~~Recent~~ Alternative Top Quark Mass Measurements

Invariant mass of the secondary vertex w/ >= 3 tracks + lepton.

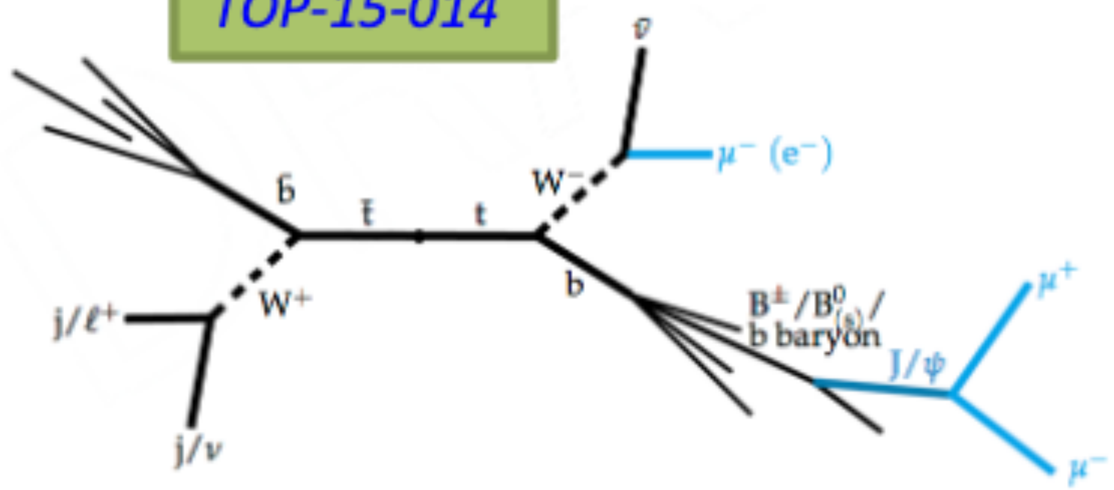
J/Ψ+lepton mass

$M_{l\nu b}$ in single top topology

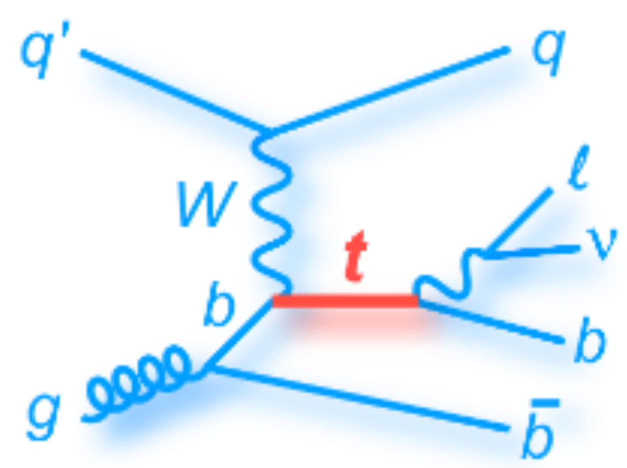
PRD 93 (2016) 092005

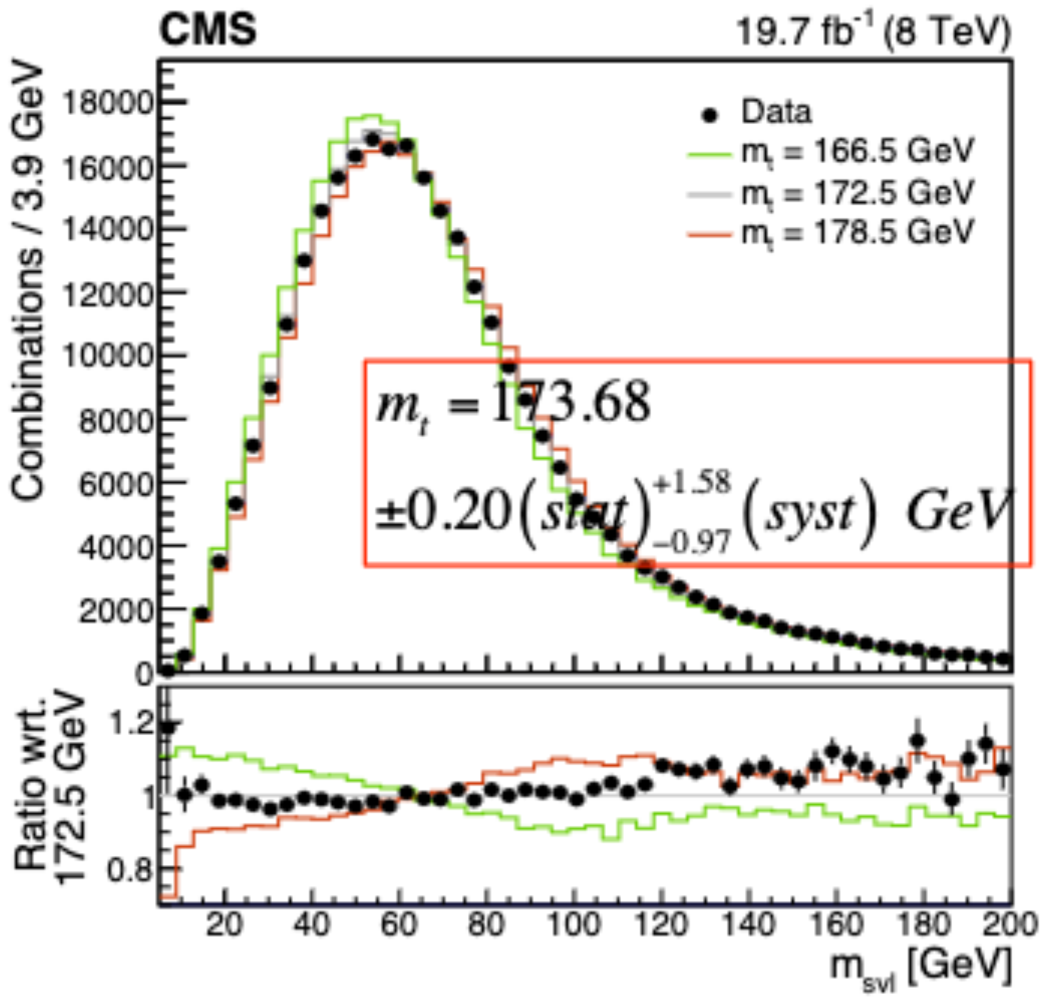


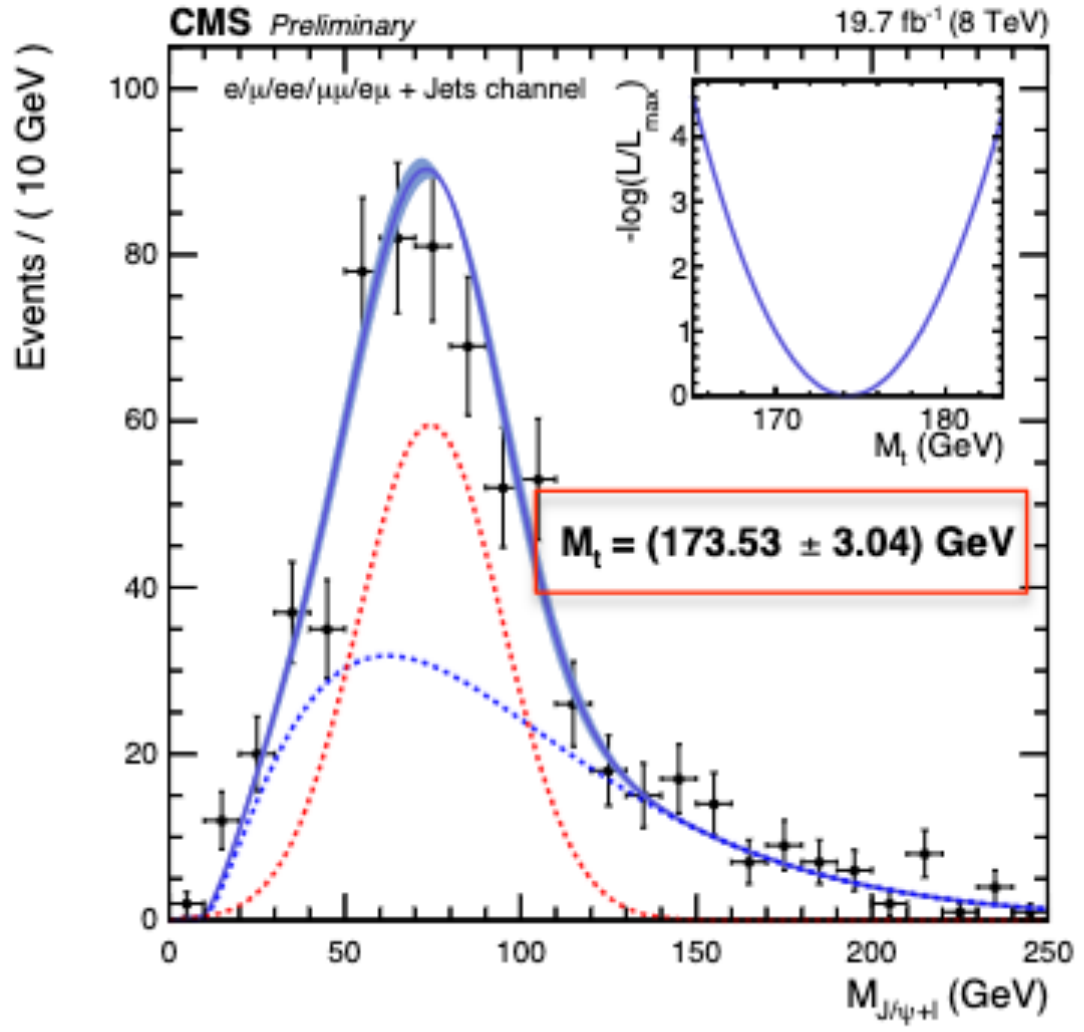
TOP-15-014

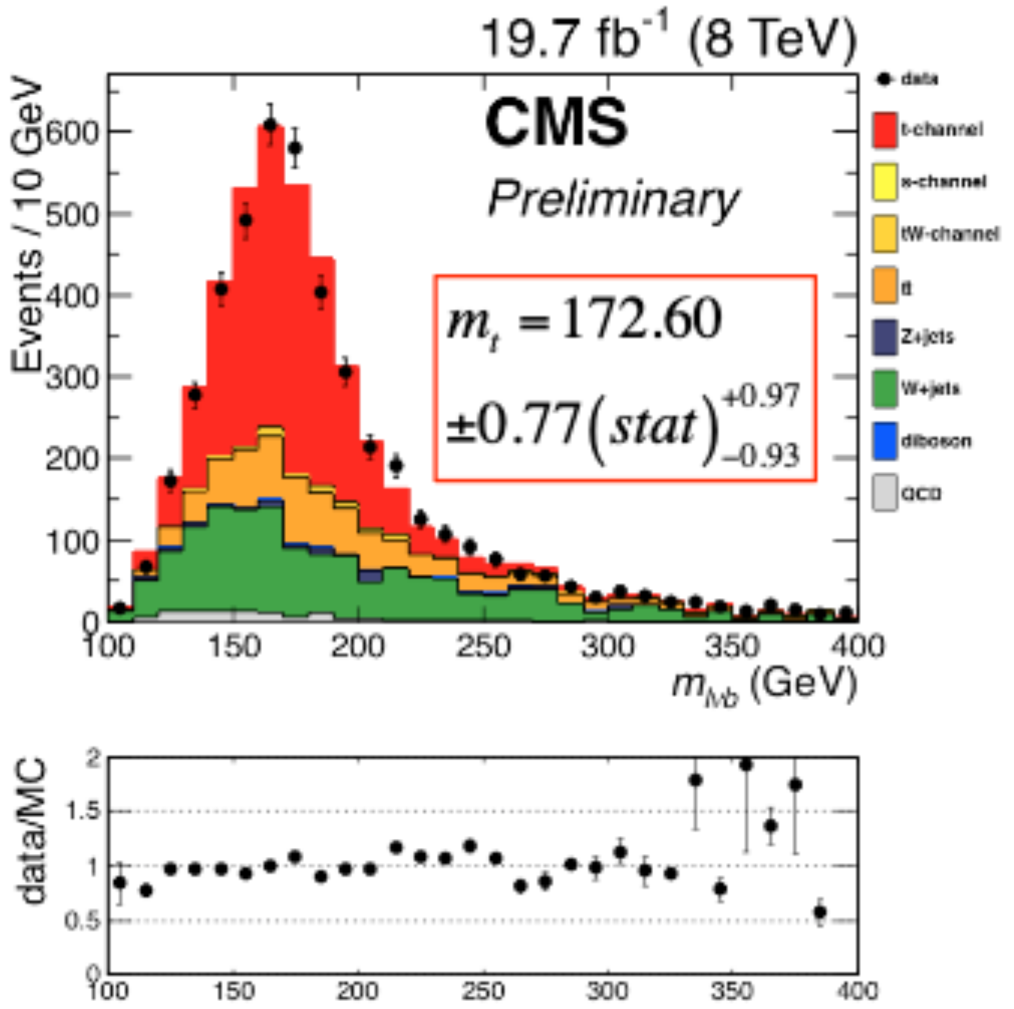


TOP-15-001









Minimal experimental uncertainties.
Large dependence on fragmentation modeling.

M_{svtx} mass:
b fragmentation

J/Ψ+lepton mass:
Result statistically limited

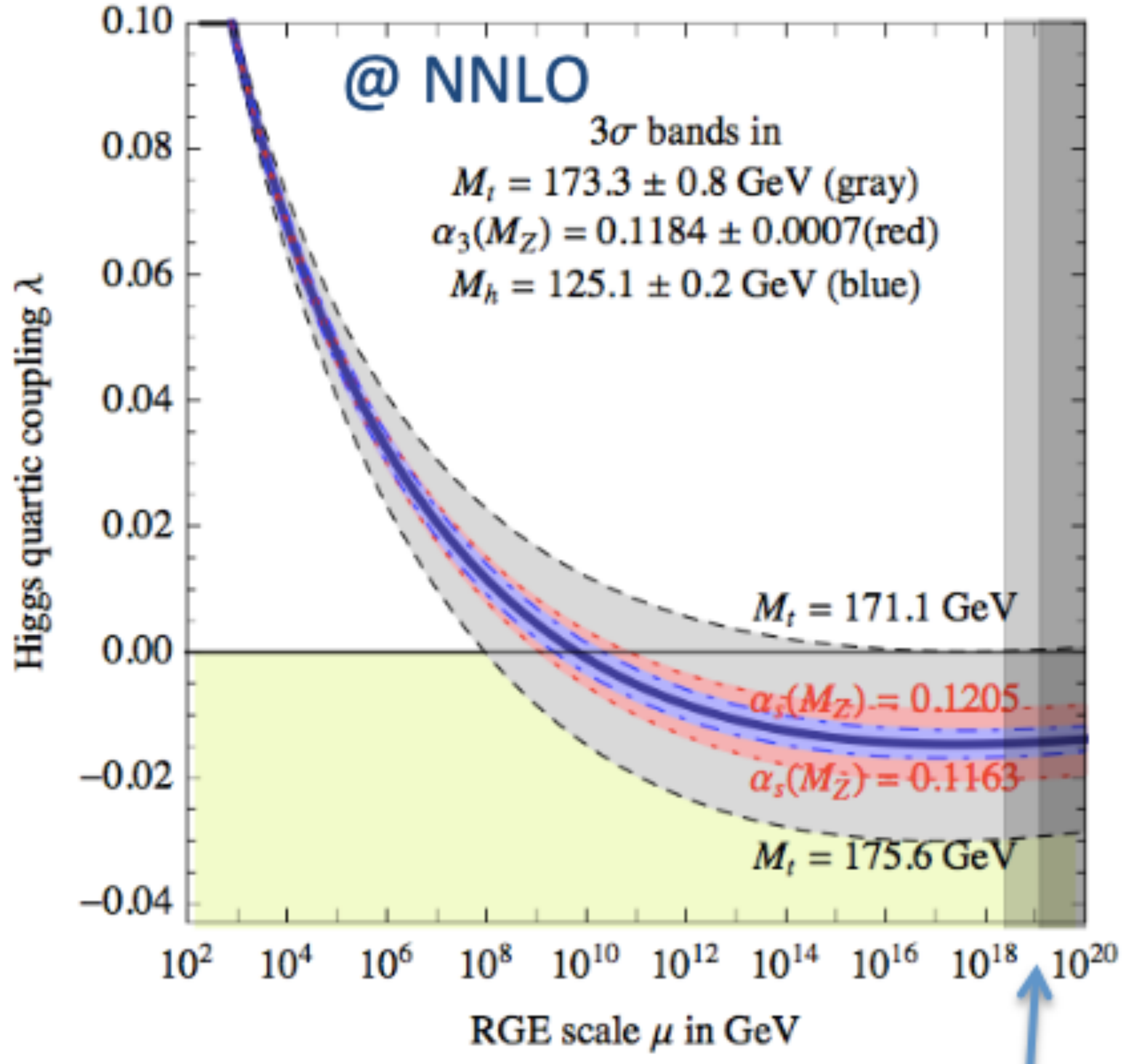
Alternative event topology
Partially uncorrelated systematics
Different color flow→ check for "unknown" syst.

Top Quark Physics ", E. Yazgan, Lectures in Hadron Collider School HASCO 2016, Gottingen, Germany, 17-22 July 2016.

Top quark mass and the electroweak vacuum (fate of the universe)

The Top Quark Mass and Vacuum Stability (Fate of the Universe)

Degrassi, et. al. arXiv:1205.6497
JHEP 08 (2012) 098



Planck scale

- Measured m_H → λ (the quartic scalar coupling)

$$V^{\rm eff} \approx -\frac{1}{2}m^2(\mu)\phi^2(\mu) + \lambda(\mu)\phi^4(\mu) \sim \lambda(\mu)\phi^4(\mu)$$

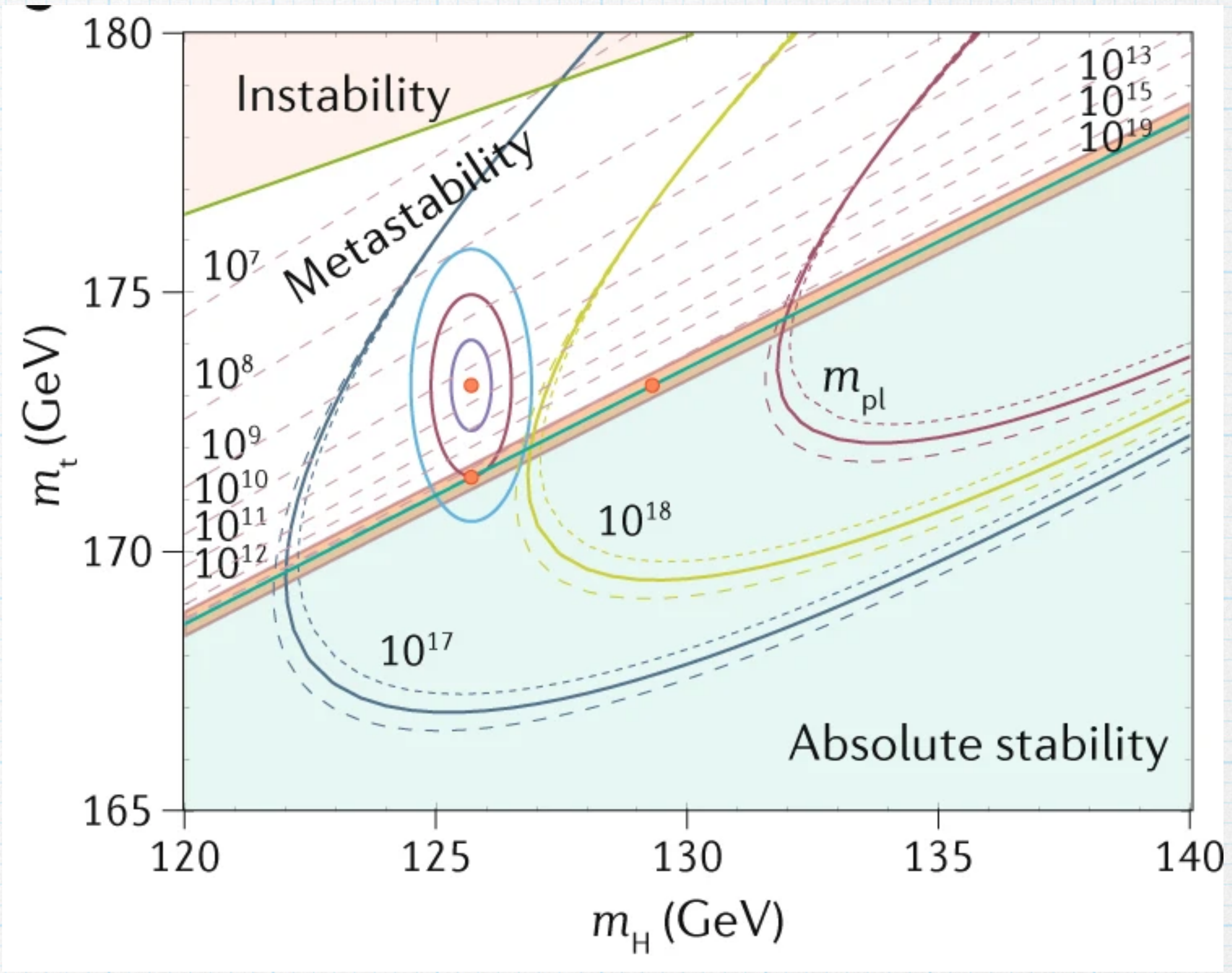
for $\phi(\mu) >> v$

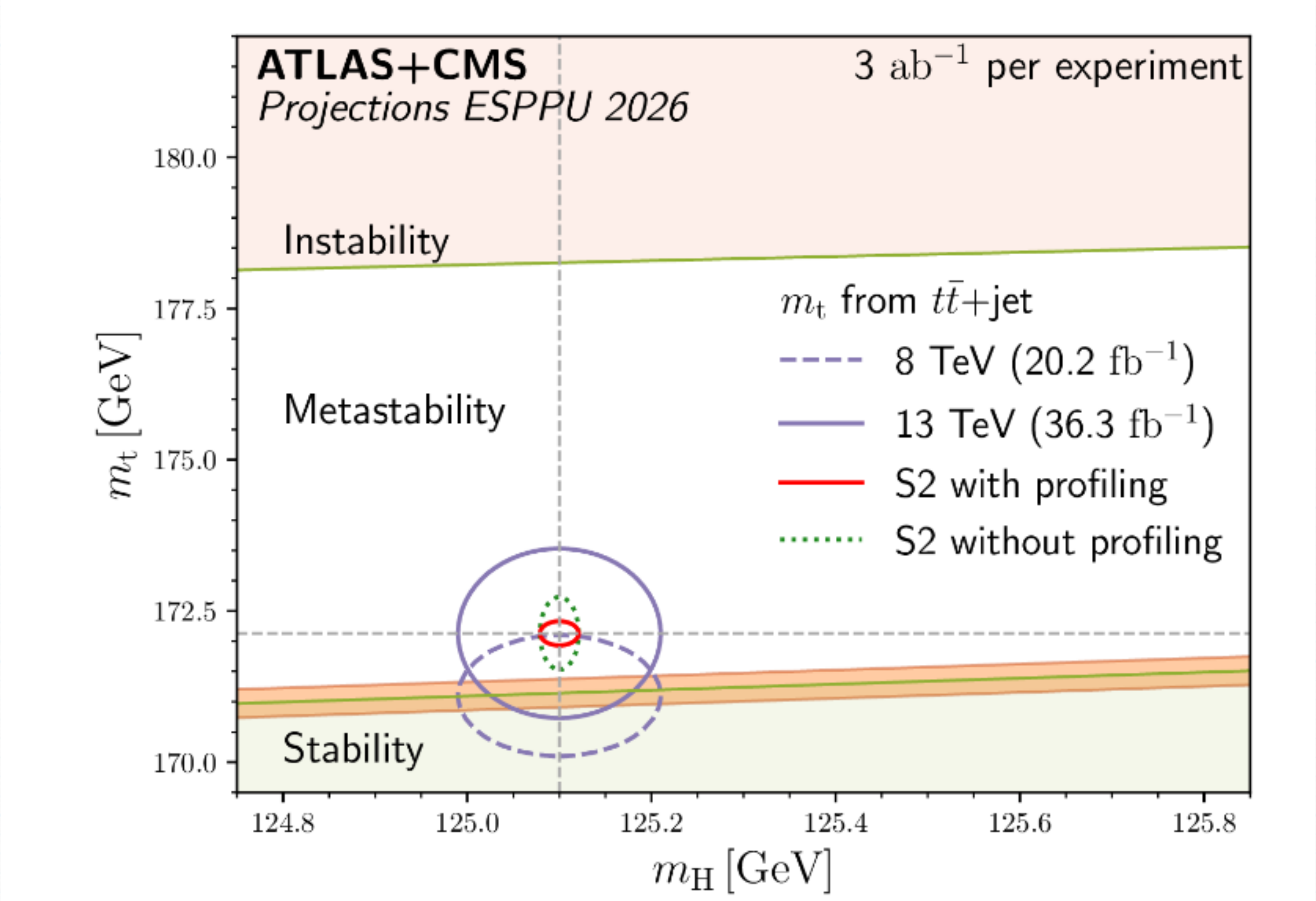
→ stability

→ meta-stability

v: electroweak minimum

Measured top and Higgs masses
→ SM valid up to the Planck scale?





https://pdg.lbl.gov/2025/reviews/rpp2025-rev-top-quark.pdf

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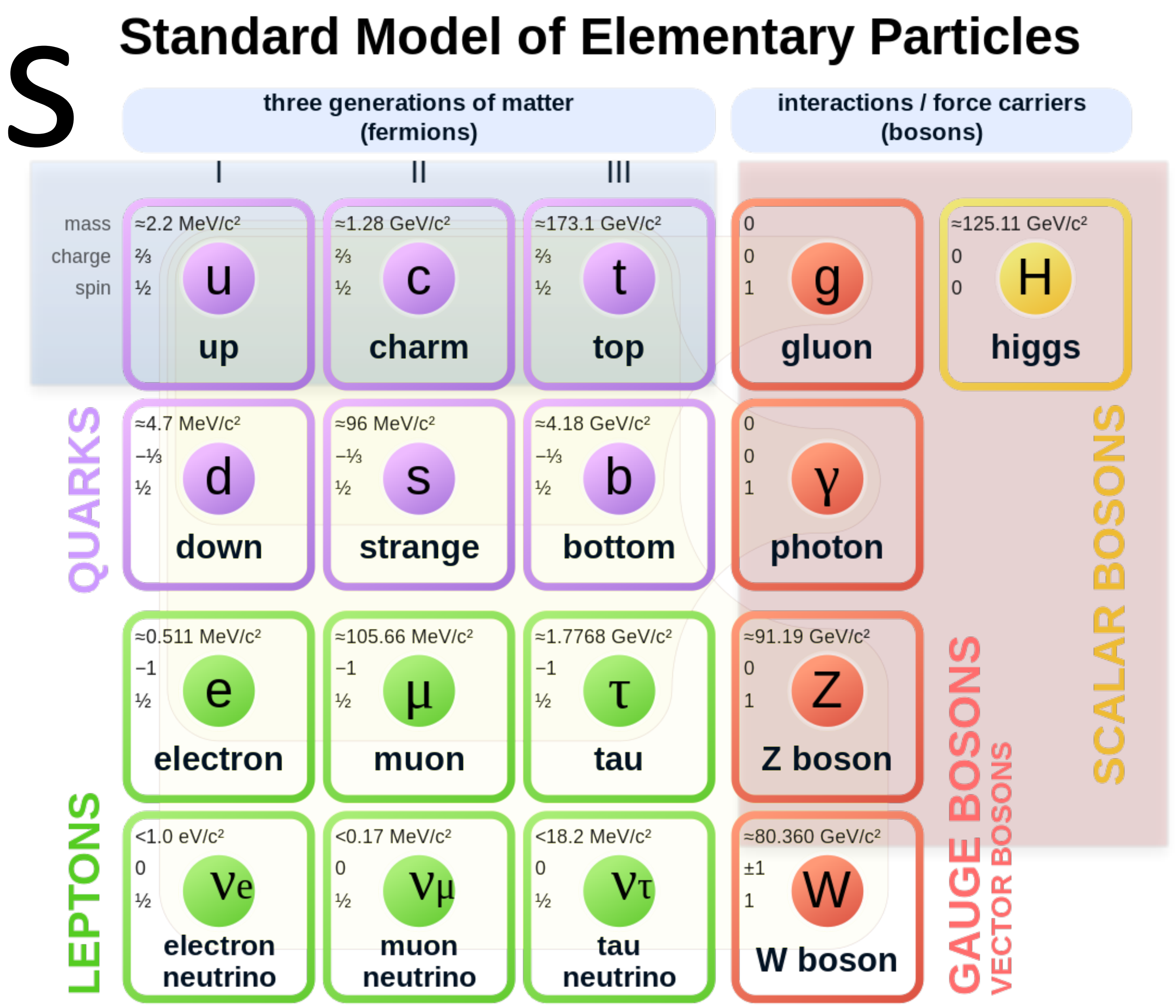
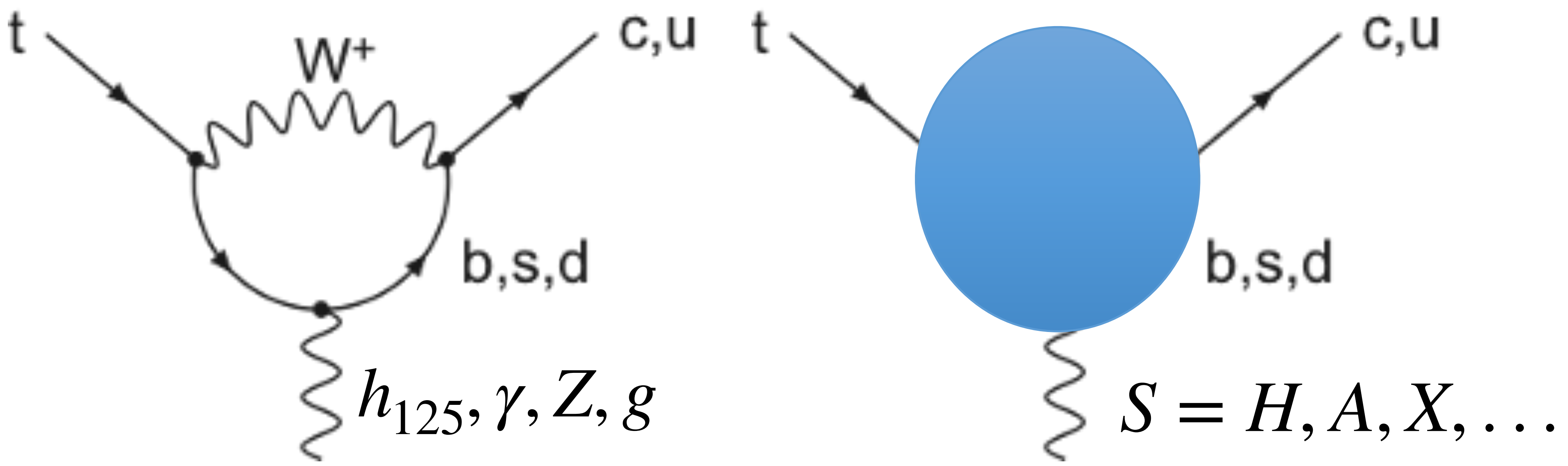
Top Quark Physics (Production and Mass), E. Yazgan, Lectures in Hadron Collider School - HASCO 2015, Gottingen, Germany, 19-24 July 2015.

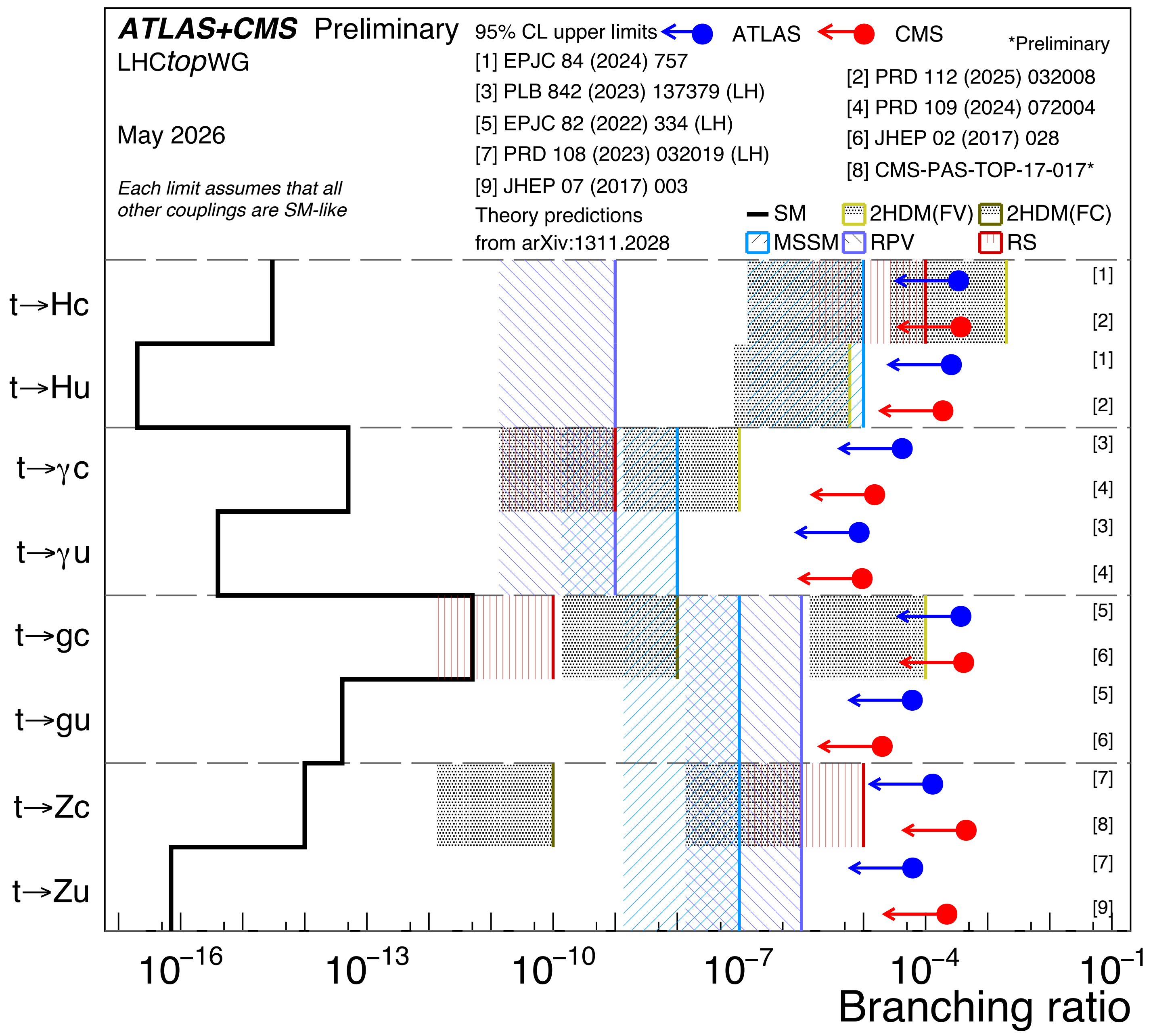
Flavor Changing Neutral Currents

- Transitions that change the flavor of a fermion w/o changing charge.
- Forbidden at tree level in the SM.
- Suppressed at higher orders due to GIM mechanism.
    - Due its high mass, Top-Higgs FCNC transitions have the largest suppression in the SM.
- Occurs only at the level of quantum loop corrections.

$$\mathscr{B}(t \to Xq) \sim 10^{-17} - 10^{-12}$$







→ Any evidence of FCNC indicates the existence of new physics.

- * No sign of FCNC in $t\bar{t}$ or single top measurements.
- * Top quark modelling and heavy flavour tagging crucial in many searches (as in SM top quark measurements).
- * FCNCs in extended Higgs sector still remain to be studied in more detail.

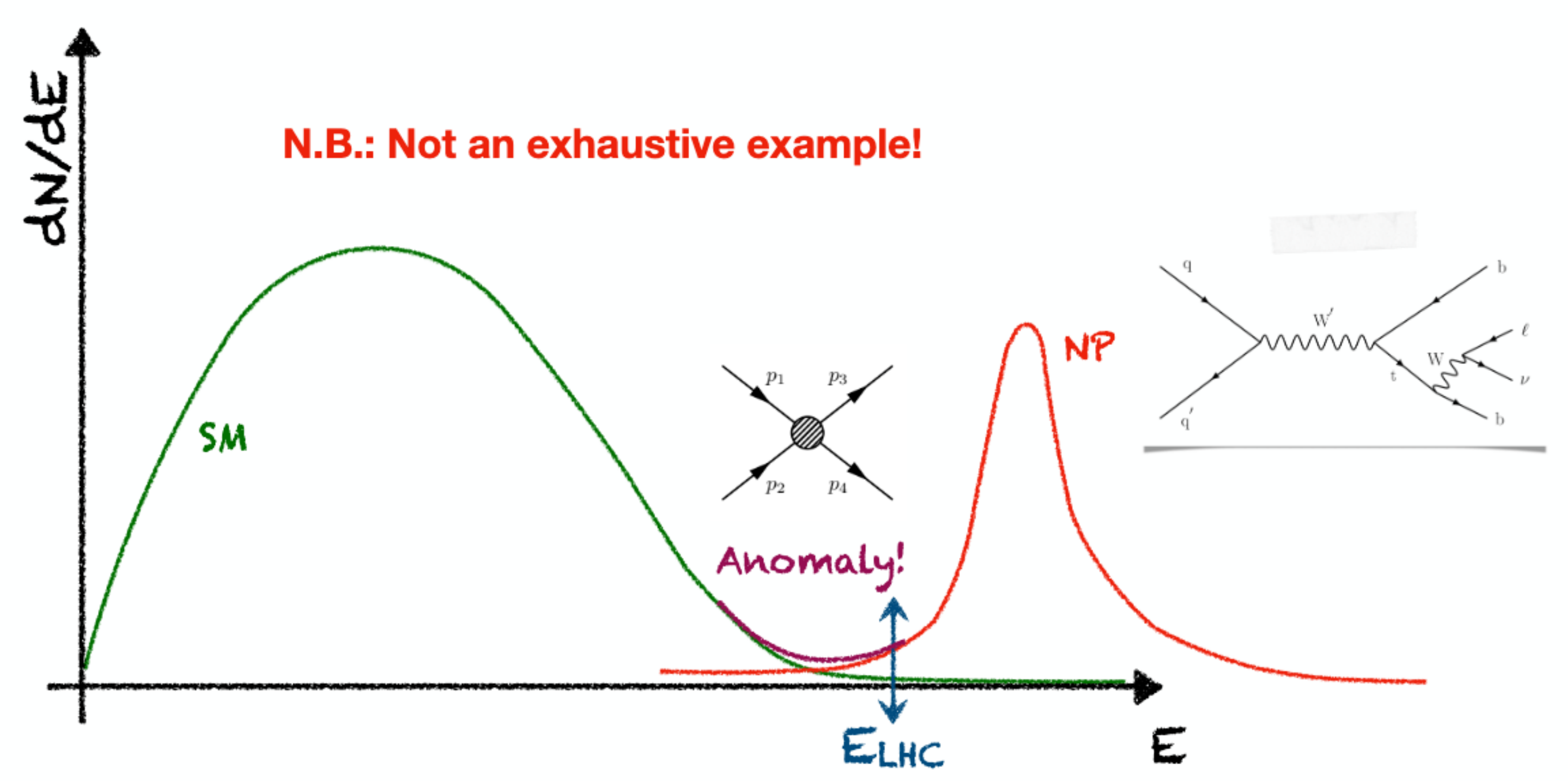
SM Effective Field Theory

* New physics effects as a small addition to the SM Lagrangian using higher order ($\mathscr{D} = 6$) operators ($\mathscr{O}_i$) in a power series of the new physics scale $\Lambda \sim 1$ TeV with coupling strength coefficients C_i constrained by precision measurements in a global fit.

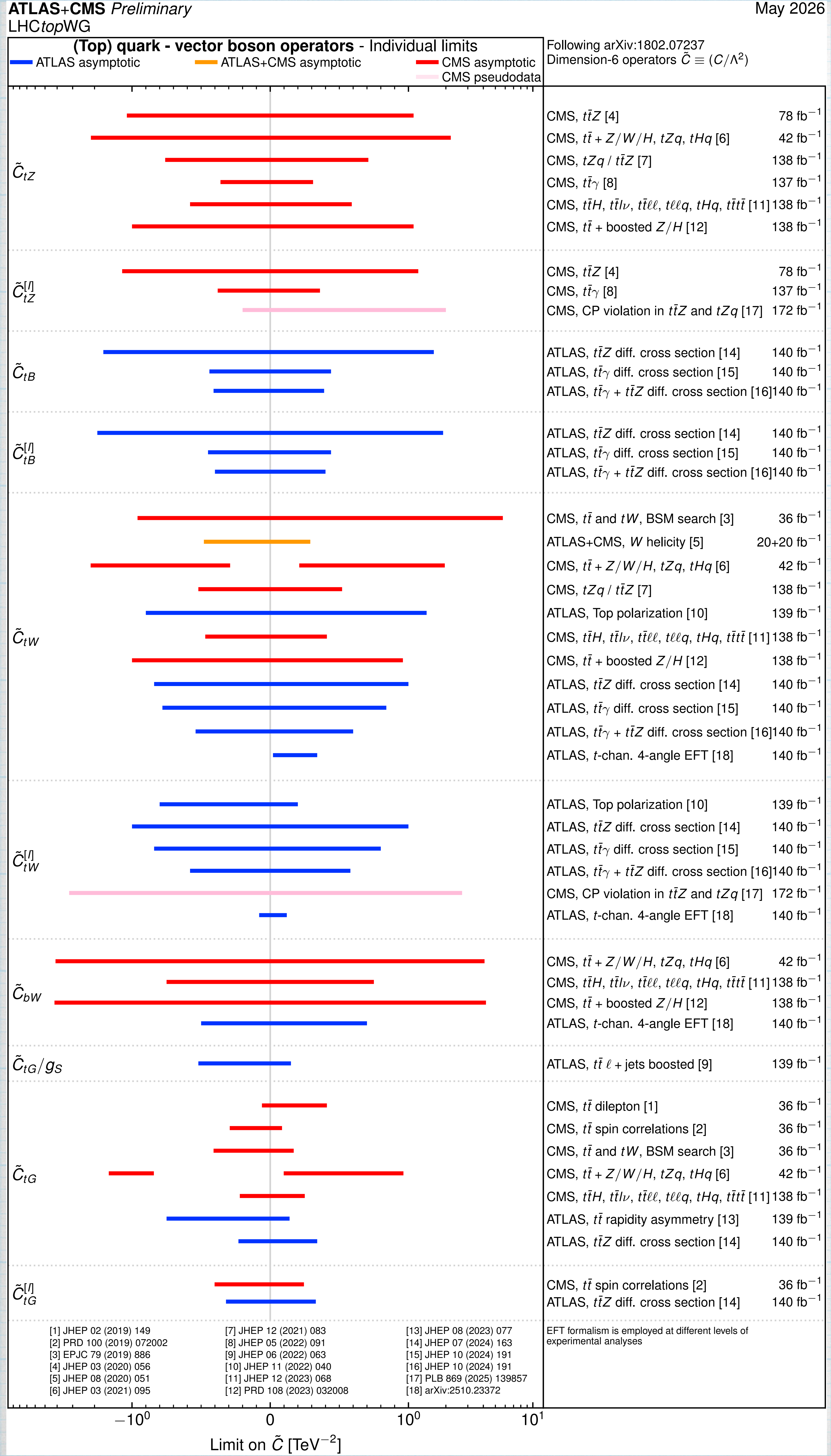
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{\forall, \mathscr{D} \geq 5} \frac{C_i O_i^{\mathscr{D}}}{\Lambda^{\mathscr{D}-4}}$$

Effective interactions with SM fields

$\mathscr{D} = 4$
Interactions between SM fields



Stolen from A. Piccinelli's slides - TOP2025 Workshop



SM Effective Field Theory

* 95% CL observed limits on EFT Wilson coefficients of the dim-6 operators related to (top) quark interaction with vector bosons from ATLAS and CMS collaborations.

* Individual constraints assuming new physics contributions from one specific operator at a time.

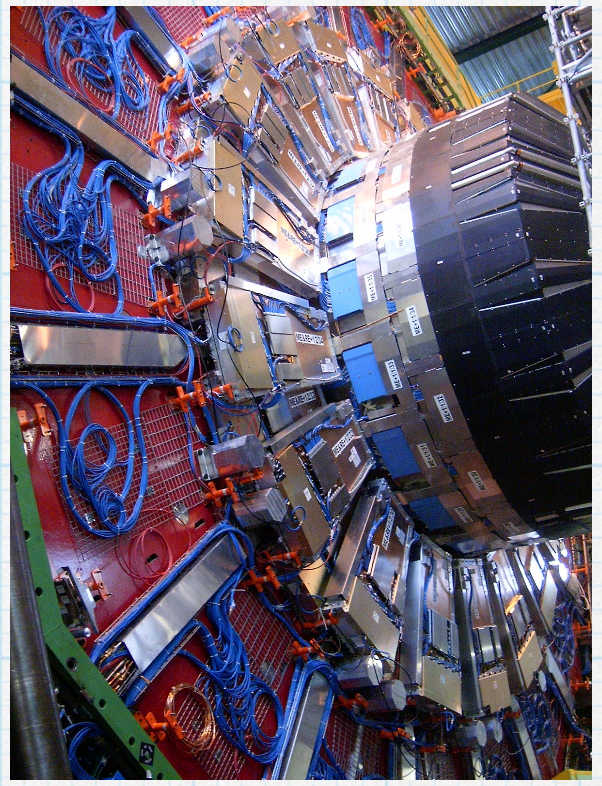
* Interpretations use SMEFT framework and Warsaw basis.

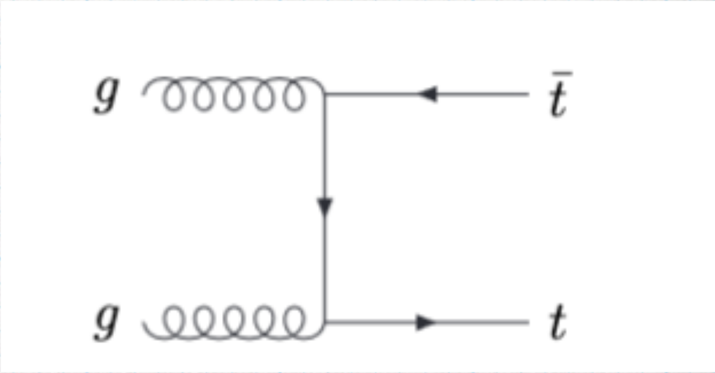
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots#Top_EFT

Summary

* Top quark plays an important role in precision measurements and new particle searches.
* Top re-discovered at the LHC (ATLAS, CMS, LHCb).
* « Toponium » observed by both ATLAS and CMS.
* Top pair entanglement observed by both ATLAS and CMS.
* Most LHC measurements dominated by systematic uncertainties and precision still increasing with new analyses using
  * more data.
  * Improving modelling and systematic uncertainties.
  * improved methods with advanced machine learning techniques.
* So far, all results (not only from top quark) are in agreement with SM predictions and no evidence of any unknown particles.

Closing





* « A measurement that cannot be done accurately, can never be divorced from politics and must therefore generate mythologies. The more such shades of meaning there are, the less scientific the discussion becomes. Accurate measurement in this sense is scientific law, and a milieu in which accurate measurement is impossible is lawless. The need for precision, in turn, redoubles the need for that other great Greek tradition, open discussion for ideas and ruthless separation of meaningful things from meaningless ones. Precision alone does not guarantee good law... »

from « A different Universe », R. B. Laughlin