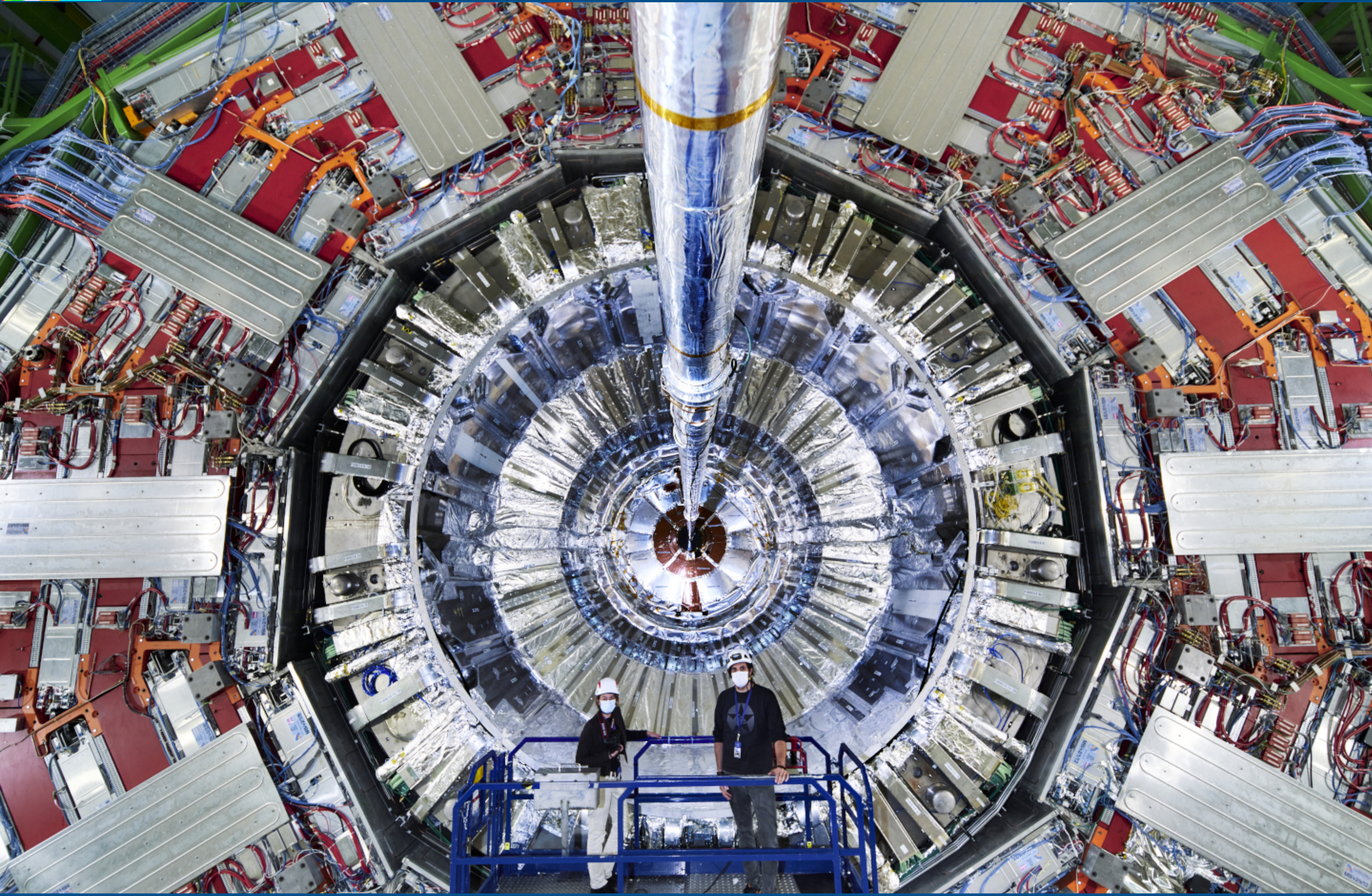
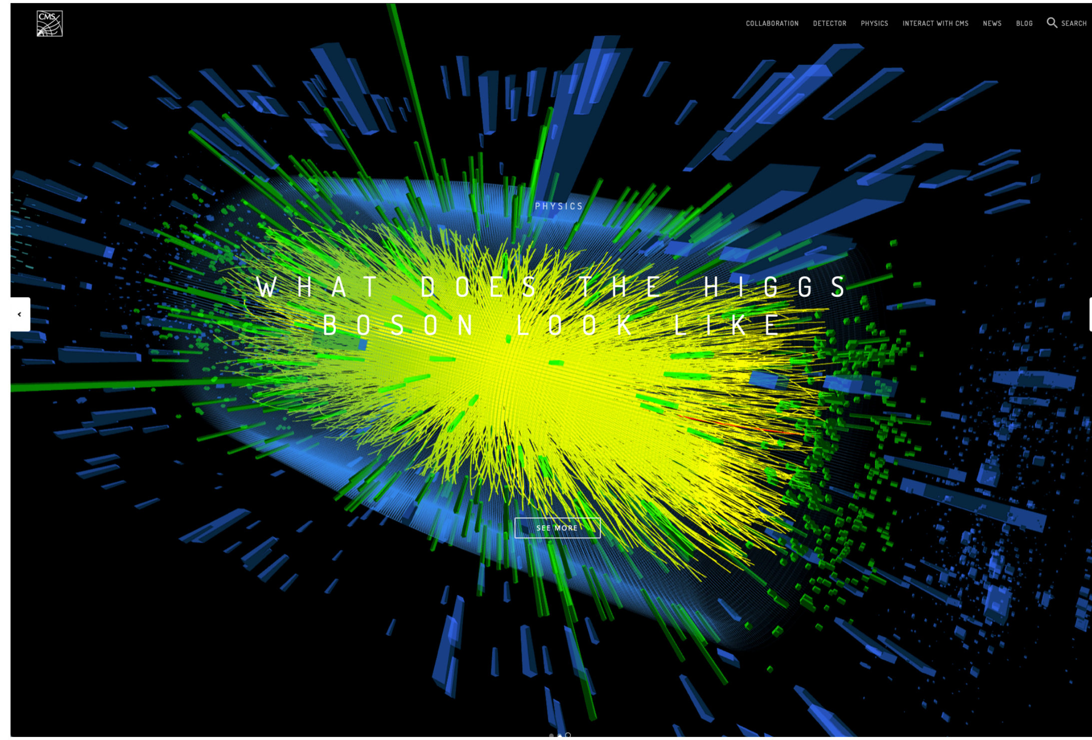
Particle Physics Day 2023

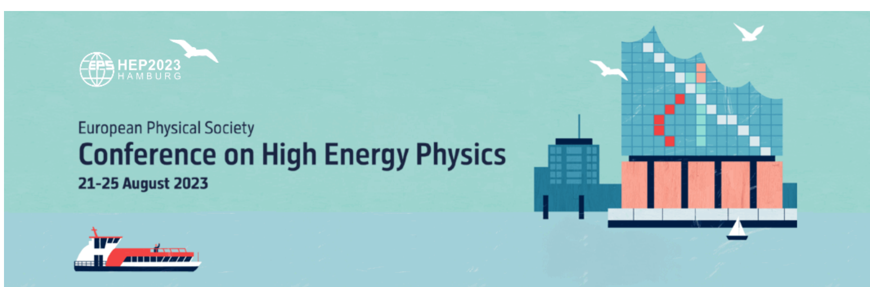


Overview

- LHC and CMS performance in Run 3
  - integrated luminosity, detector challenges
  - Helsinki focus: PCL, PUPPI, JEC
- First Run 3 results
  - tt, Z, long-lived particles
- Standard Model physics
  - strong coupling constant α_s, top quark mass m_t, Higgs boson mass m_H
- New physics searches
  - rare Higgs, multijets, leptoquarks
- Heavy ion physics
  - f0(980) composition, jet narrowing, flow in high-multiplicity pp
- TOTEM+PPS physics
  - TOTEM central exclusive ππ
  - PPS searches: Z/γ+X,γγ,tt,WW & ZZ
- Summary and outlook



Caveat: very Finnish perspective
For broader overview: EPSHEP2023

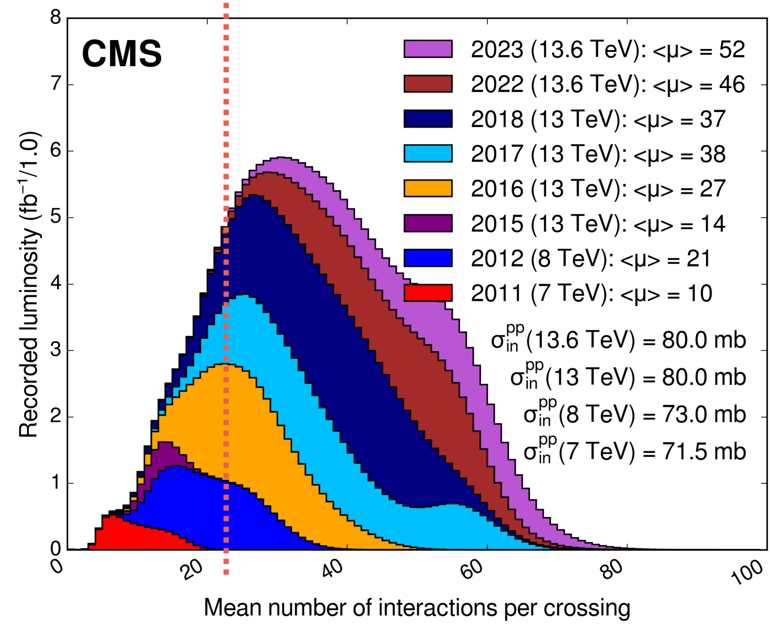


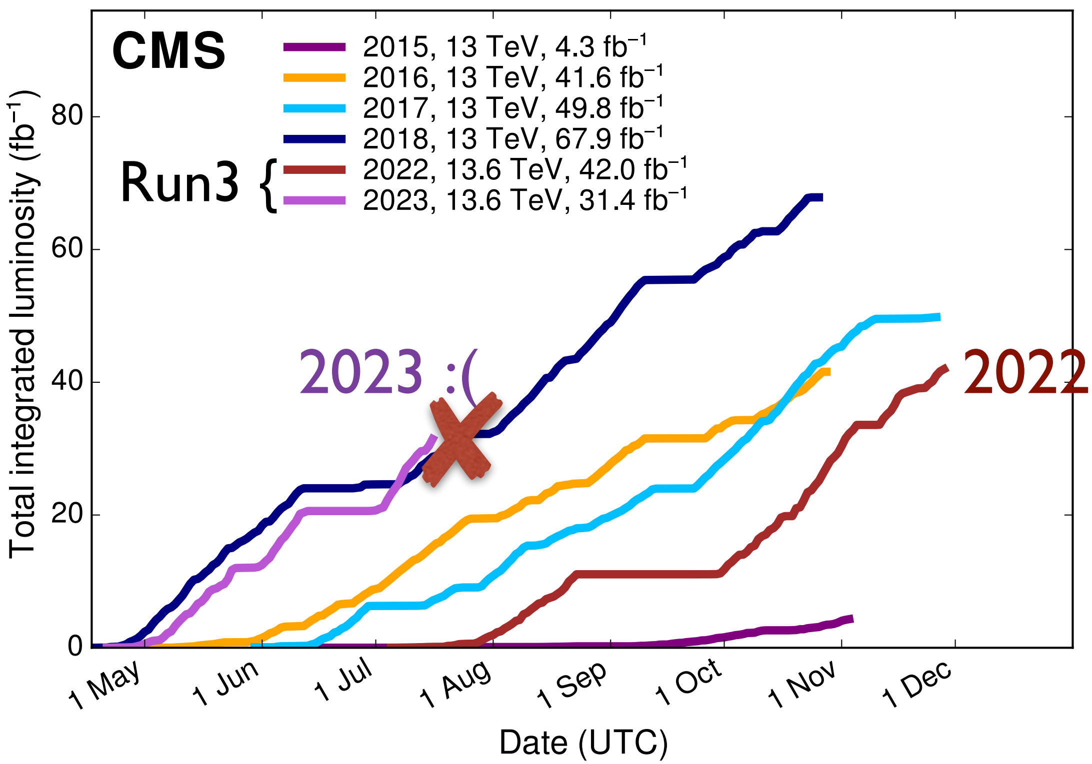
Some slides from F. Canelli's CMS overview

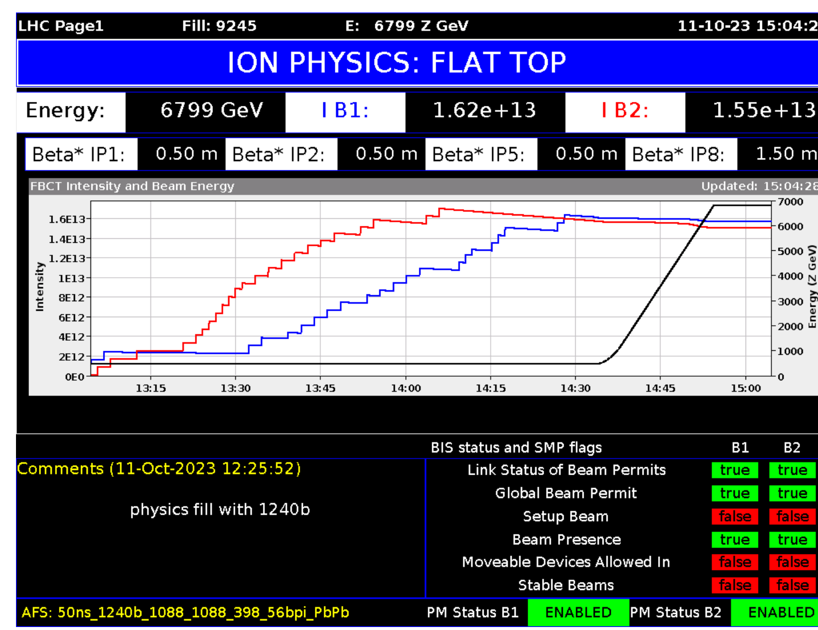
LHC+CMS performance

Integrated luminosity

- This year was cut short, so bit behind of target
  - Good data 60 fb^{-1} in Run3 vs 138 fb^{-1} in Run 2 (43%)
  - LHC running beyond design luminosity of 25 PU
- Run2 sensitivity potentially reached at M_{jj}=8 TeV
  - Interesting for checking tentative hints from Run2!
- Heavy ion run as planned in 2023, though
  - Still on-going, first heavy ion run since 2018!



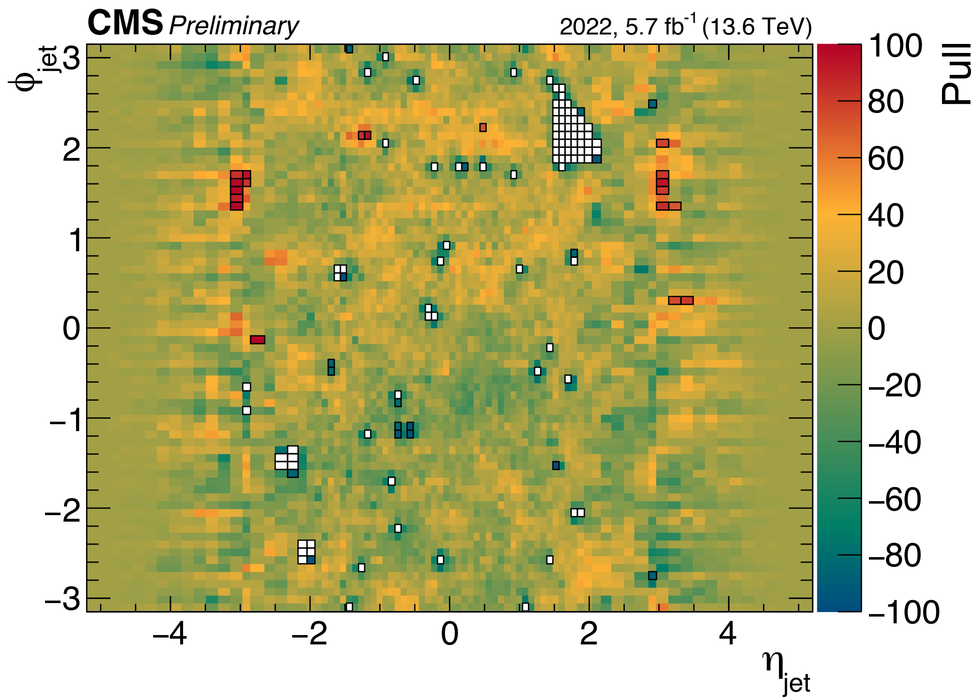




Detector challenges

CMS DP-2023/045

- Detector keeping experimentalists busy:
  - HCAL barrel noise in 2022
  - ECAL endcap water leak in 2022
  - Barrel pixel failures in 2023
  - HCAL trigger prefire in barrel 2022—23
- Monte Carlo production and data re-reconstruction big challenge now
  - Cannot afford many re-reco cycles, and need dedicated MC for each era with bigger failures
  - Automatising workflows as much as possible



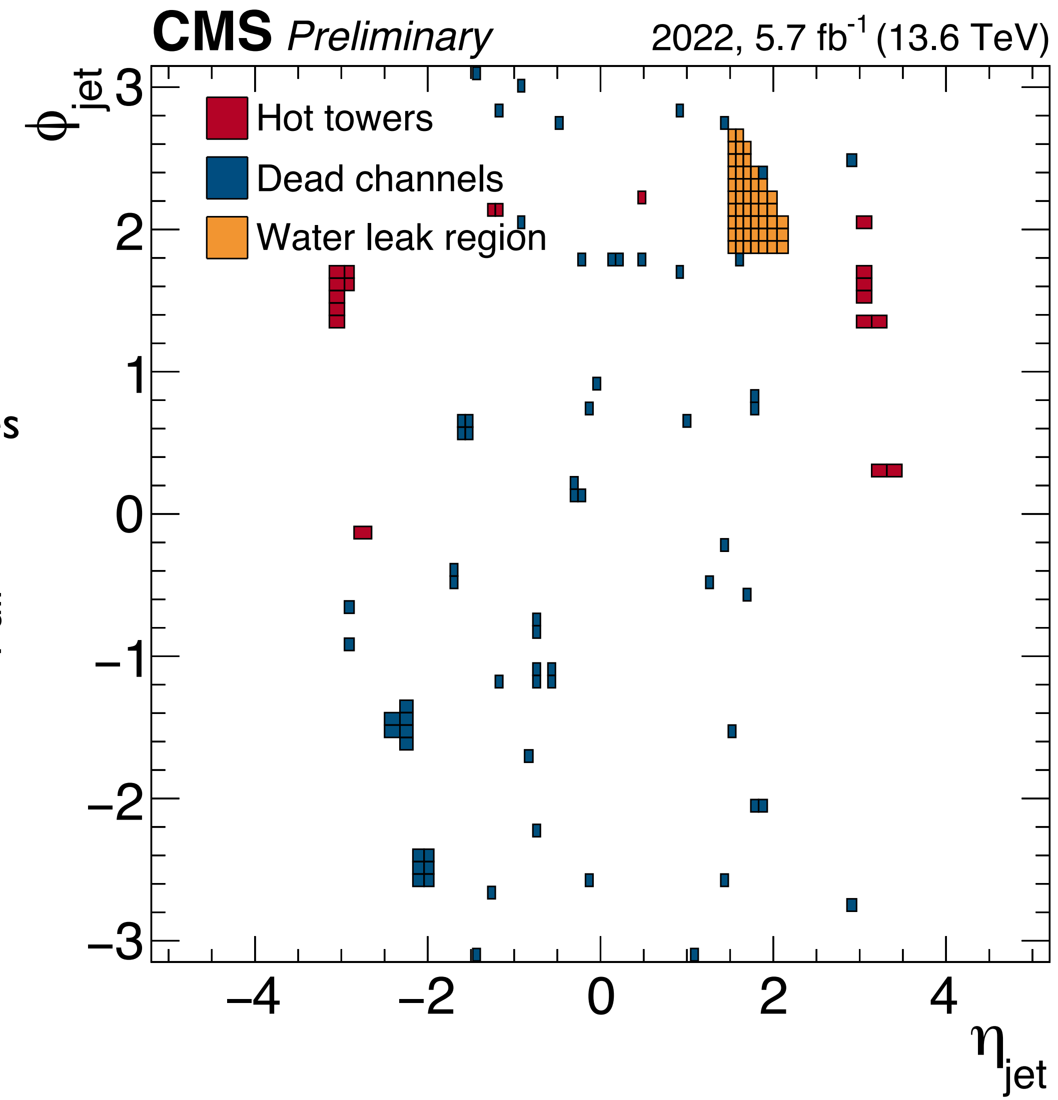
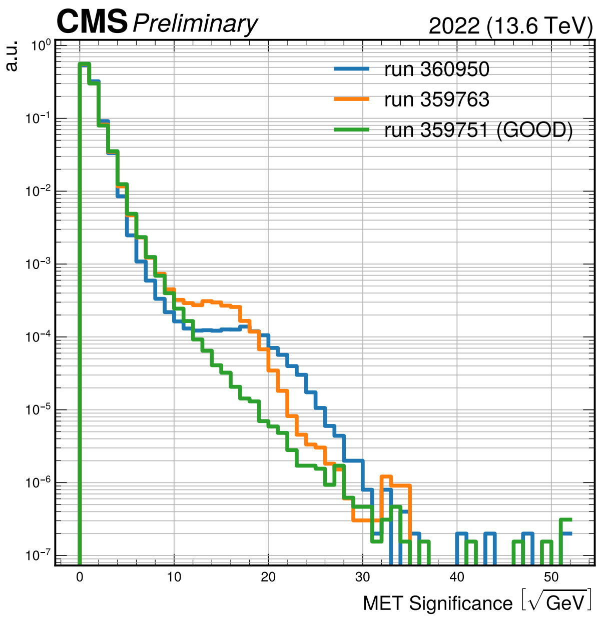


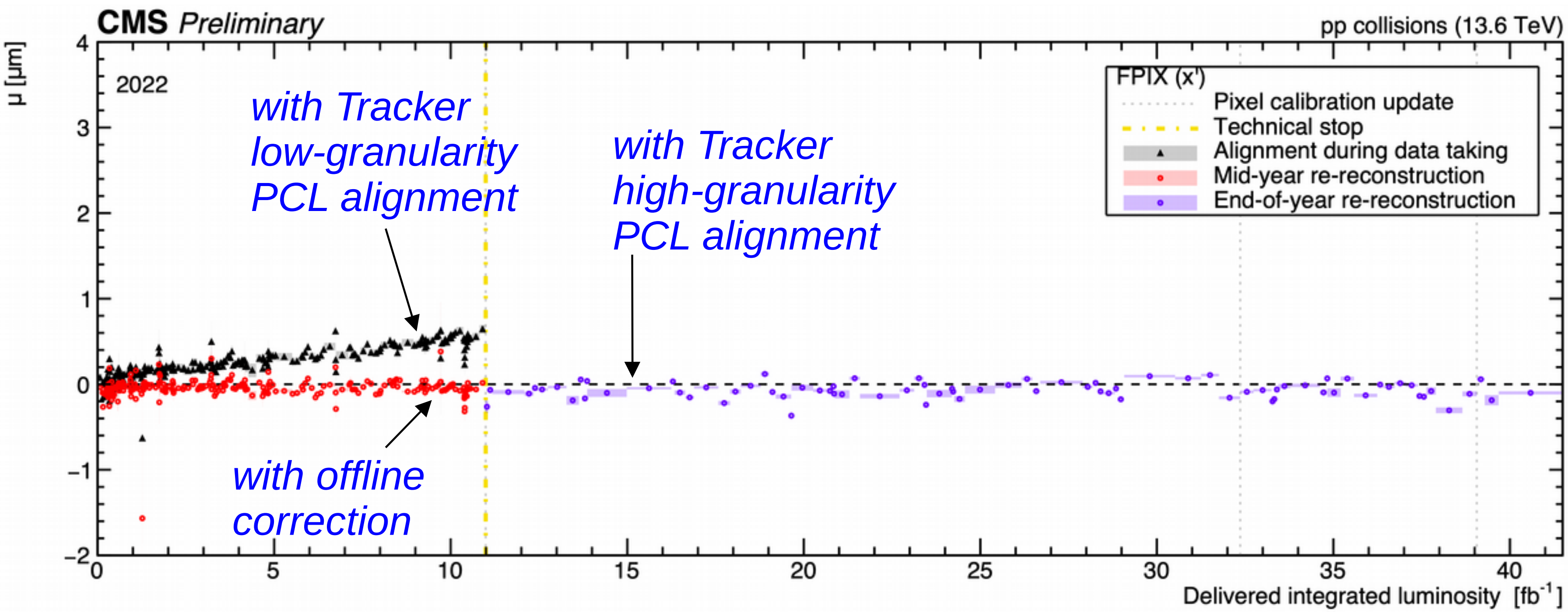
Fig. Sum of pulls of multiple observables in jet data sets (left) used to generate jet veto maps (up)

Prompt Calibration Loop

- Automatic calibration improves quality and saves time for analysis
- Already in Prompt Calibration Loop:
  - tracker high-granularity calibration
  - ECAL calibration
- Next steps:
  - HCAL calibration
- Our future plans:
  - **JEC4Prompt**

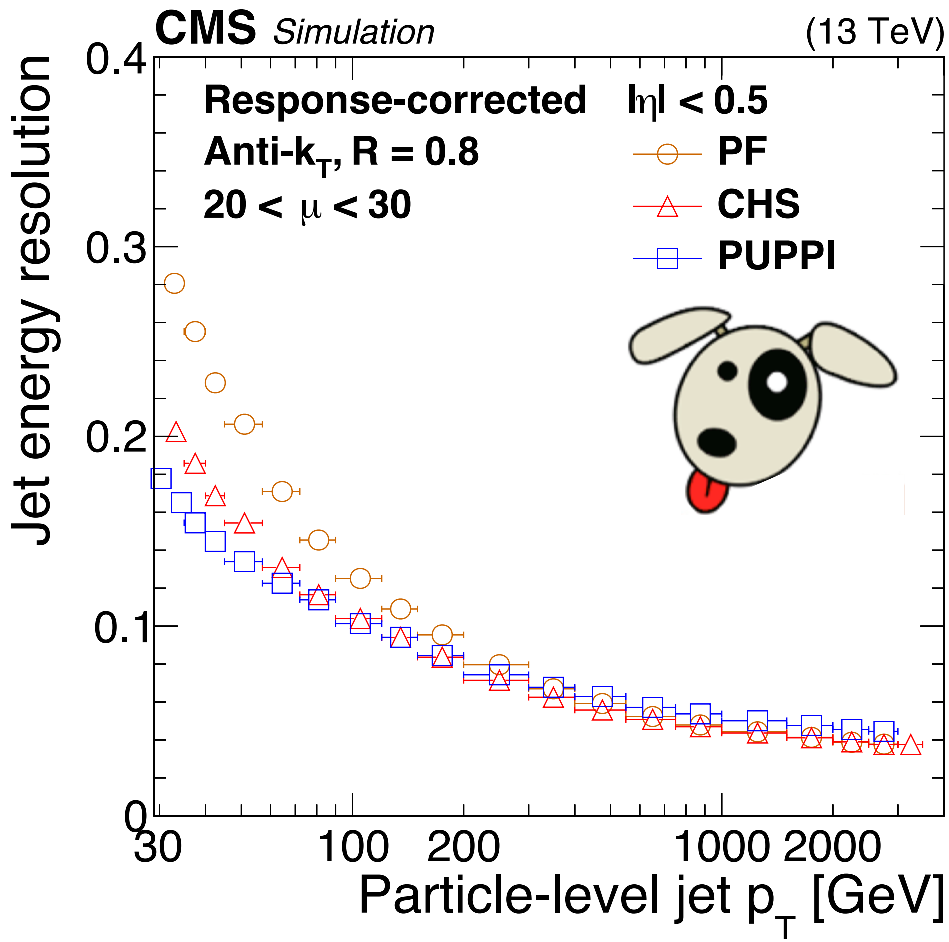


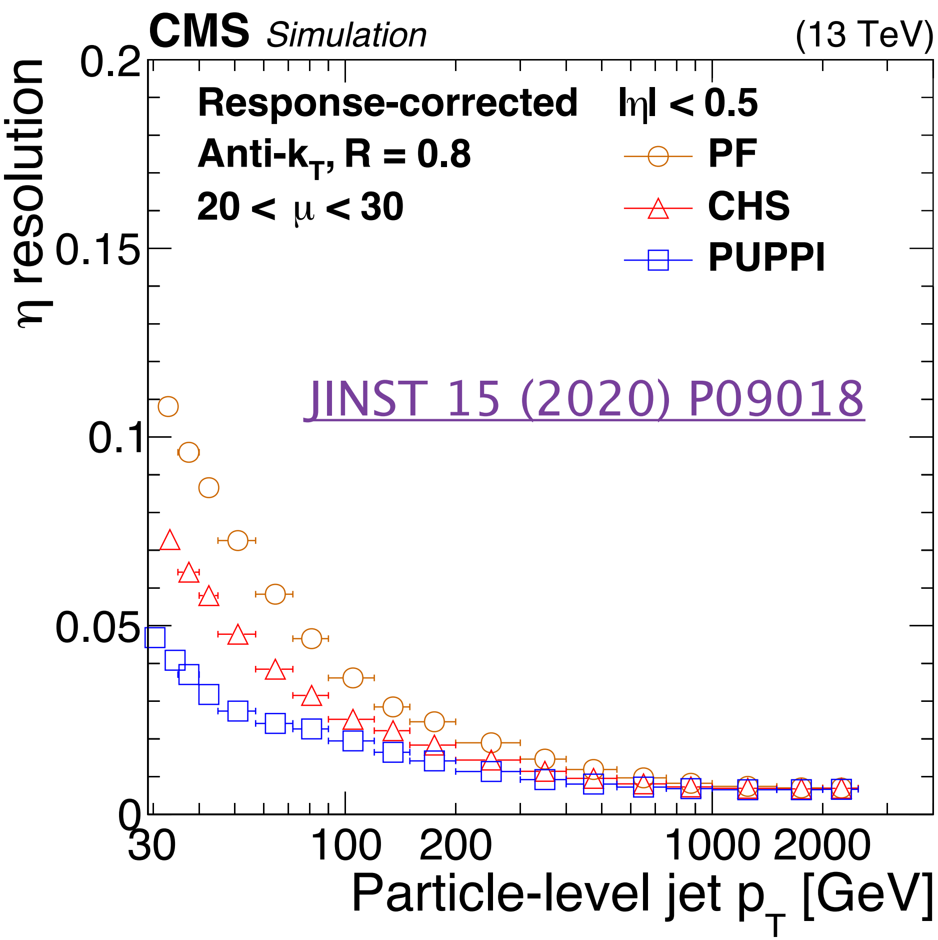
- Another advance: data certification per *luminosity section* (24 seconds) with Machine Learning:
  - can easily recover hours of data



Pileup mitigation in Run3

- **Particle Flow** reconstruction complemented with PileUp Per Particle Id (**PUPPI**)
- Handles pileup subtraction per event, keeps jet substructure observables intact
  - Good performance so far, has streamlined calibration procedure considerably
- Future step: combined jet flavour + energy regression with **ParticleNet** or **ParT**
  - State-of-the-art Graph Neutral Network and Transformer architectures

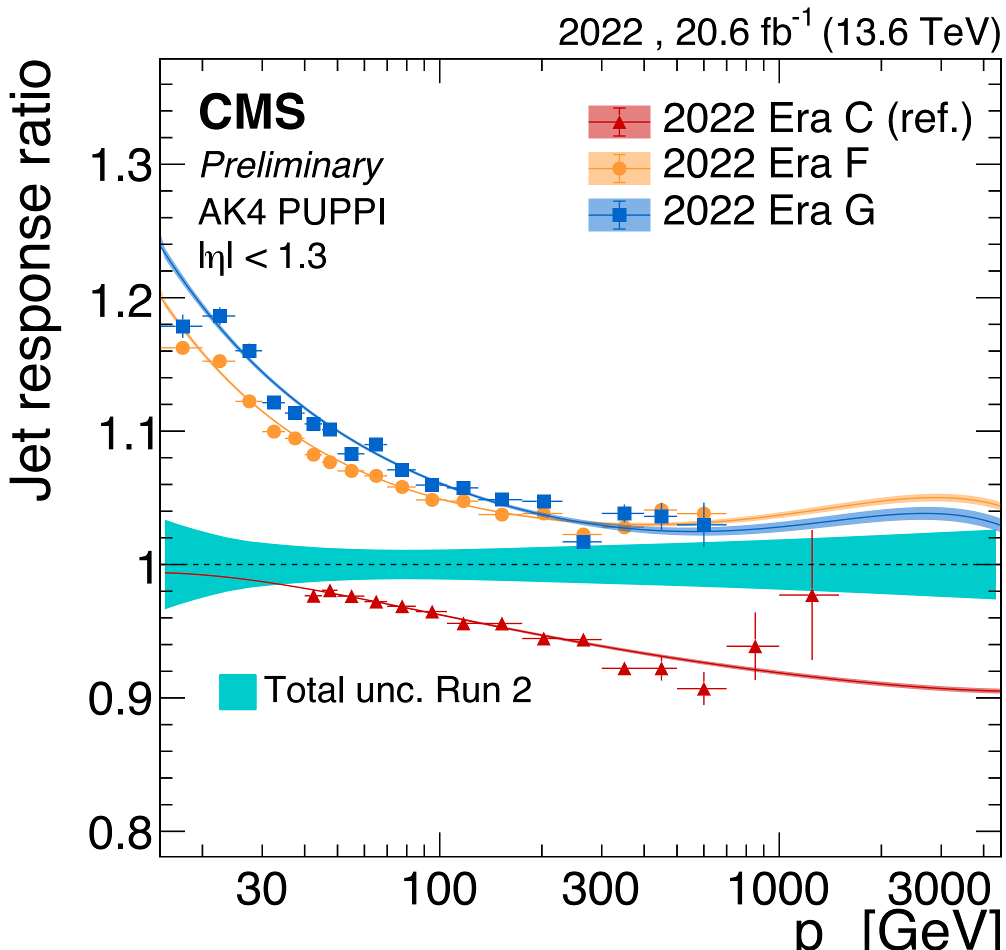




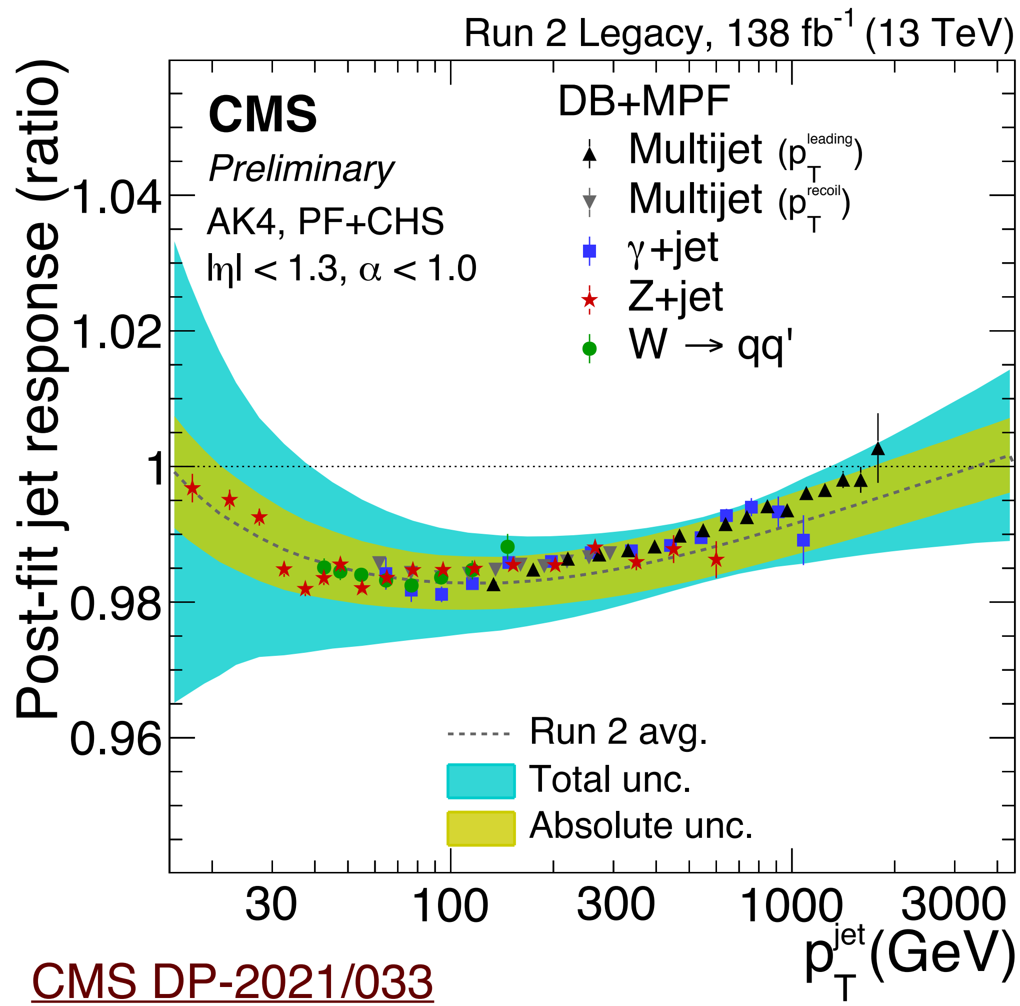
JINST 15 (2020) P09018

Jet energy corrections

- Jet energy corrections core expertise and key contribution of Helsinki
- Maintained steady flow of calibrations in Run 3 despite generational transition
  - HCAL scale and noise in barrel primary causes for large residual corrections => re-reco on-going
- Resuming Run 2 ultimate calibration + paper once Run 3 in steady state



CMS DP-2023/072



CMS DP-2021/033

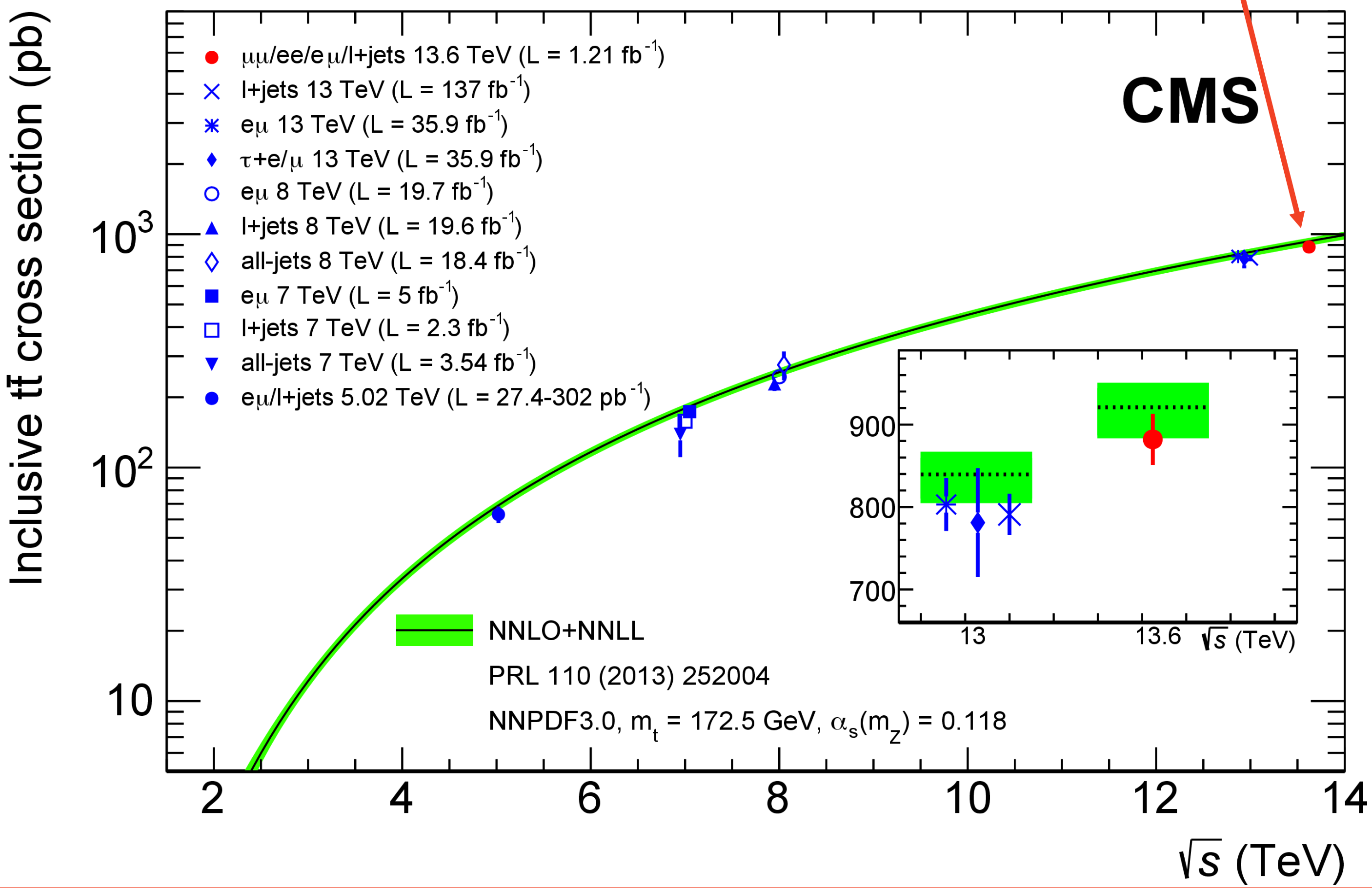
First Run 3 results

CMS results from Run 3 – Top quarks

first measurement of the top quark pair production cross section in proton-proton collisions at 13.6 TeV

Using 1.21 fb^{-1} of data from 2022 in dilepton and lepton + jets channels: **$\sigma_{(tt)}$= 882 ±± 23 (stat+syst) ±± 20 (lumi) pb**

Good agreement with SM prediction



CMS-PAS-TOP-22-012

29

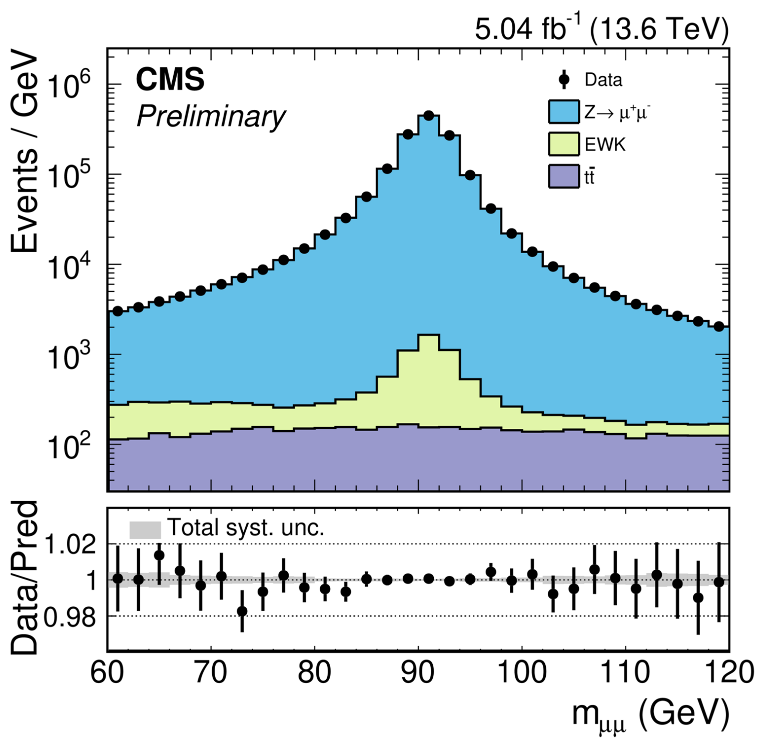
Run 3 results – Z bosons

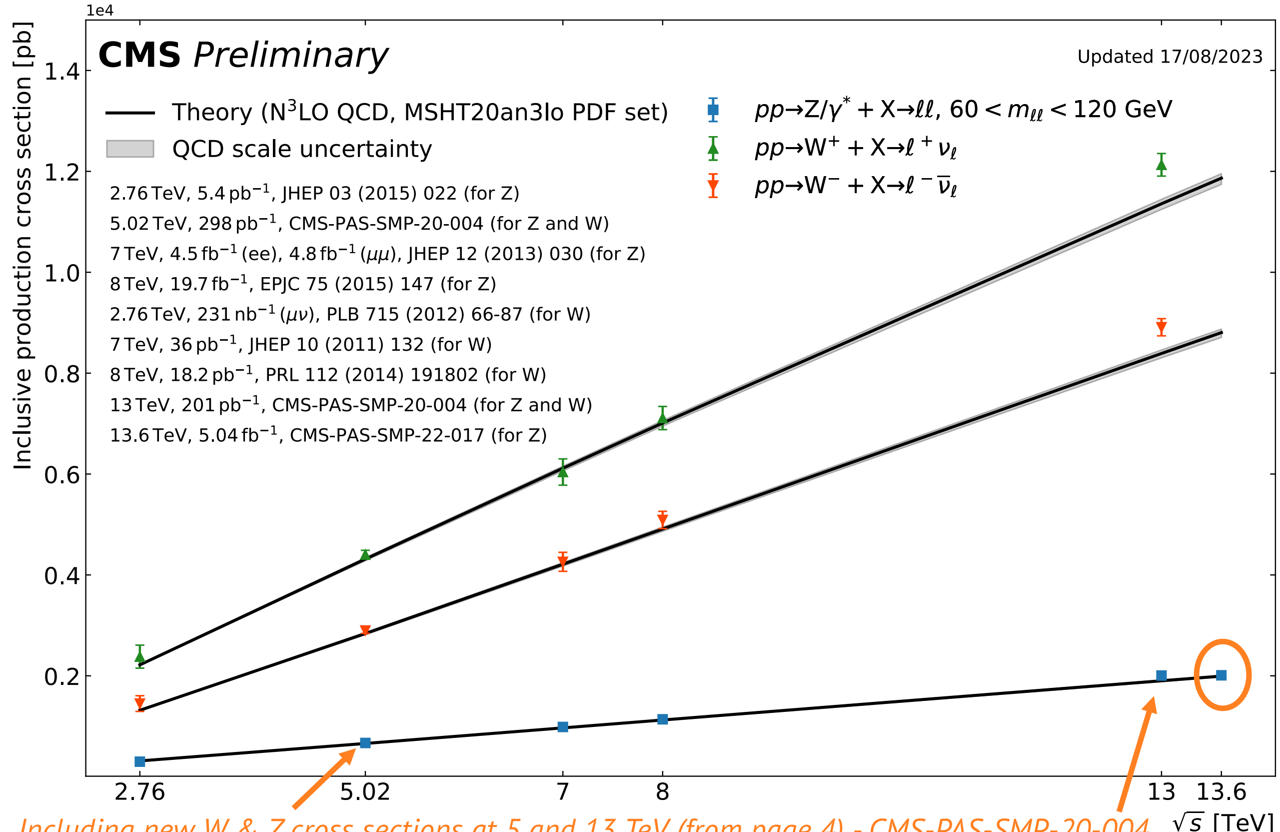
New

first measurement of the Z boson production cross section in proton-proton collisions at 13.6 TeV

Using 5.04 fb^{-1} data from 2022 with 2 identified muons

Measure fiducial and total cross sections $\sigma_{Z(Z\to\mu\mu)}$ = 2.010 ± 0.001(stat) ± 0.018(syst) ± 0.046(lumi) ± 0.007(theo) nb for the invariant dimuon mass in the range 60 to 120 GeV





Including new W & Z cross sections at 5 and 13 TeV (from page 4) - CMS-PAS-SMP-20-004

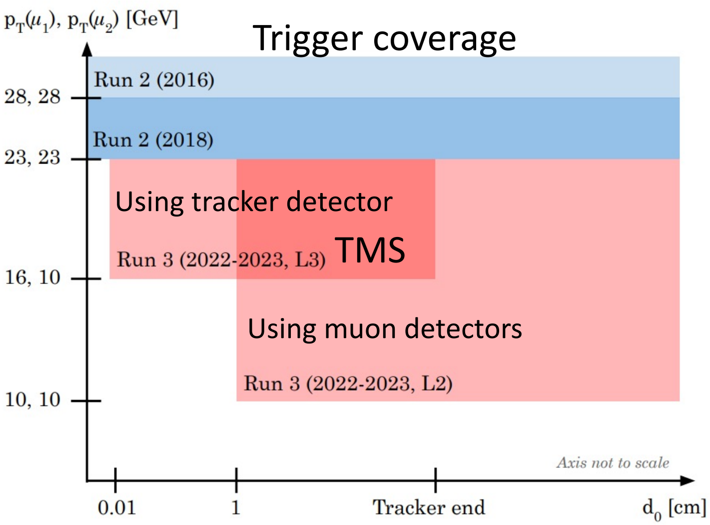
CMS-PAS-SMP-22-017

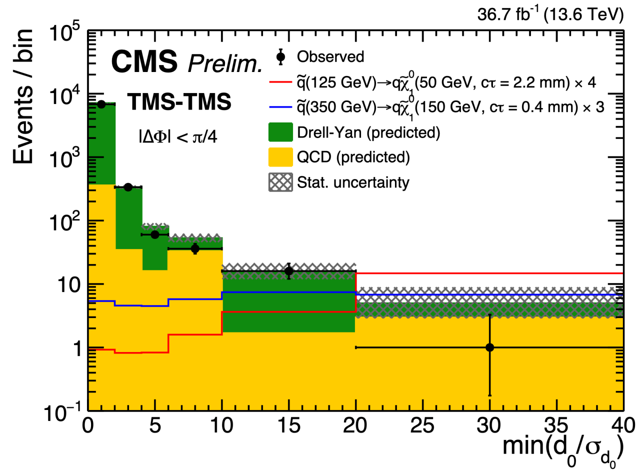
30

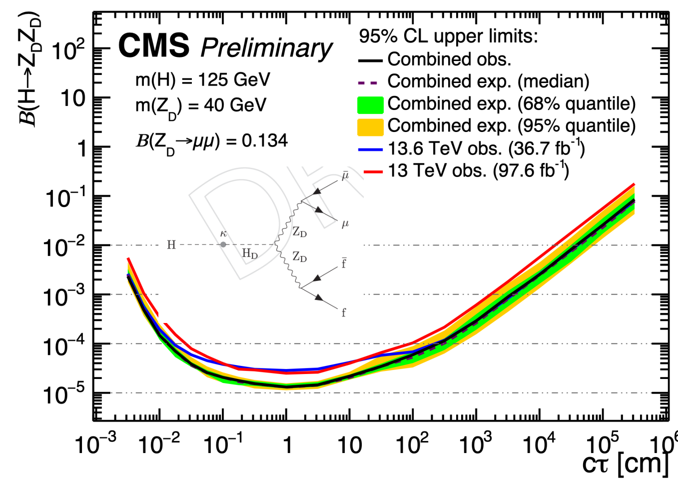
Run 3 results – long lived particles

New

first search for new physics: inclusive search for long-lived exotic particles decaying to a pair of muons
Using 36.7 fb^{-1} data taken in 2022, selecting muons originating from a common secondary vertex spatially separated from the primary interaction point by distances ranging from several hundred μm to several meters







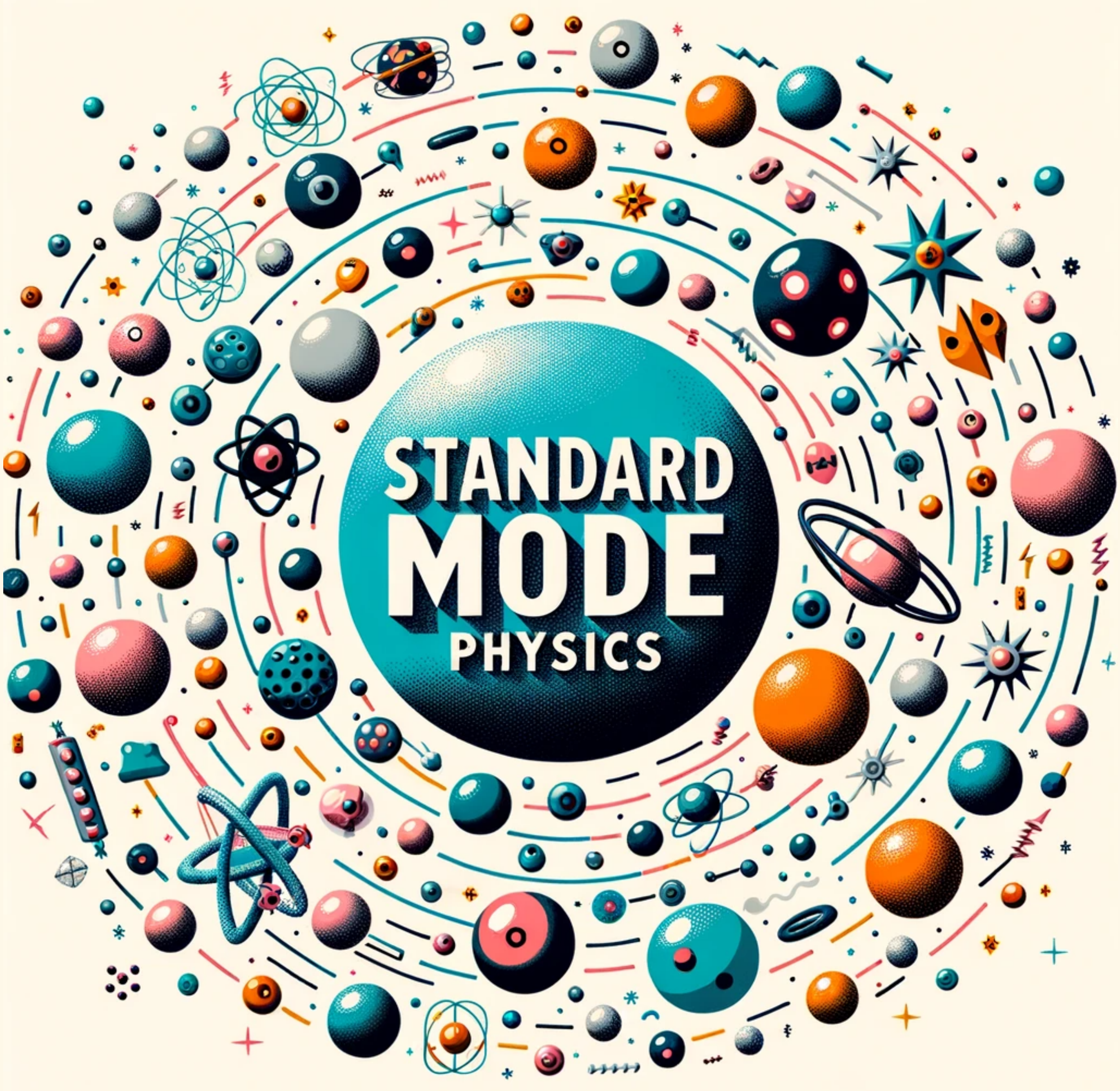
Substantial improvements in efficiency as compared to the Run 2 analysis, particularly at low masses and long lifetimes, mainly because of improved triggers for displaced muons and analysis refinements

Limits set for two benchmark models: the hidden Abelian Higgs model (HAHM), in which displaced dimuons that could rise from dark photons, and RPV SUSY model

Run 3 is opening opportunities for exploring physics beyond statistical improvements over Run 2

CMS-PAS-EXO-23-014

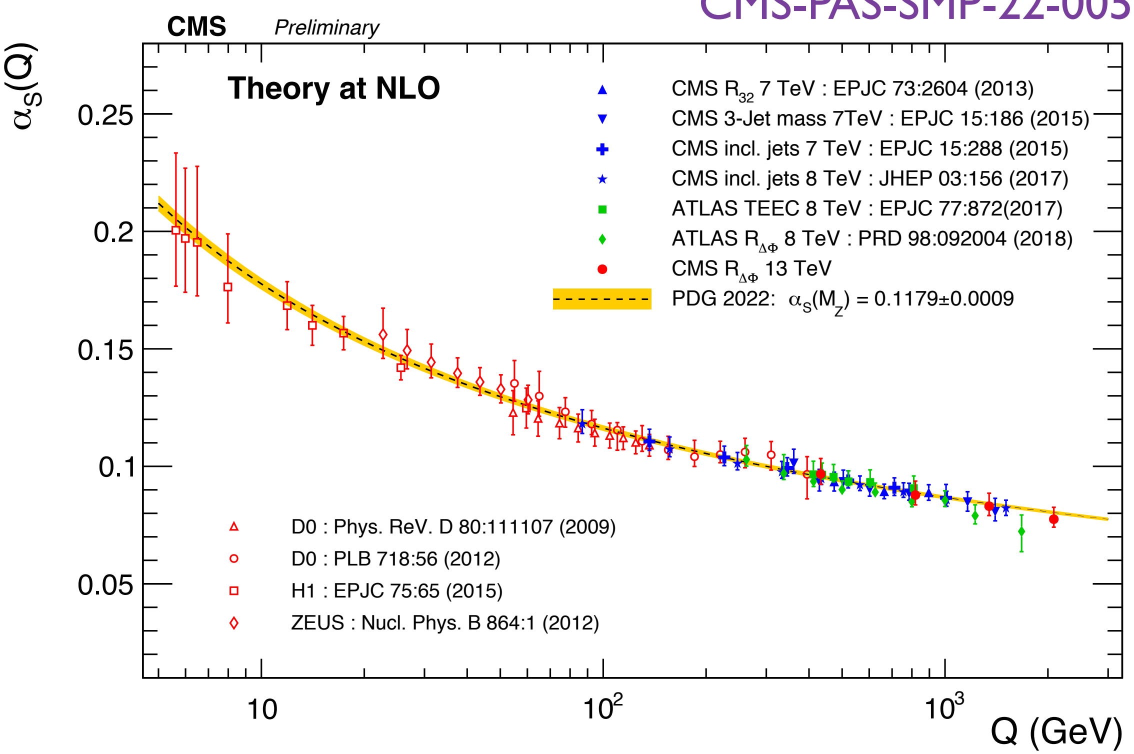
Standard Model Physics

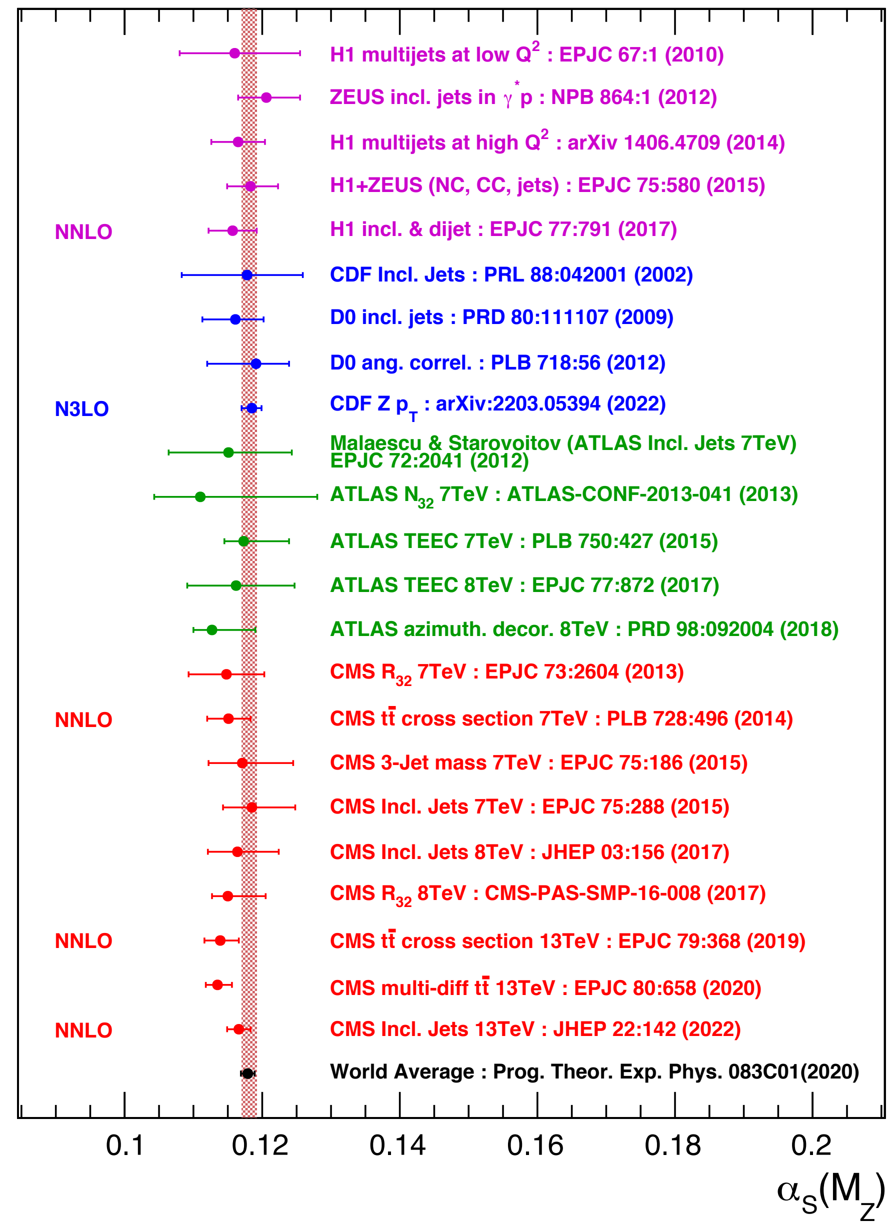


Strong coupling

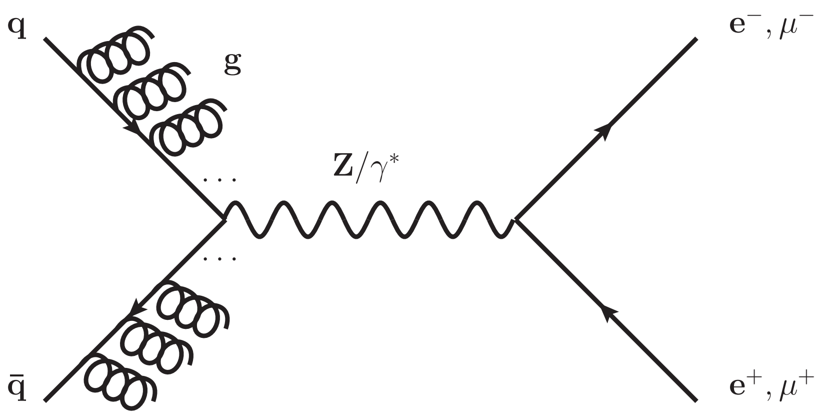
- Strong coupling constant running now measured up to Q=2 TeV with $R_{\Delta\Phi}$
- CMS inclusive jets at 13 TeV was most precise determination of α_s at hadron colliders
  - **theory at NNLO**, minimum required by PDG
- Full Run2 measurement without final JEC by Laura Martikainen: **defense Oct 23**

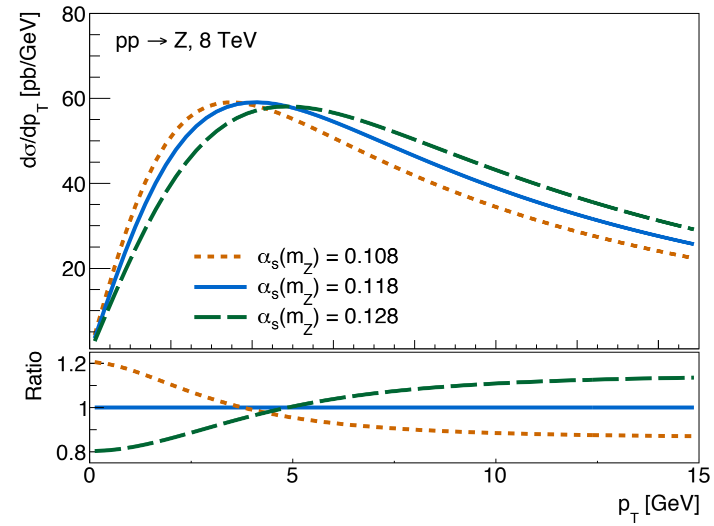
CMS-PAS-SMP-22-005

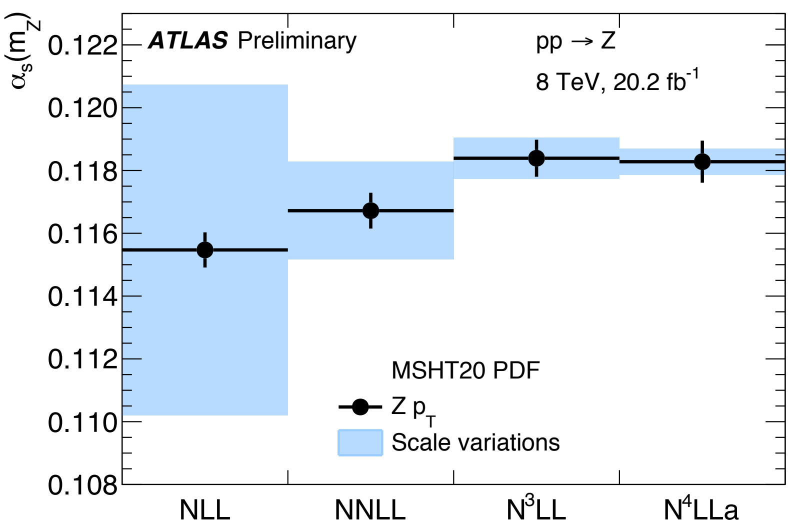


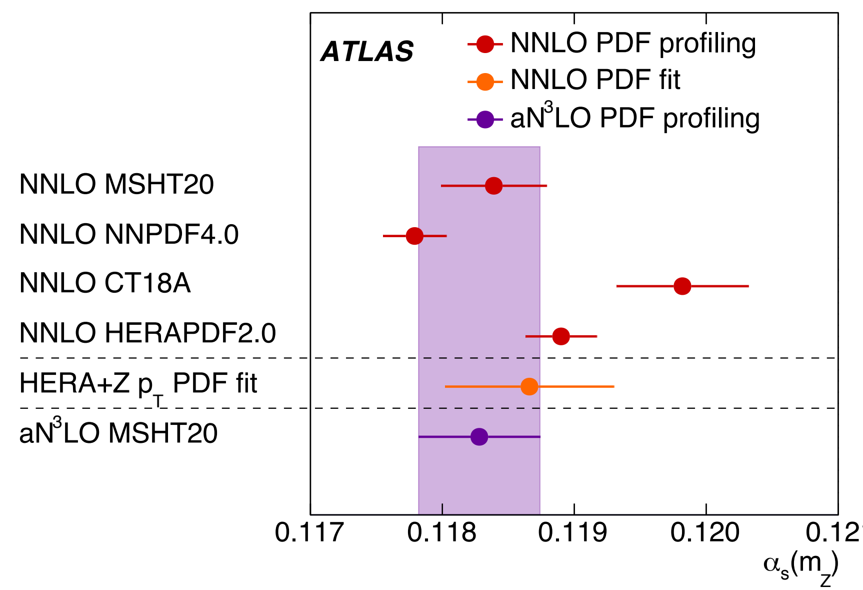


- New measurement of α_s from Z p_T @ N^3LO by **ATLAS on par with lattice QCD?!**
- Expect/hope inclusive jets Run 2 with ultimate JEC to also reach similar ball-park









arXiv:2309.12986, submitted to Nature Phys. (22 Sep 2023)

Energy correlators in jets

Confinement and asymptotic freedom

New

Measurement of $R_{\Delta\phi}(p_T)$ as function of p_T in 3-jet topology

CMS-PAS-SMP-22-005

Data compared with PHYTHIA and POWHEG

Extract α_S with fixed-order predictions of pQCD at NLO order, corrected for EWK effects

$\alpha_S(M_Z) = 0.1177^{+0.0117}_{-0.0074}$ using the NNPDF3.1 NLO PDF, dominated by scale in NLO prediction

Measurement of energy correlators inside jets

N-point energy energy correlator (**EnC**): a jet substructure variable with information of energy flows inside a jet

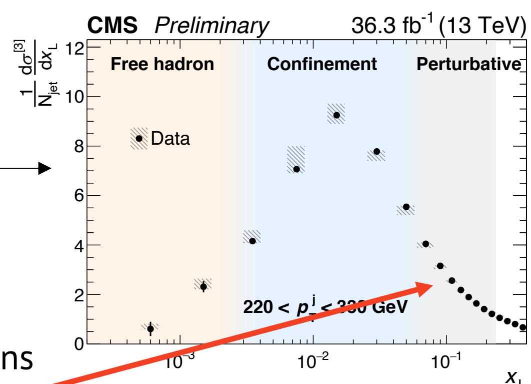
Measure 2-point and 3-point correlations (E2C, E3C, and E3C/E2C) in multiple jet p_T regions

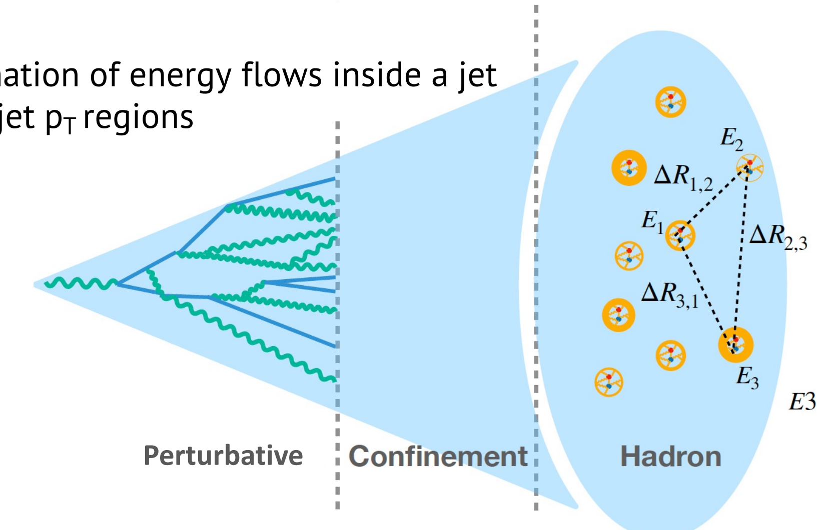
- Using neutral and charged particles with $p_T > 1$ GeV within the jets
- **Observes transition from parton to hadron**

$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j}),$$

$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k})).$$

χ_L = largest ΔR between the 2 or 3 particles





CMS-PAS-SMP-22-015

Compare the particle level E3C/E2C distribution to NNLL-approx predictions

- Extract α_S using the perturbative region of E3C/E2C

$\alpha_S(M_Z) = 0.1229^{+0.0040}_{-0.0050}$ (4%, most precise determination using jet substructure)

A new means of studying QCD in collider experiments, can help validate future higher-order implementations in parton-showers

17

Force is strong inside jets!

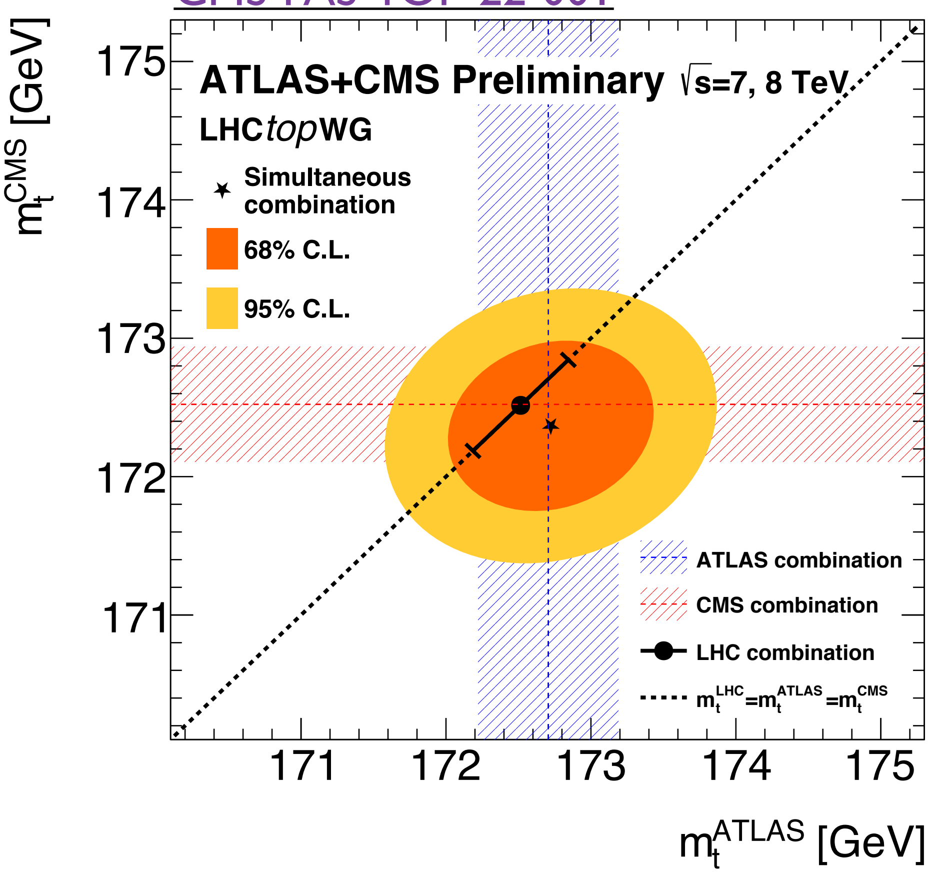
Top quark mass

- Run 1 CMS+ATLAS combination just out, precision now 0.33 GeV
- On par with profile likelihood, but full Run 2 expected is 0.19 GeV (H. Siikonen, thesis)
- More precision, new questions: b vs light quark final state radiation? Semileptonic b decays?

Run 1 combination, CMS+ATLAS

m_t = 172.52 ± 0.14 (stat.) ± 0.30 (syst.) GeV

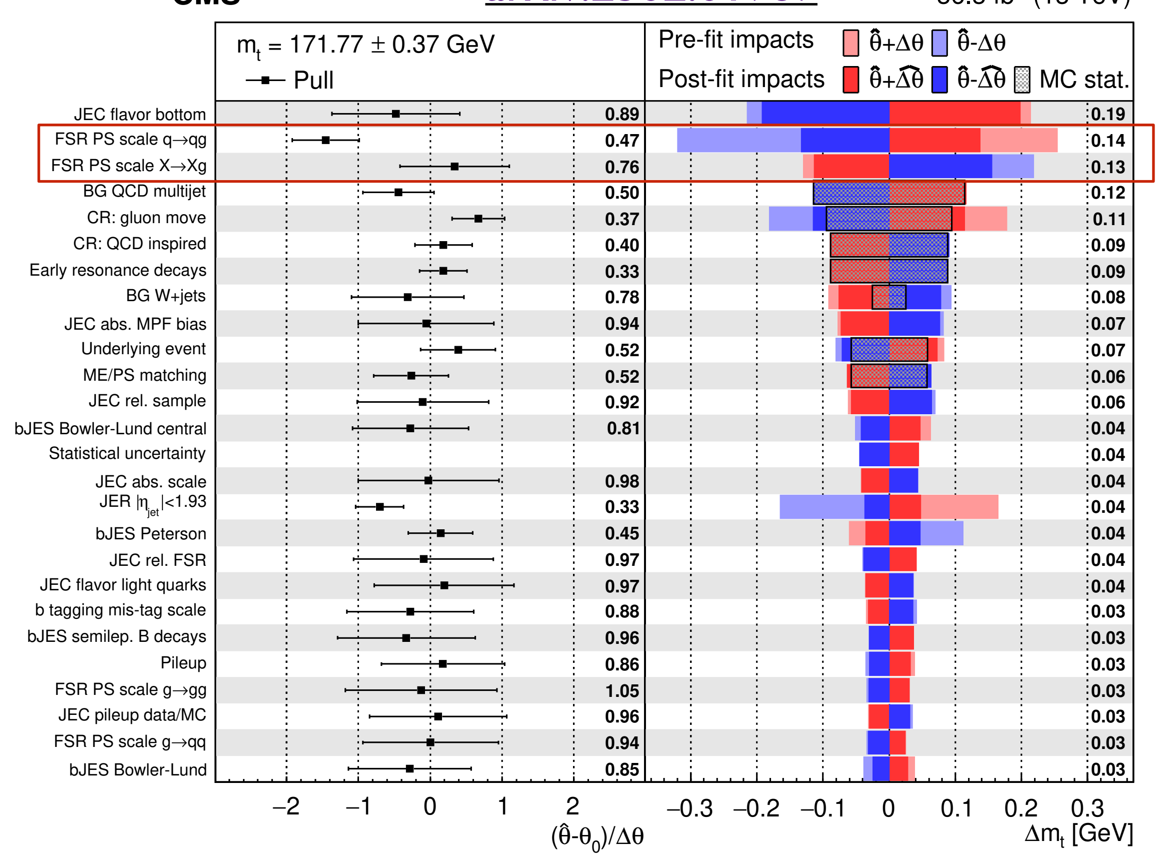
CMS-PAS-TOP-22-001



Run2 (2016) profile likelihood

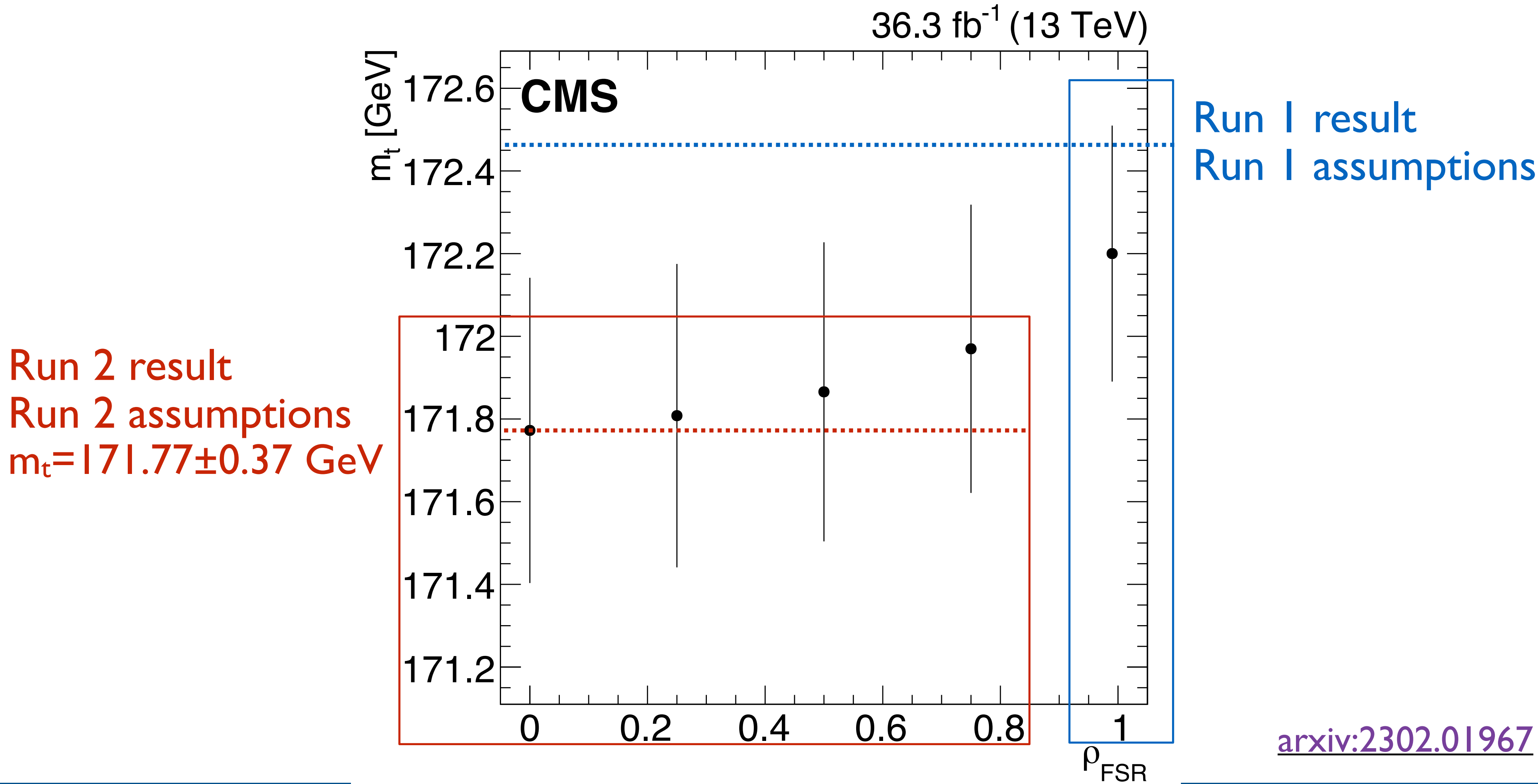
m_t = 171.77±0.37 GeV

arxiv:2302.01967



Bottom line

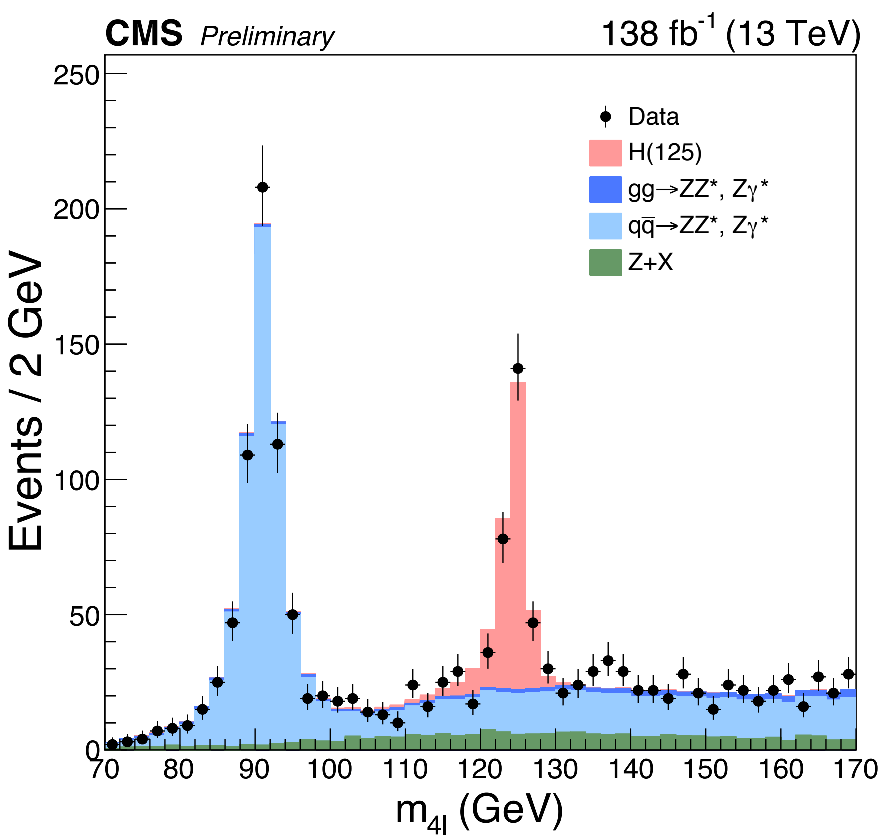
- Bottom quark uncertainty *correlations* now dominate top quark mass (t>Wb 100%):
  - correlation between b-FSR and udsc-FSR (here marked ρ_{FSR})
  - b recoil in top center-of-mass frame
- More in Mikael's talk, summarising m_t plenary from TOP2023 conference



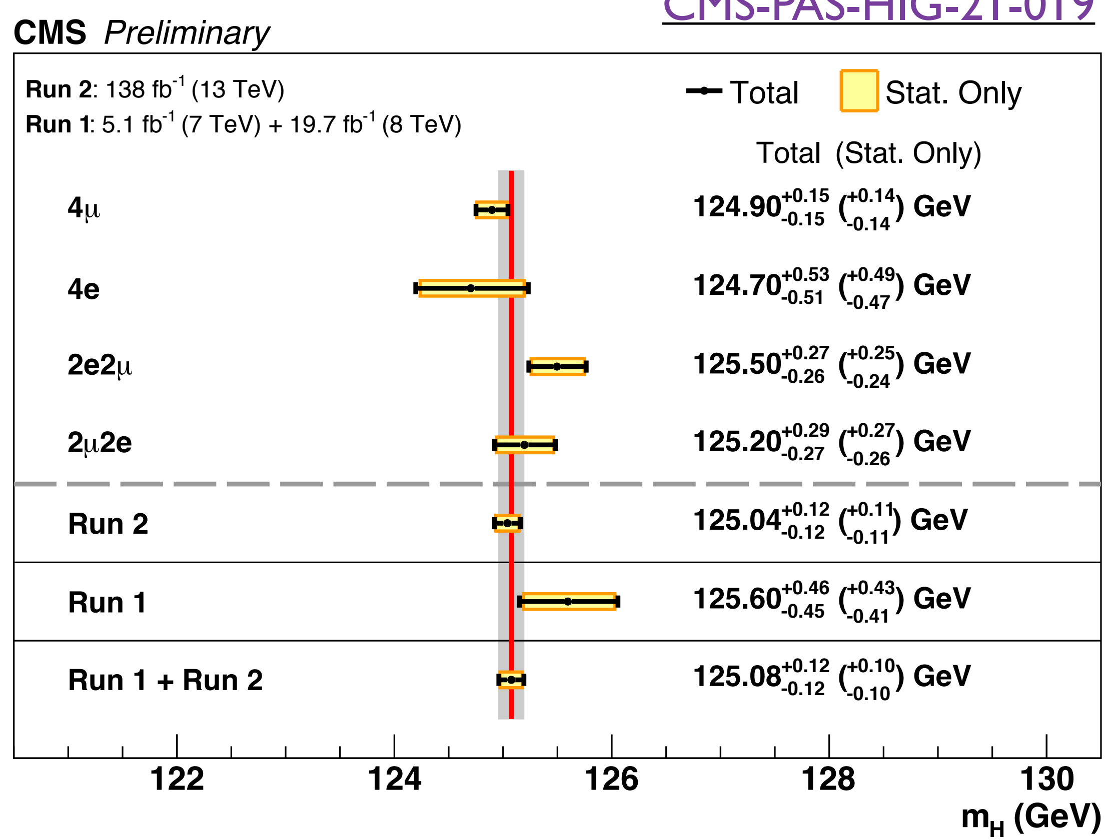
arxiv:2302.01967

Higgs boson mass

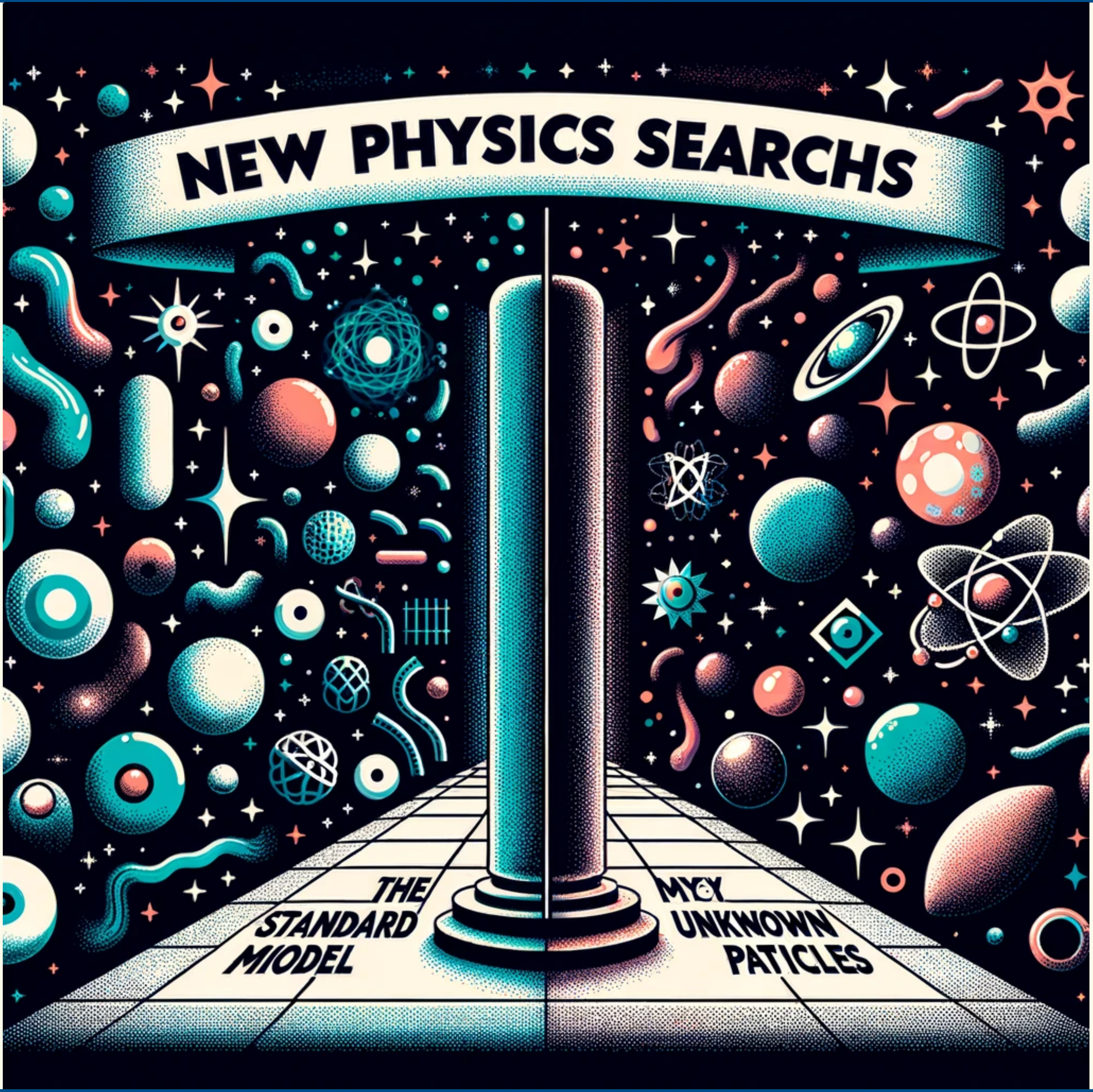
- Higgs boson mass measured very precisely from leptons and photons
  - CMS 4l: $m_H = 125.08 \pm 0.12$ GeV (HIG-21-019, 20 Sep 2023)
  - ATLAS γγ+4l: $m_H = 125.11 \pm 0.11$ GeV [arxiv:2308.04775] (8 August 2023)
  - $\sqrt{(m_Z{}^*(m_W+m_Z))} = 125.078 \pm 0.007$ GeV, $m_W+m_Z = 171.58 \pm 0.01$ GeV ($^*m_t = 171.77 \pm 0.37$ GeV)
- Higgs width from on-shell vs off-shell: $2.9^{+2.3}_{-1.7}$ MeV vs 4.1 MeV in SM



CMS-PAS-HIG-21-019



New physics searches



Rare decays - *Higgs boson*

New

Evidence of H→ Zɣ decays *CMS-PAS-HIG-23-002*

CMS + ATLAS combined evidence: observed 3.4σ (expected 1.6σ)

Search for lepton flavor violating H→ eμ decays

In 110 – 160 GeV mass region of a eμ pair

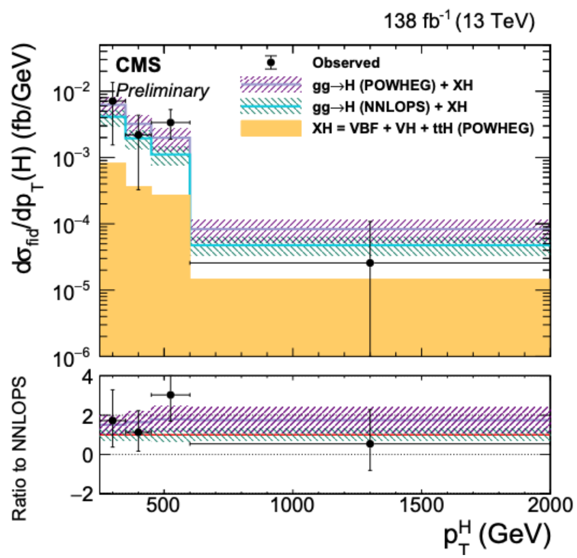
Observed (expected) upper limit on BR is 4.4 (4.7) × 10^{-5} at 95% CL

Most stringent limit from direct searches *CMS-PAS-HIG-22-002*

Measure highly Lorentz-boosted H→ττ events

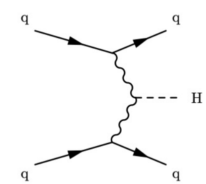
Using dedicated algorithms to resolve overlapping τ_s the signal with $p_T^H > 250$ GeV is observed (expected) 3.5 (2.2) σ

CMS-PAS-HIG-21-017



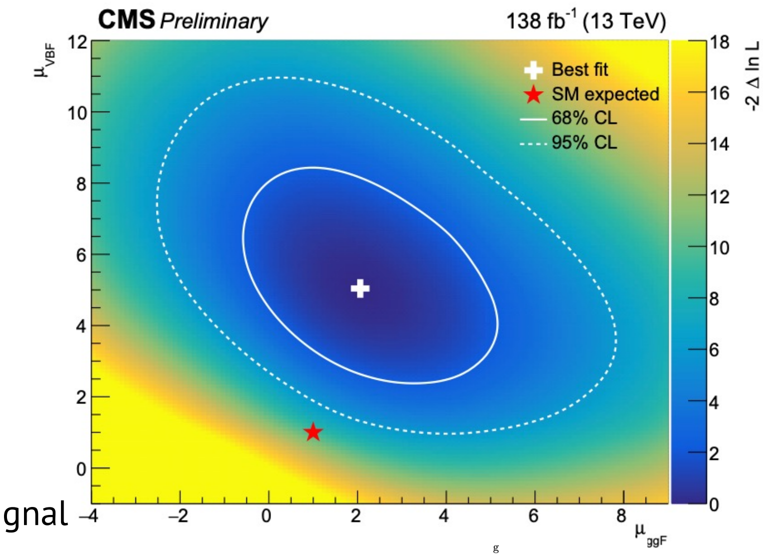
Measure VBF and ggF production simultaneously with H→bb

Using boosted Higgs decays since the relative contribution to Higgs cross-section from ggF decreases with p_T^H



$\mu_{VBF}=5.0^{+2.1}_{-1.8}$

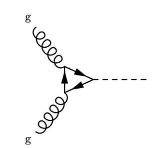
3.0 σ (0.9σ)



The observed signal strengths and corresponding observed (expected) significances

$\mu_{ggF}= 2.1^{+1.9}_{-1.7}$

1.2 σ (0.9 σ)



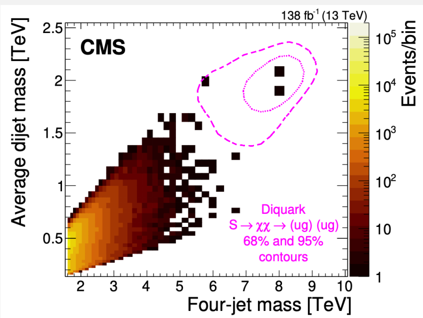
CMS-PAS-HIG-21-020

Higgs decays and high p_T are particularly sensitive to BSM ➔ these results provide an important step forward in the exploration of the Higgs boson and its interactions

Search for multi-jet resonances

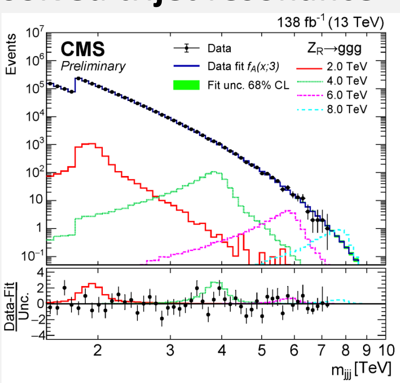
New

High mass resonant and non resonant pair of dijet resonances



JHEP07(2023)161

Resolved trijet resonance

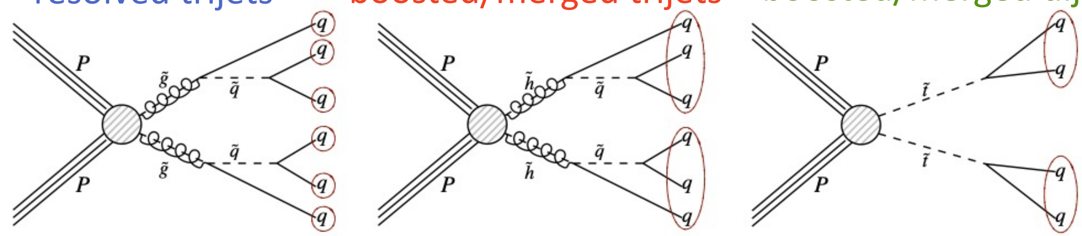


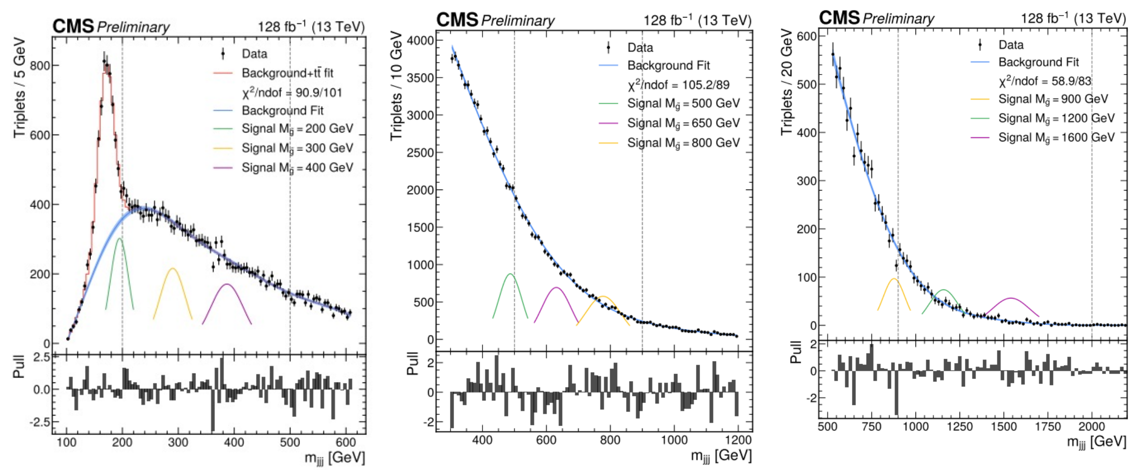
CMS-PAS-EXO-22-008

Extending bump hunt to lower resonance masses and more signatures

Uses **scouting dataset**: saves only event data reconstructed by the high-level trigger
Low mass resonance are produced with significant Lorentz boosts

resolved trijets | boosted/merged trijets | boosted/merged dijets





(can clearly see SM resonances in boosted and resolved channels)

CMS-PAS-EXO-21-004

Use RPV SUSY as benchmark models: stringent limits on RPV gluinos, top quarks, and first limits on RPV Higgsinos

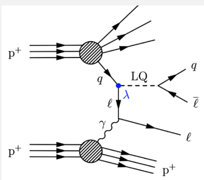
23

Searches for leptoquarks

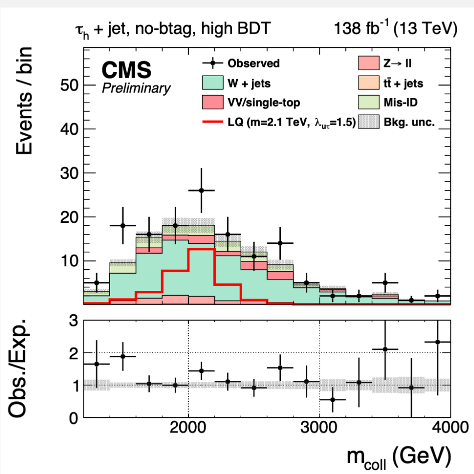
New

Lepton-induced production of LQs coupling to tau

LQ produced from the collision of a quark and a lepton inside the proton



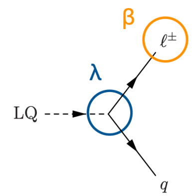
Using final states: $(\tau_e, \tau_\mu, \tau_h)$ + (jet, b-jet)



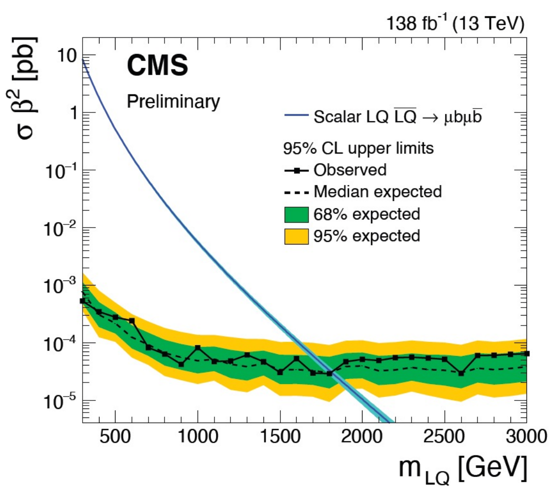
CMS-PAS-EXO-22-018

Leptoquarks in 2nd generation

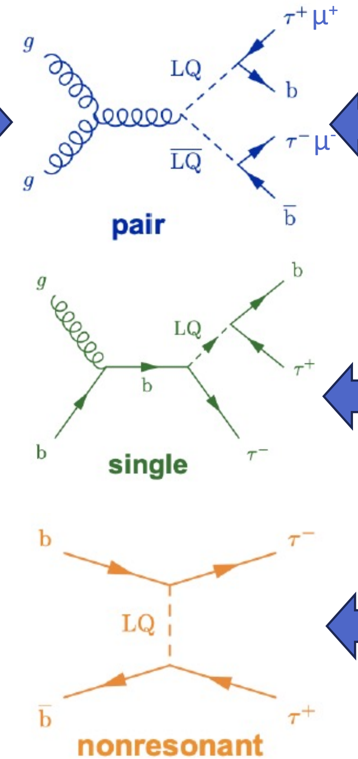
Search for pair produced LQ decaying to **muons** and **bottom quarks,** force β = 1 (no decays to neutrinos)



Signature of two high-p_T muons and two high-p_T b-jets



CMS-PAS-EXO-21-019



Leptoquarks in 3rd generation

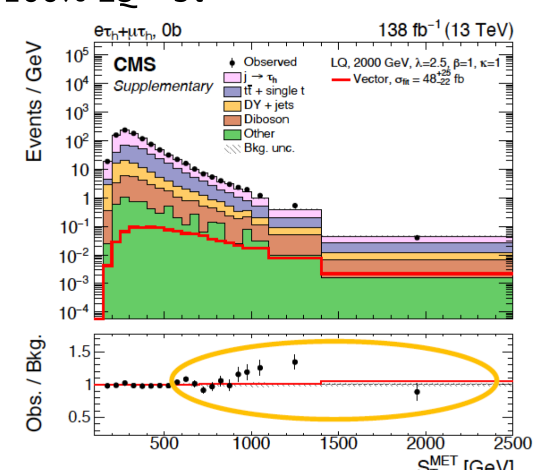
Search with **tau** and **bottom quarks**, Updates in recent submitted paper:

- fake tau model
- minor backgrounds added

Excess is most prominent :

- non-resonant LQ production
- probes high mass
- at high S_T MET with 1 jet but 0 b-tags ➞ 3.4 – 3.7σ

Not compatible with signal model of 100% LQ➞bτ



arXiv.2308.07826

24

Heavy ion physics

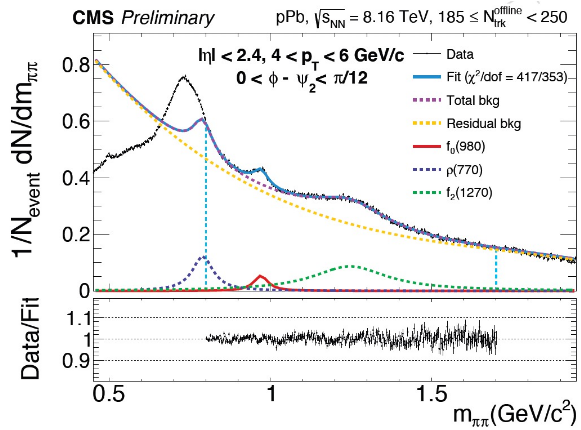
Determination of the quark content of $f_0(980)$

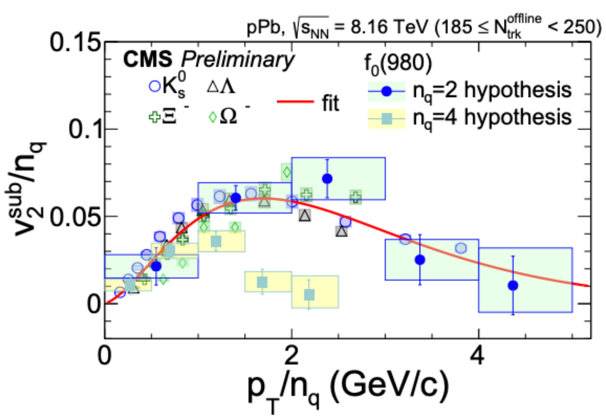
New

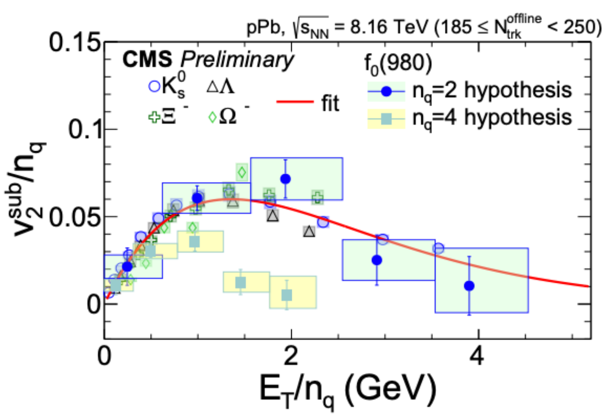
Discovered half century ago, the quark content of the **$f_0(980)$** hadron has not been settled

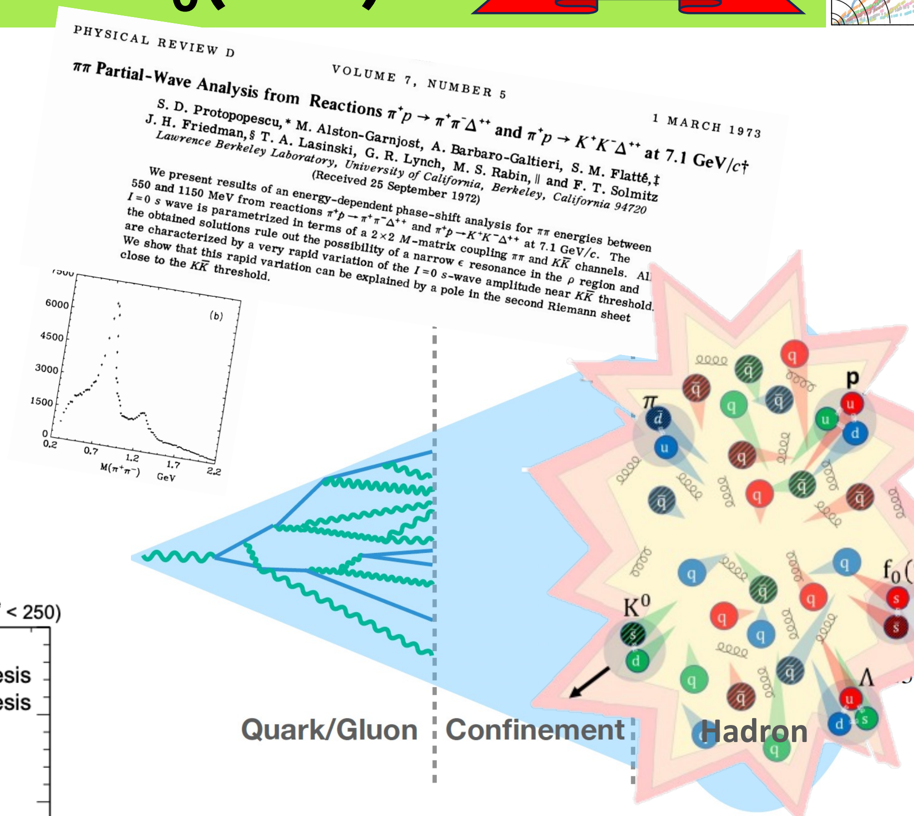
Using pPb data, the $f_0(980)$ is reconstructed via the invariant mass of its main decay channel $f_0(980) \rightarrow \pi^+\pi^-$

Measure the elliptic flow anisotropy v2 of $f_0(980)$ as function of p_T









The number of constituent quarks of $f_0(980)$ is consistent with 2

7.7 σ away from being a tetraquark state or KK molecule, or 6.3 σ (3.1 σ) if considering only restricted p_T range up to 8 GeV (6 GeV)

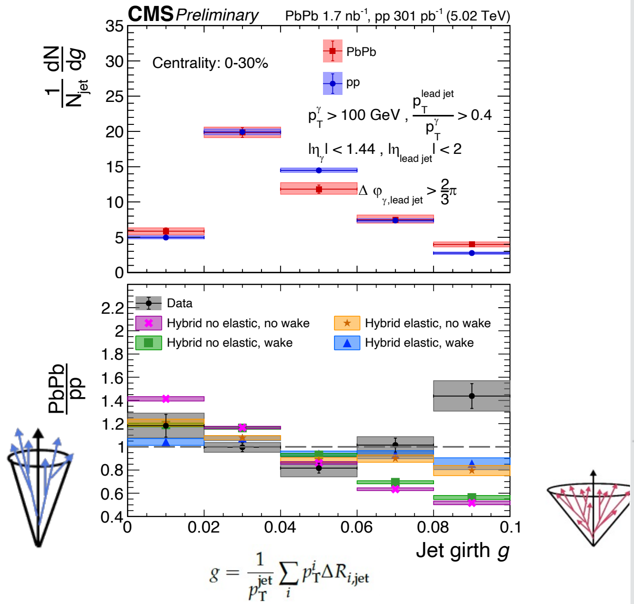
CMS-PAS-HIN-20-002

New insights on strong interactions

New

Girth of jets in quark-gluon plasma

Interactions with medium are expected to degrade the jet energy and modify the jet radiation pattern in QGP relative to pp



$$g = \frac{1}{p_T^{\text{jet}}}\sum_i p_T^i \Delta R_{i,\text{jet}}$$

Use **γ+jets** events in pp and PbPb

p_T jet/p_T^γ >0.4 (strongly quenched jets)

➔ **no narrowing is observed**

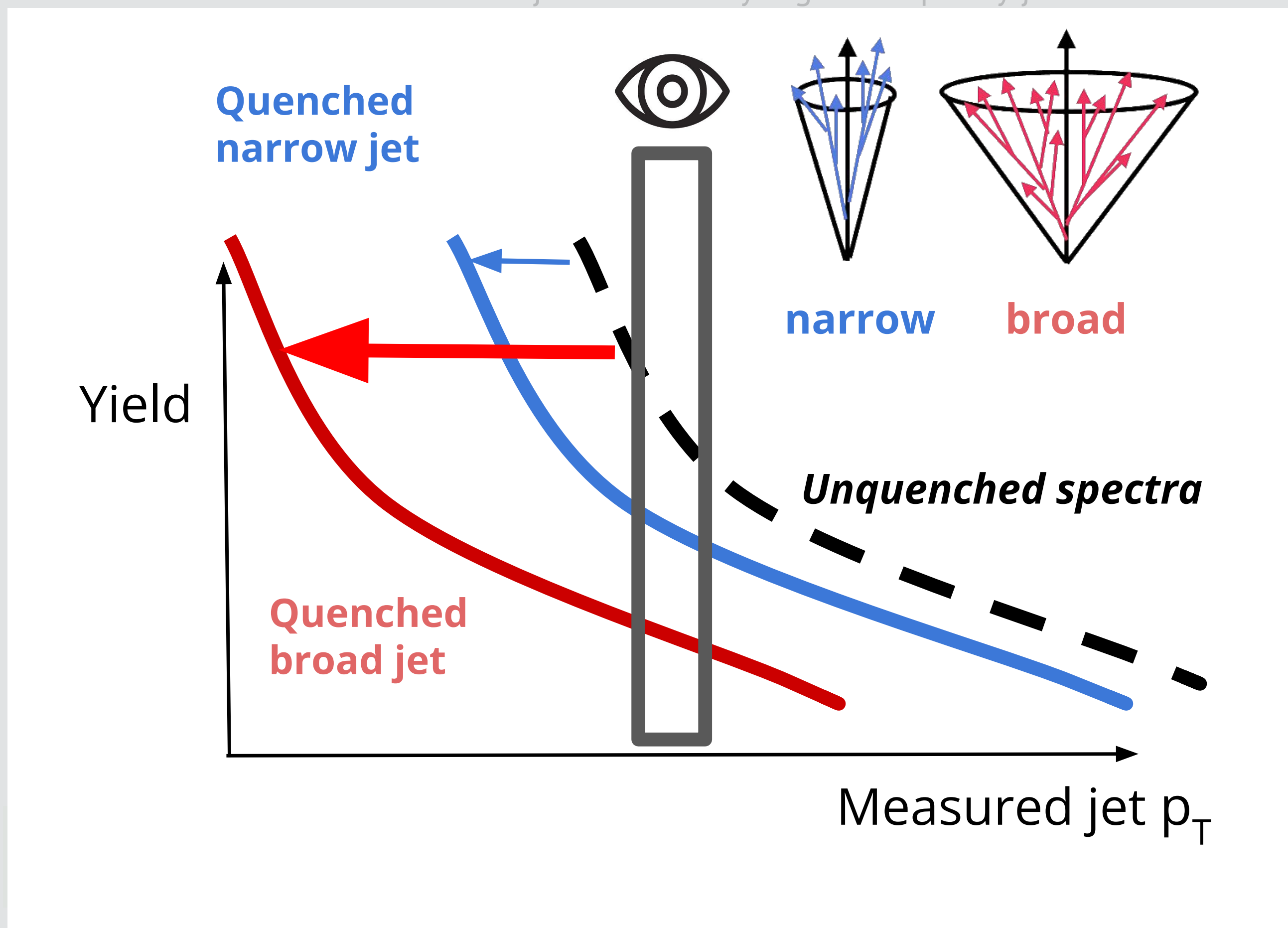
p_T jet/p_T^γ>0.8 (less quenched jets)

➔ **narrowing is observed**

CMS-PAS-HIN-23-001

Particle correlations inside a jet

Search for collective effects inside jets: can a very high multiplicity jet lead to the flow-like



More information at LHC seminar

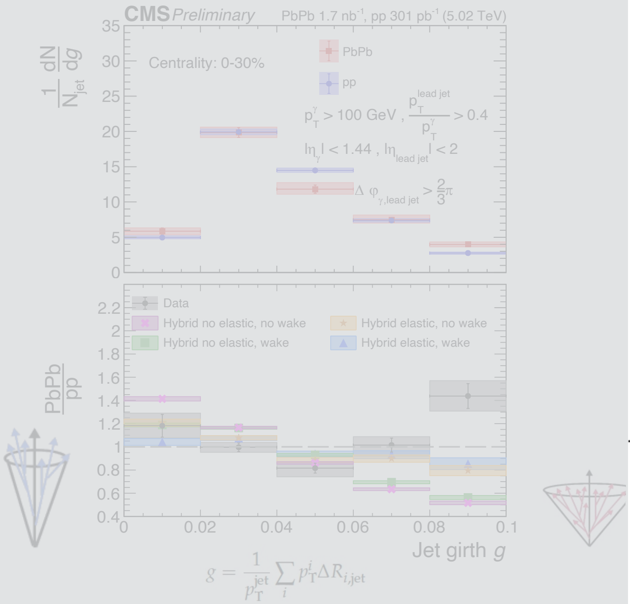
CMS-PAS-HIN-21-013 18

New insights on strong interactions

New

Girth of jets in quark-gluon plasma

Interactions with medium are expected to degrade the jet energy and modify the jet radiation pattern in QGP relative to pp



Use **γ+jets** events in pp and PbPb

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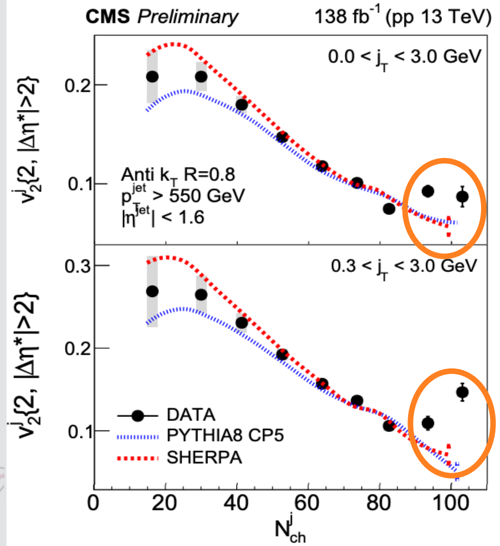
➔ **narrowing is observed**

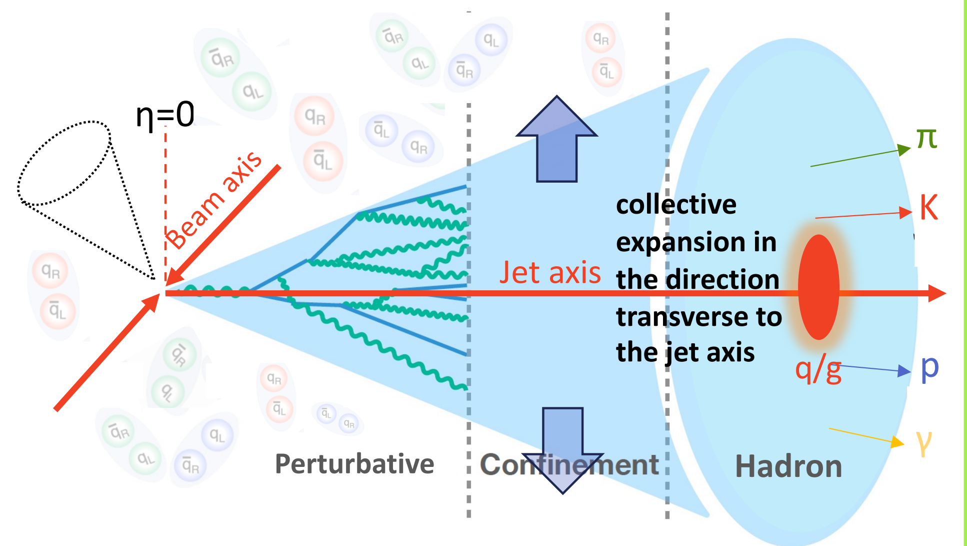
CMS-PAS-HIN-23-001

Particle correlations inside a jet

Search for collective effects inside jets: can a very high multiplicity jet lead to the flow-like behavior seen in QGP?

Using jets with anti-k_T=0.8, p_T>550 GeV, |η|<1.6 in high-pileup pp collisions





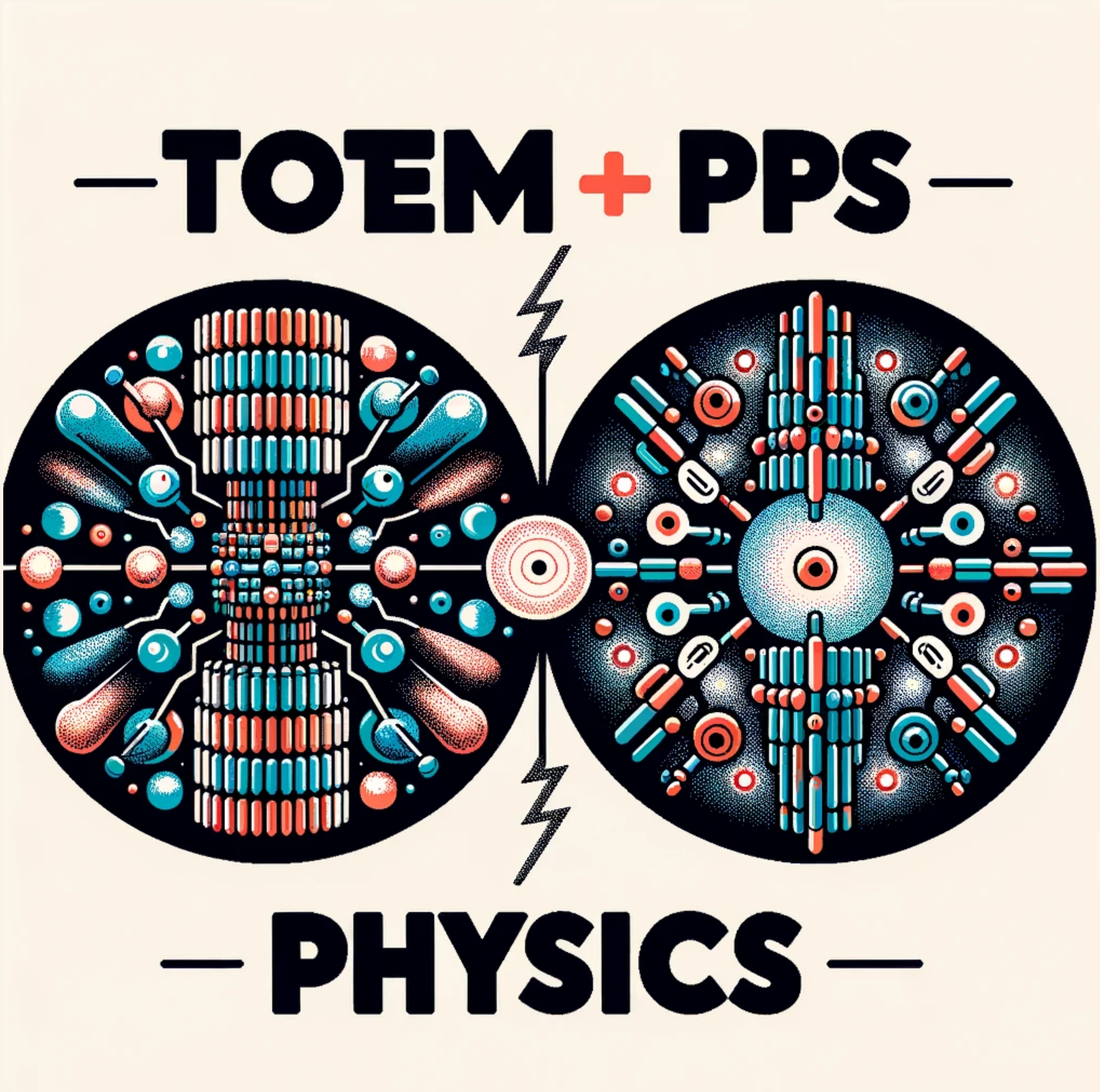
Measure 2-particle correlations function of charged constituents of a jet as a function of the charged-particle multiplicity inside a jet

Discrepancy in long-range many be an indication of the onset of new QCD effects, e.g., collectivity, in the parton fragmentation processes

More information at LHC seminar

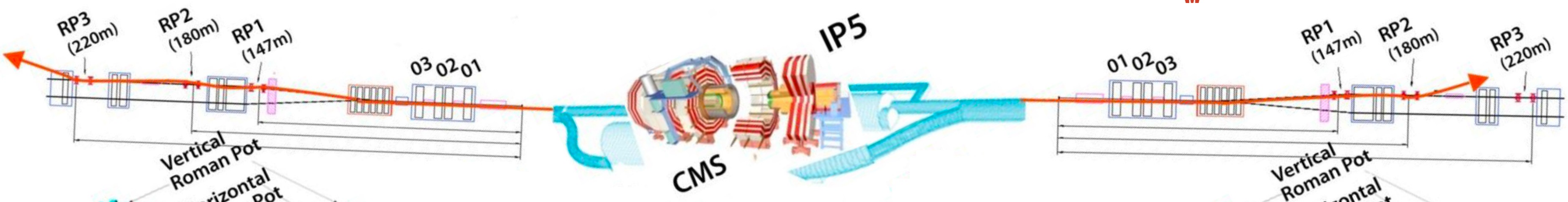
CMS-PAS-HIN-21-013

18


TOTEM + PPS
PHYSICS

Non-resonant central exclusive production

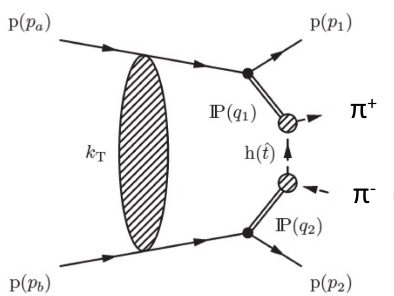
New



RP

CMS+TOTEM: examined about 80 M events with data taken with a special β* run of LHC in July 2018

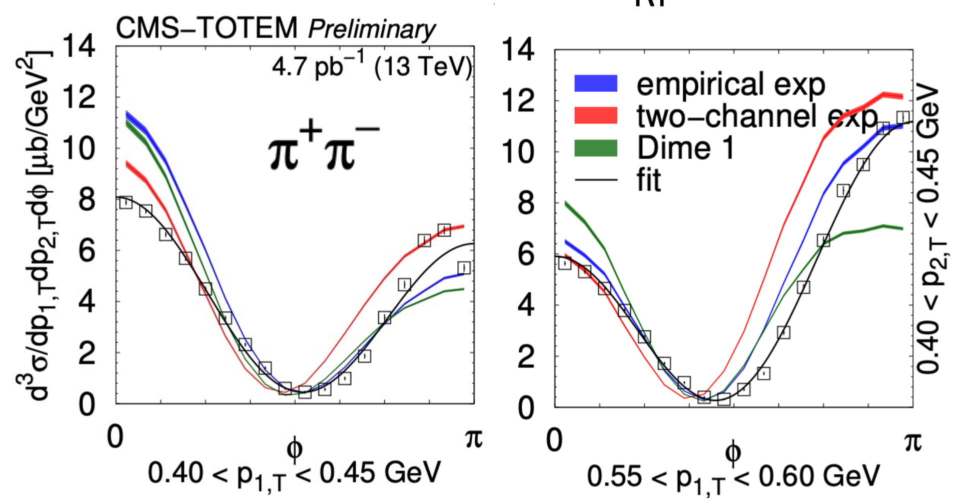
RP



Select 2 scattered **protons** detected in **TOTEM** roman pots and exactly 2 oppositely charged identified **pions** with the **CMS** silicon tracker from decays double pomeron exchange

Differential cross sections measured as functions of the azimuthal angle between the surviving protons in a wide region of scattered proton transverse momenta and hadron rapidities

Angle between protons



Studies in resonance-free region: m<0.7GeV or m>1.8GeV

Observe a rich structure of nonperturbative interactions related to double pomeron exchange, measured with good precision

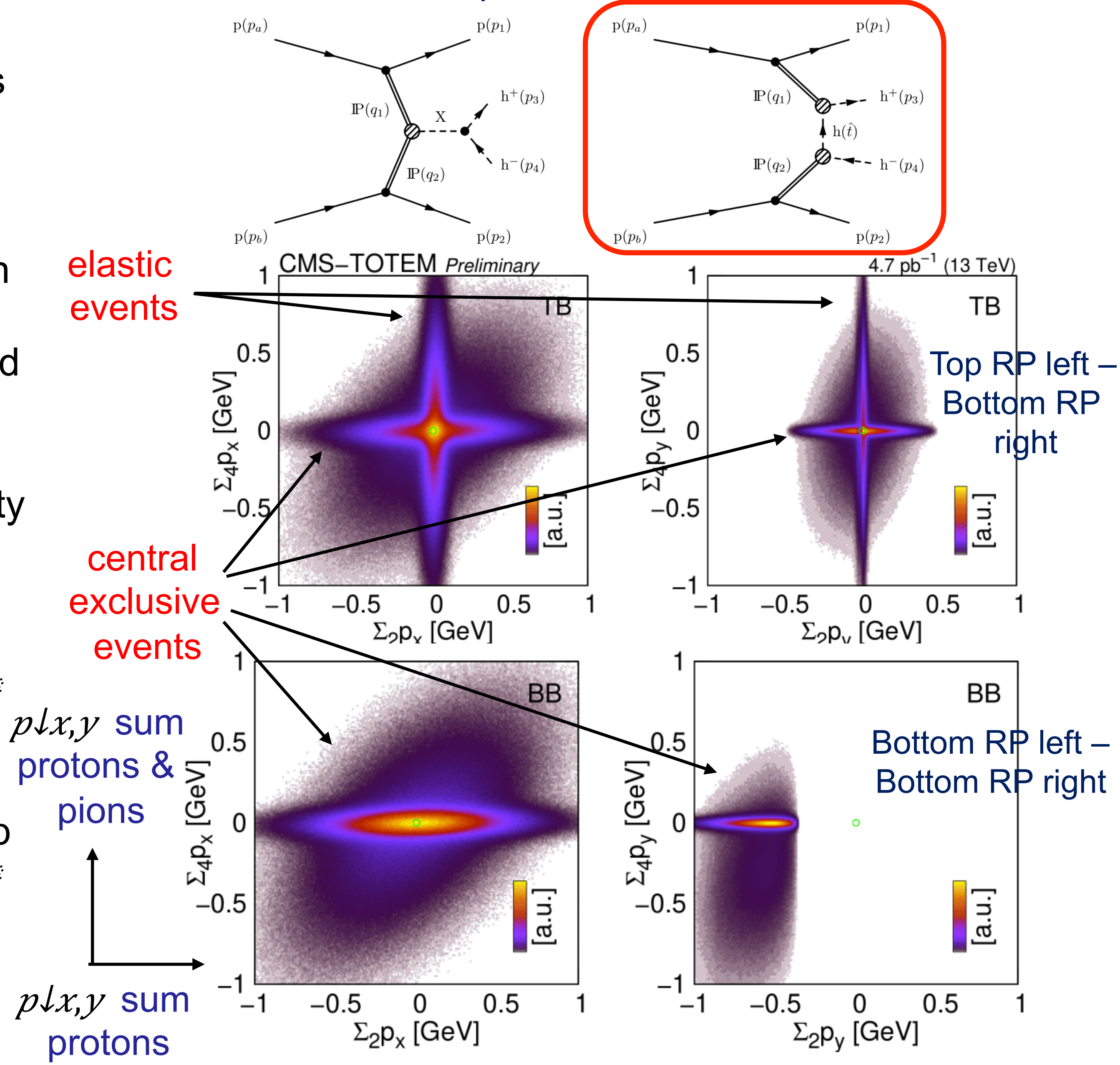
CMS-PAS-SMP-21-004

15

Central exclusive ππ

CMS PAS SMP-21-004, TOTEM NOTE 2023-001, https://cds.cern.ch/record/2867988

- Detailed study of "Pomeron" interactions using a very large sample (~ 80 M) non-resonant central exclusive $\pi^+\pi^-$ with protons measured in TOTEM RPs & charged pions in CMS tracker
- L1 trigger: double arm TOTEM RP, HLT: activity in CMS pixel detector
- Require diproton and dipion p_x & p_y to match ($\sum^4 p_x \approx 0$ & $\sum^4 p_y \approx 0$)
- Largest background: elastic + inelastic pileup ($\sum^2 p_x \approx 0$ & $\sum^2 p_y \approx 0$)

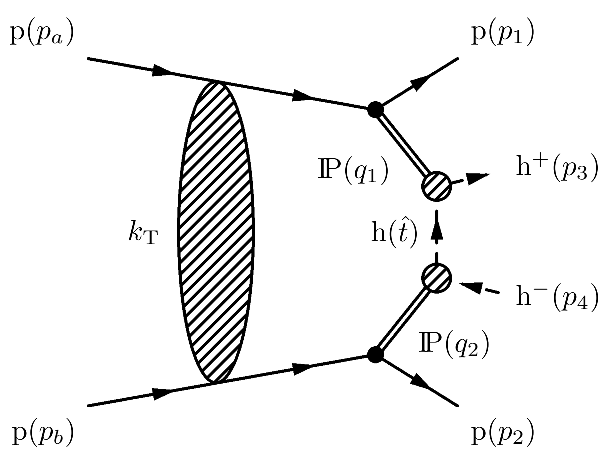


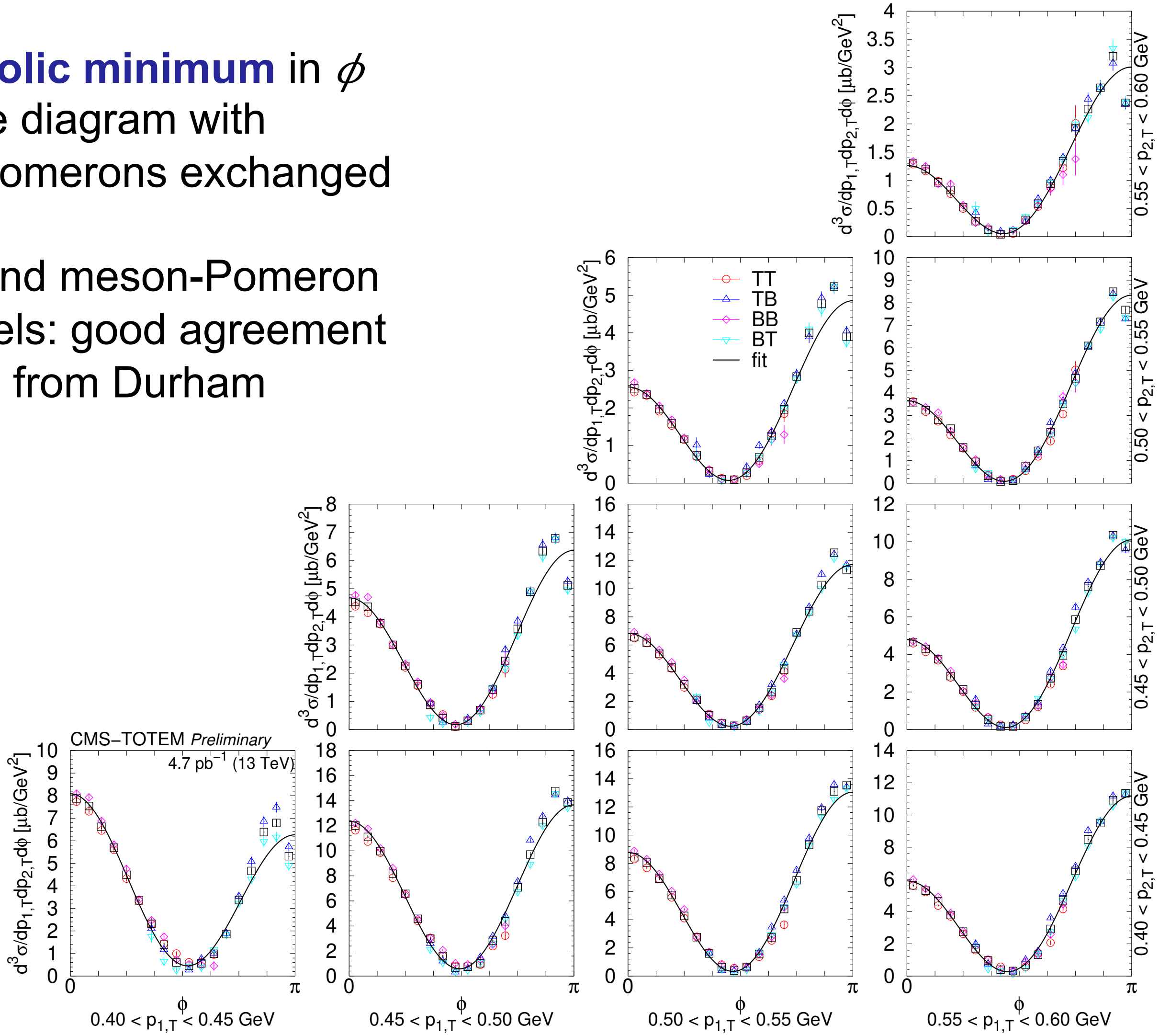
Central exclusive ππ

CMS PAS SMP-21-004, TOTEM NOTE 2023-001, *https://cds.cern.ch/record/2867988*

- Variables: $m_{\pi+\pi-}$, proton p_T's and ϕ (2-proton azimuthal angle difference)
- Focusing on non-resonant region: $0.35 < m_{\pi+\pi-} < 0.65$ GeV
- First observation of **parabolic minimum** in ϕ (due to interference of tree diagram with diagrams with additional pomerons exchanged btwn protons)
- Study nucleon-Pomeron and meson-Pomeron couplings in different models: good agreement with DIME ("soft model 1") from Durham

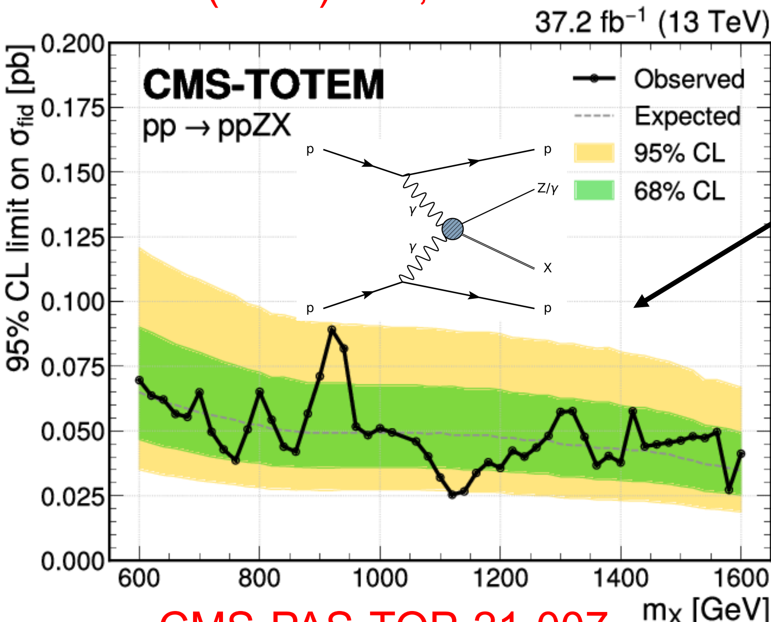
$$\frac{d^3\sigma}{\mathrm{d}p_{1,\mathrm{T}}\mathrm{d}p_{2,\mathrm{T}}\mathrm{d}\phi} = [A(R - \cos\phi)]^2 + c^2,$$





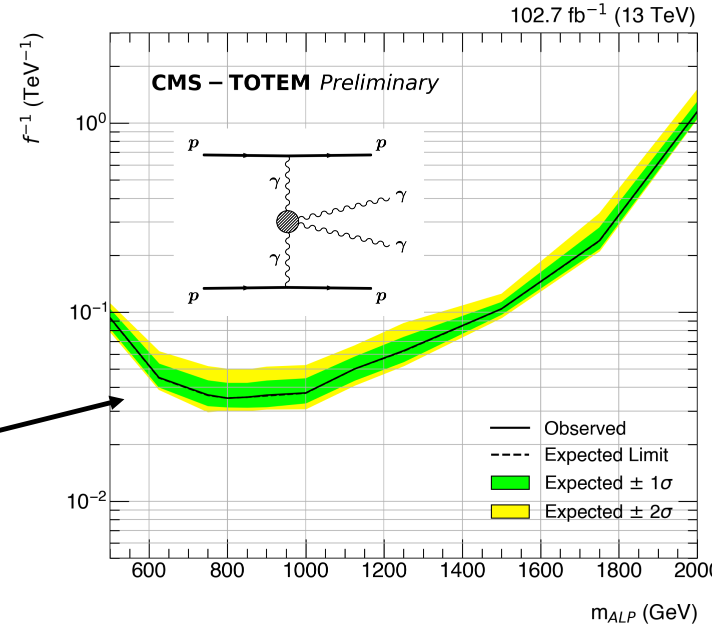
PPS results

EPJC 83 (2023) 827; arXiv:2303.04596



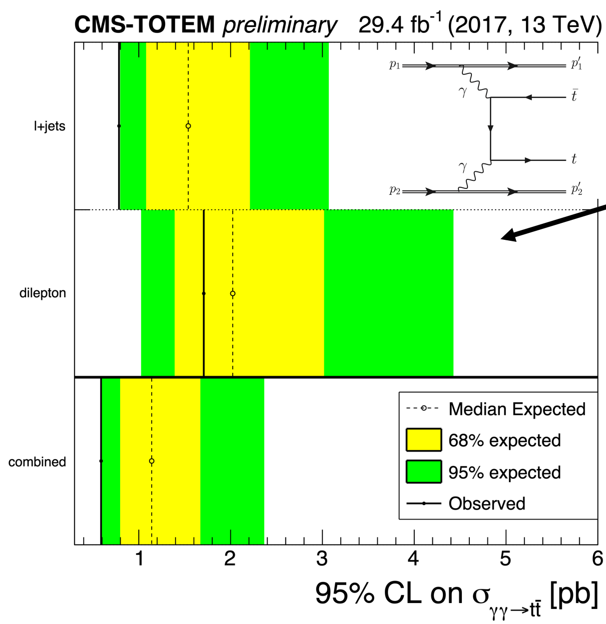
Search for Z/γ + X with PPS

CMS-PAS-EXO-21-017



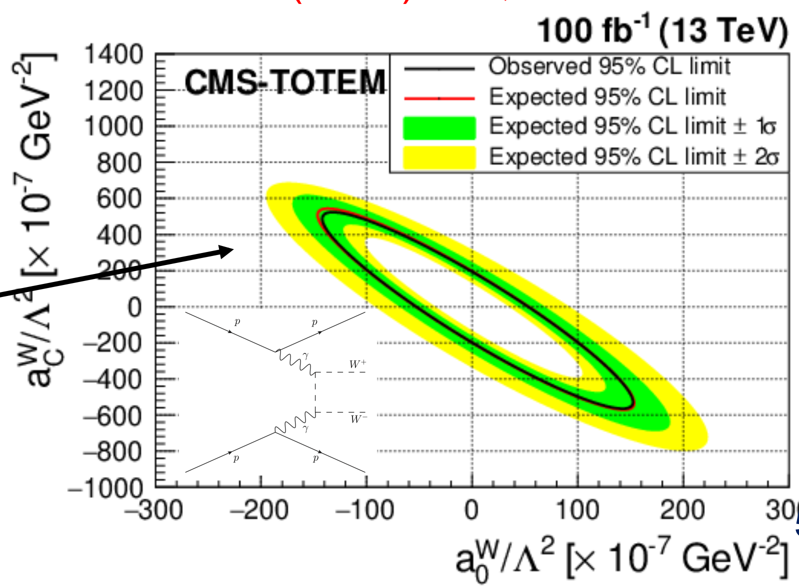
Search for exclusive $\gamma\gamma$ production with PPS

CMS-PAS-TOP-21-007



Search for exclusive $t\bar{t}$ production with PPS

JHEP 07 (2023) 229; arXiv:2211.16320



Search for exclusive WW & ZZ production with PPS

5

- Run 3 well underway, reaching parity with Run 2 integrated luminosity next year
- Run 1+2 precision results are challenging α_s from lattice QCD and improving m_t and m_H
- Many on-going searches and interesting results also from heavy ions, TOTEM and PPS