Summer conference summary

- LHCP http://lhcp2019.buap.mx/
- EPS http://eps-hep2019.eu/
- Lepton-photon http://leptonphoton2019.ca/

- ICNFP https://indico.cern.ch/event/754973/overview

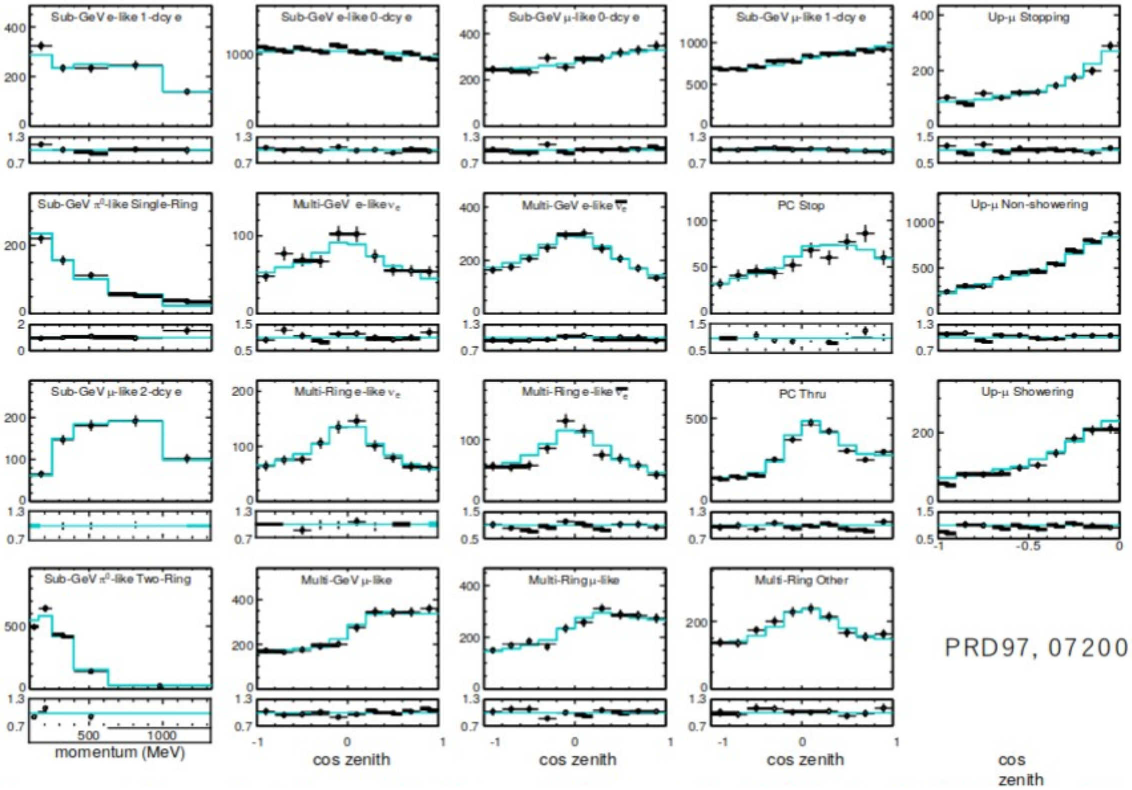
Topics

- Neutrino properties
- Flavour physics and low-energy pobes
- New particle searches
- Electroweak symmetry breaking
  - Higgs physics
  - Electroweak precision observables
  - Vector boson scattering

Neutrino properties

Atmospheric neutrinos from Super-Kamiokande

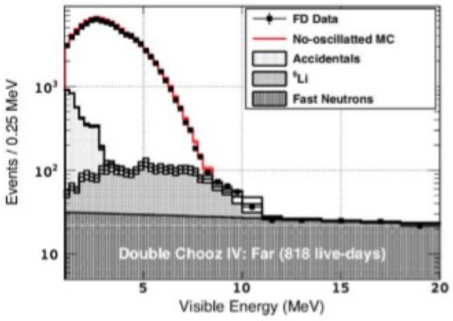
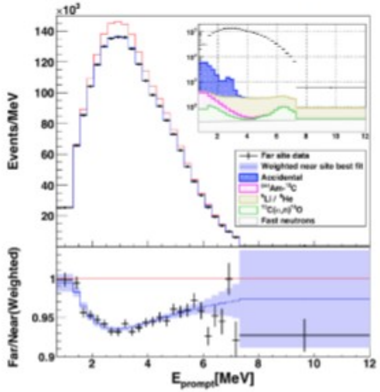
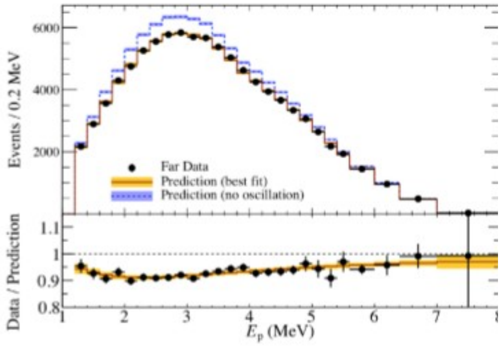
High precision and high statistics



PRD97, 072001 (2018)

Excellent agreement between data and simulation in 19 event categories….
Simultaneous analysis of Δm_{23}, $\sin^2\theta_{13}$, $\sin^2\theta_{23}$, δ_{CP}, including T2K and reactor data

Reactor neutrinos : θ_{13}

Double Chooz	Daya Bay	RENO
		

$\sin^2(2\theta_{13})$

Double Chooz	Daya Bay	RENO
0.105 ± 0.014	0.0856 ± 0.0029 (best precision)	0.0896 ± 0.0068

Mass splitting

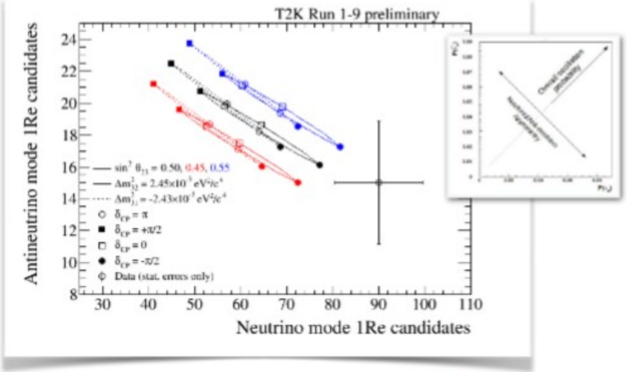
Double Chooz	Daya Bay	RENO
N/A (external constraint)	$\Delta m^2_{32} = (2.471^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV}^2$ (NO) $-(2.575^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV}^2$ (IO)	$\lvert\Delta m^2_{ee}\rvert = (2.68 \pm 0.14) \times 10^{-3}\ \mathrm{eV}^2$

arxiv: 1901.09445 (unpublished) — Phys.Rev.Lett. **121** (2018) 241805 — Phys.Rev.Lett. **121** (2018) 201801

“Normal” hierarchy strongly favoured : 90-95%CL, depending on analysis

Neutrinos beams : T2K

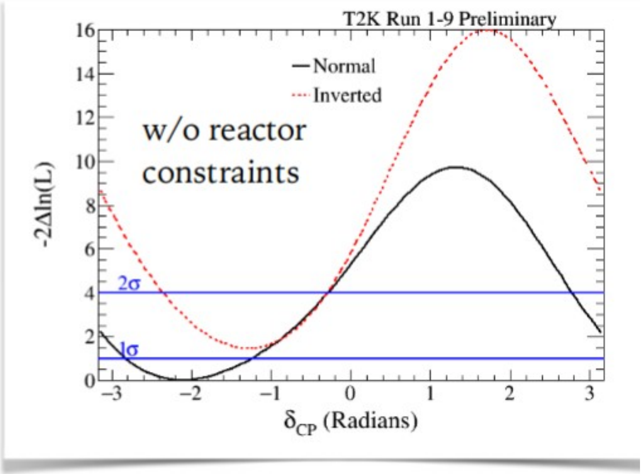
δ_{CP} MEASUREMENT

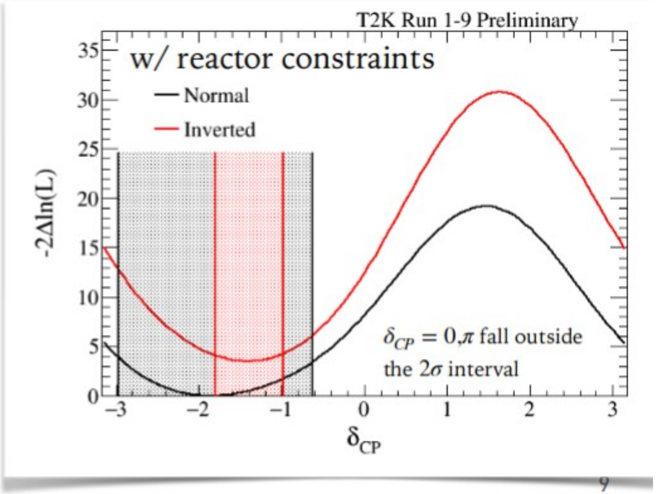


T2K data prefer values of $\delta_{CP} \sim -\frac{\pi}{2}$: mostly driven by the large number of events observed in the e-like sample in neutrino mode.

CP conservation ($\delta_{CP} = 0, \pi$) disfavoured at 2σ for both mass hierarchies.

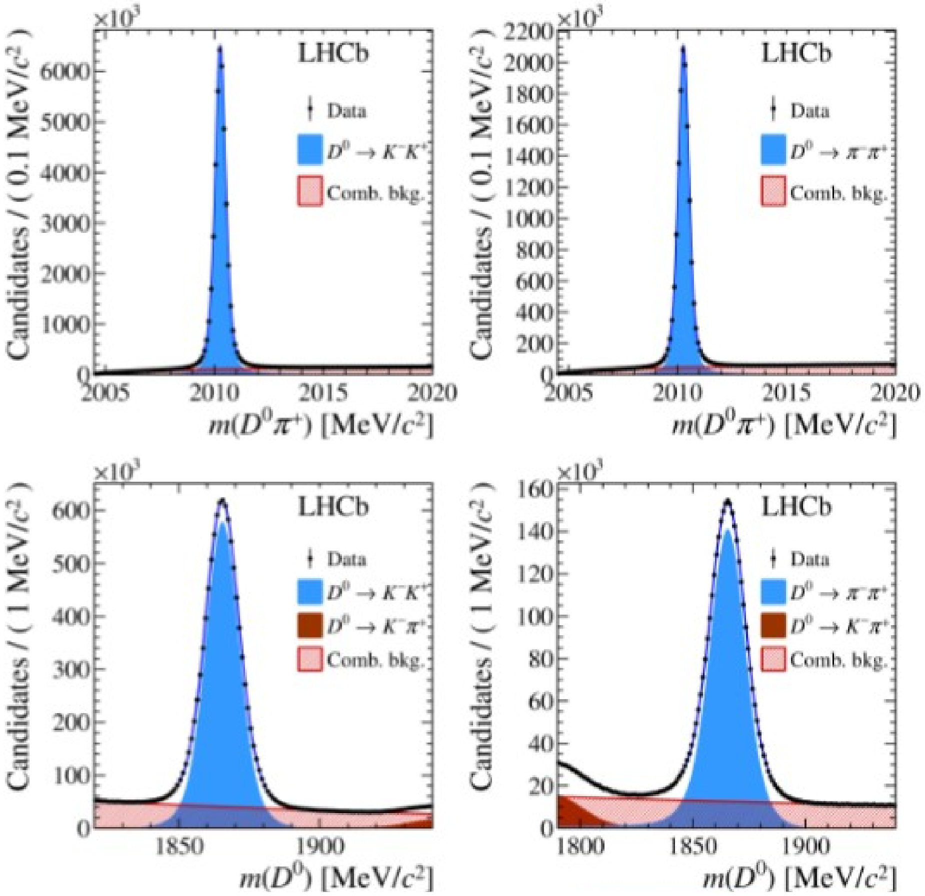
C.L.	Normal hierarchy	Inverted hierarchy
68%	[-2.51, -1.26]	-
90%	[-2.80, -0.84]	-
2σ	[-2.97, -0.63]	[-1.78, -0.98]





Flavour physics

Direct CP violation in Charm meson decays!



$$A_{raw} = A_{CP} + A_D + A_P$$

$$\Downarrow$$

$$\frac{N(D^0 \to h^+h^-) - N(\overline{D^0} \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\overline{D^0} \to h^+h^-)}$$

Asymmetry of our interest

Detection asymmetry from π (prompt) or μ (semileptonic)

Production asymmetry of D^* (prompt) or B (semileptonic)

To eliminate A_D and A_P:

$$\Delta A_{CP} = A_{K^+K^-} - A_{\pi^+\pi^-} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

Phys. Rev. Lett. **122**, 211803

- From Run II:

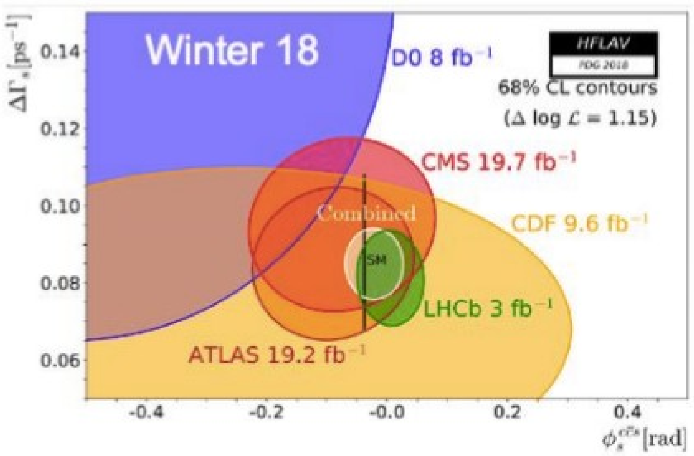
$$\Delta A_{CP}^{\pi-tag} = (-18.2 \pm 3.2 \pm 0.9) \times 10^{-4},$$
$$\Delta A_{CP}^{\mu-tag} = (-9 \pm 8 \pm 5) \times 10^{-4}$$

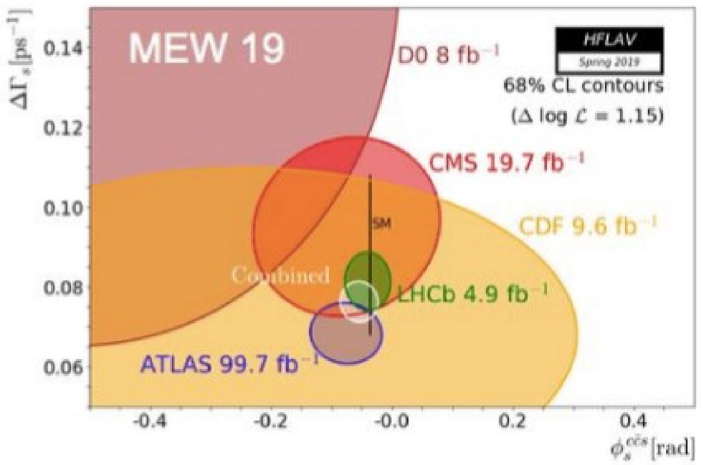
- Combine with LHCb Run I data:

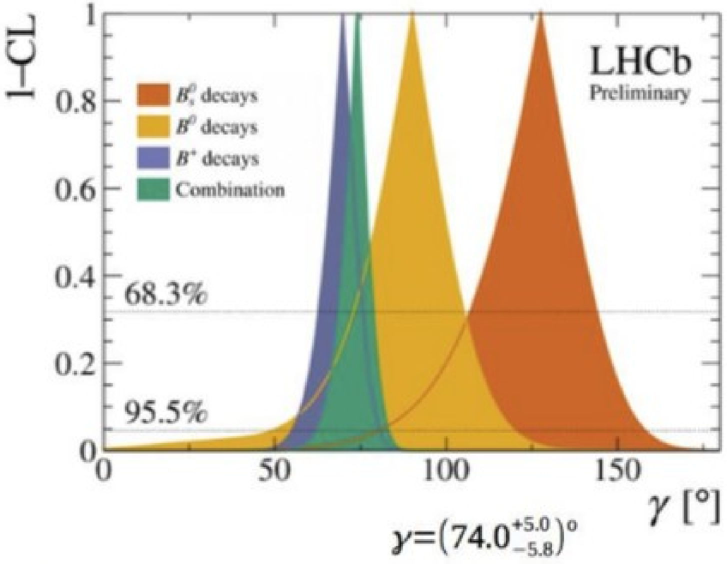
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

Observation of CP violation with 5.3σ significance!

B physics







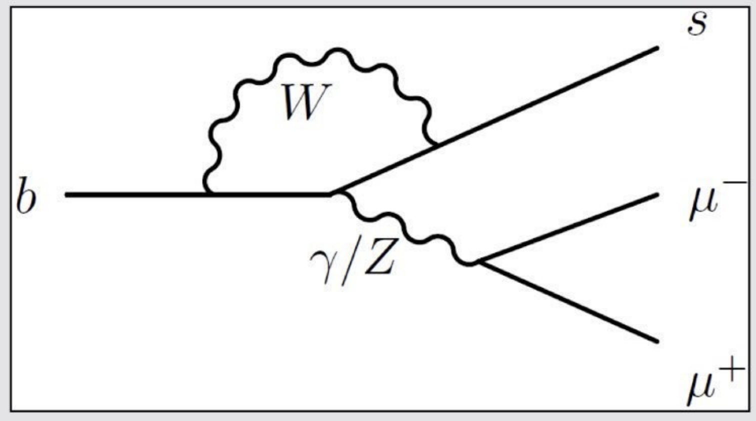
Impressive improvements in B_s mixing parameters in LHCb

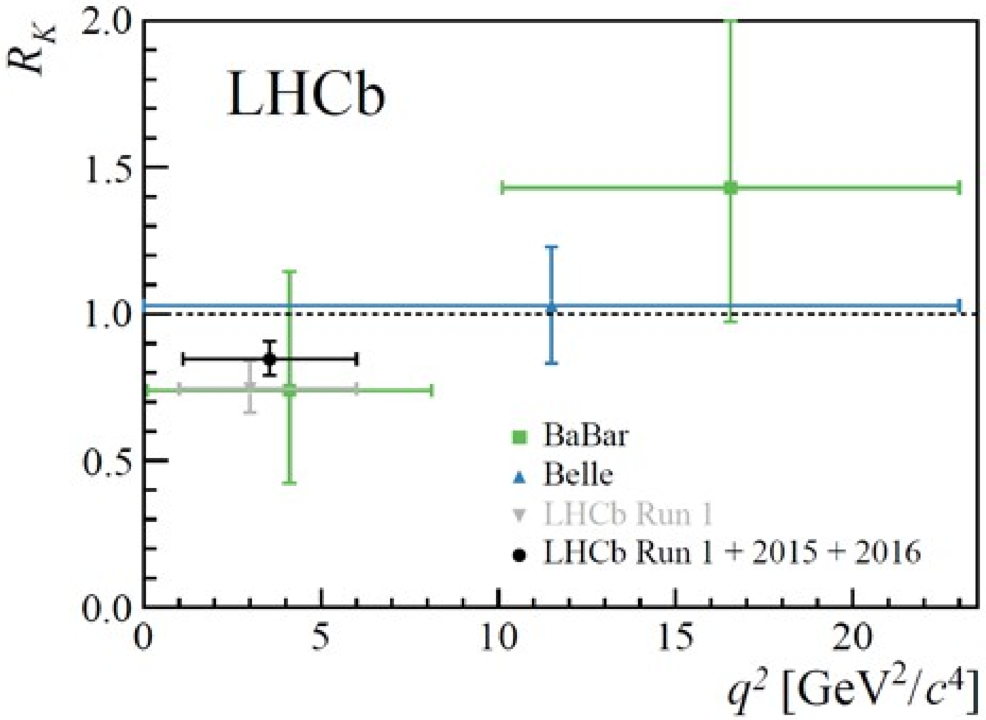
CKM angle γ : tensions (~2 std.dev.)

- between measurement results (B^0_S, B^+)
- between experimental world average and "prediction" from triangle unitarity

B physics

R_K = BR(B+ → $K^+\mu\mu$) / BR(B+ → K+ee)

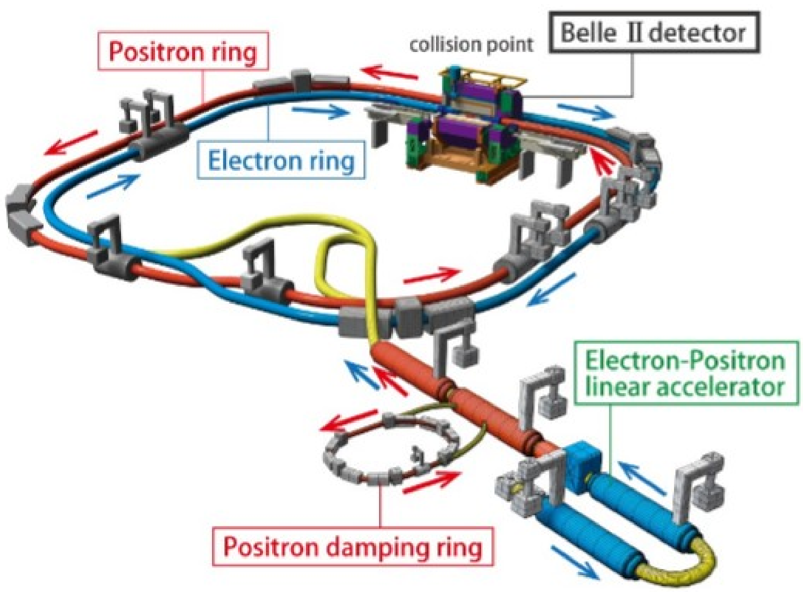


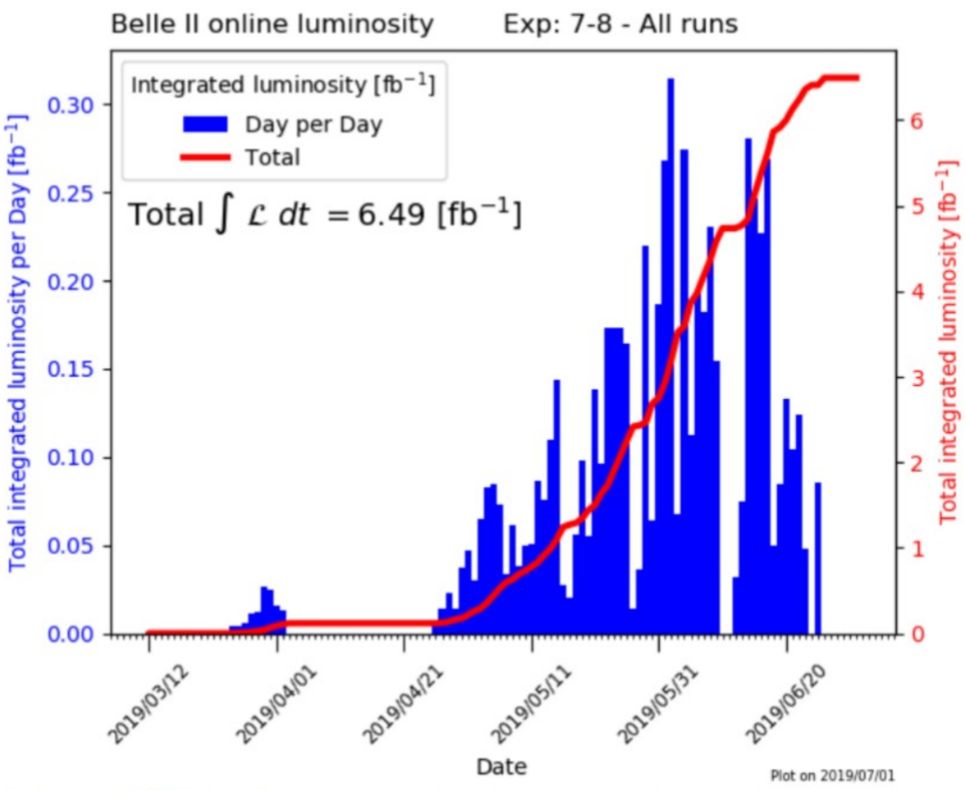


$$R_K = 0.846\ ^{+0.060}_{-0.054}\ ^{+0.016}_{-0.014}$$

→ Belle 2

Upgrade to achieve 40x peak $\mathcal{L}$ under 20x bkgd



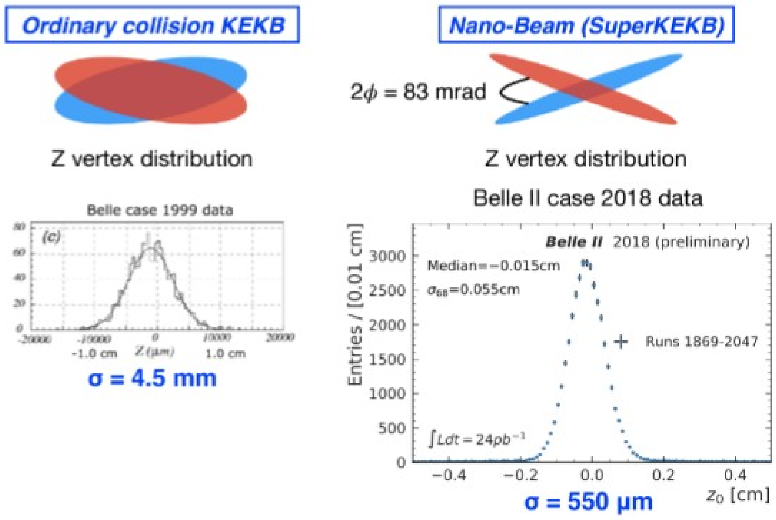


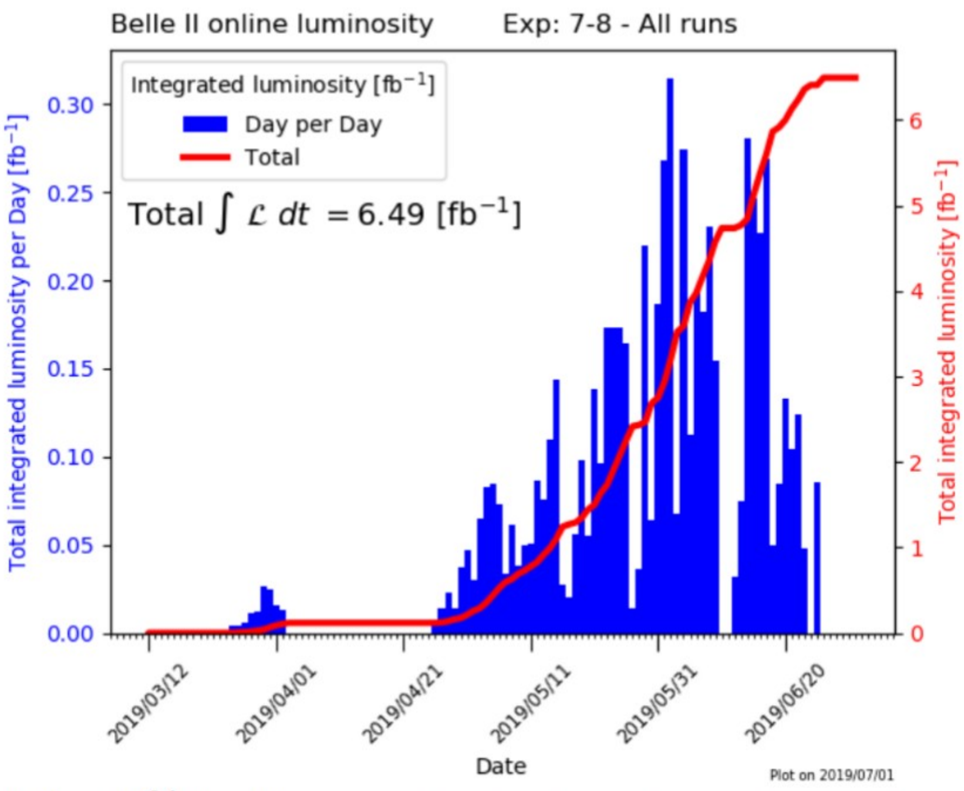
→ Belle 2

$$\mathcal{L} = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_{\mathcal{L}}}{R_{\xi_y}}\right)$$

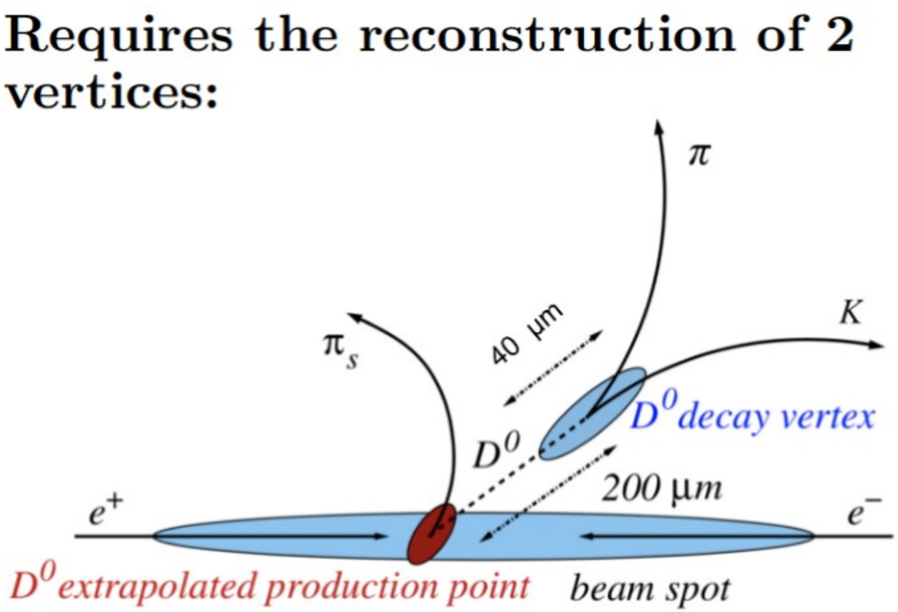
Doubling the beam currents.

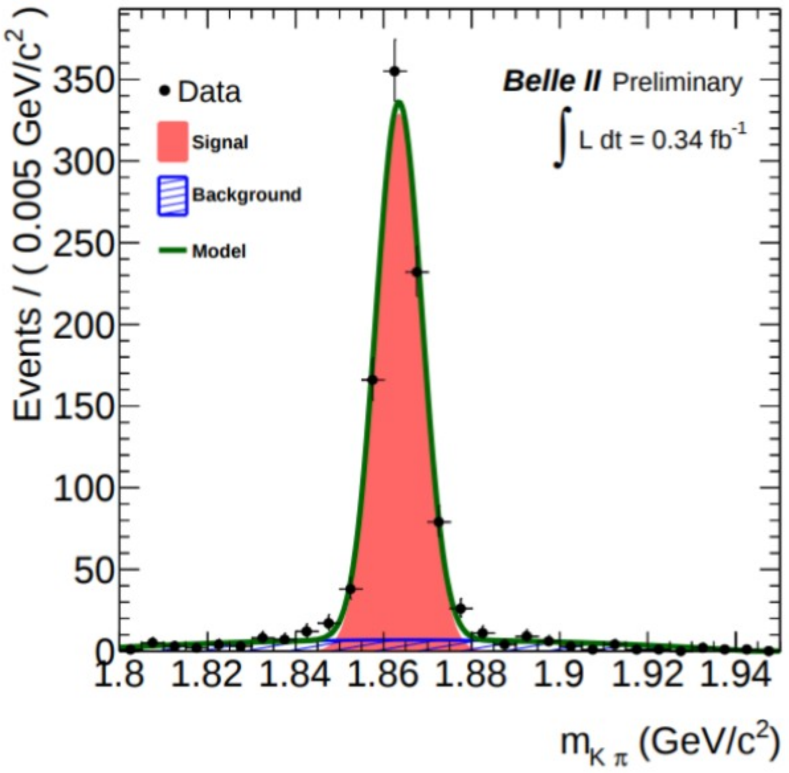
Reduction in the beam size by 1/20 at the IP.





→ Belle 2 “physics commissioning” : D^0 lifetime in D* decays

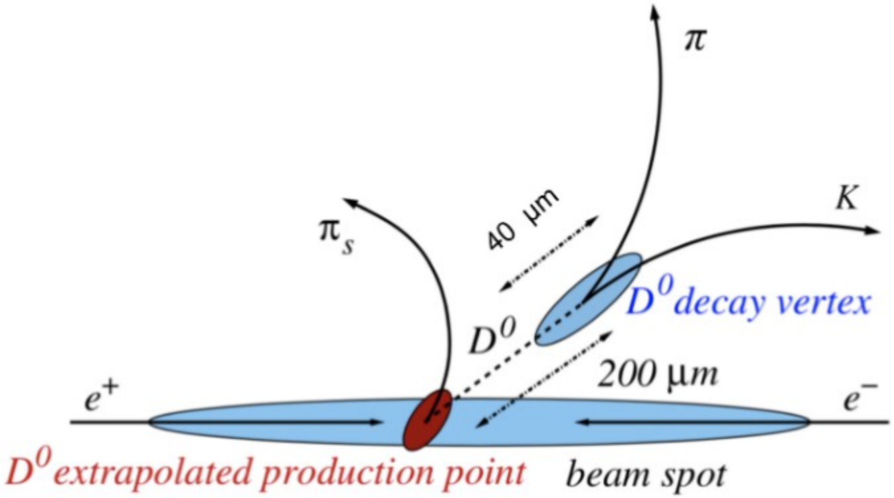


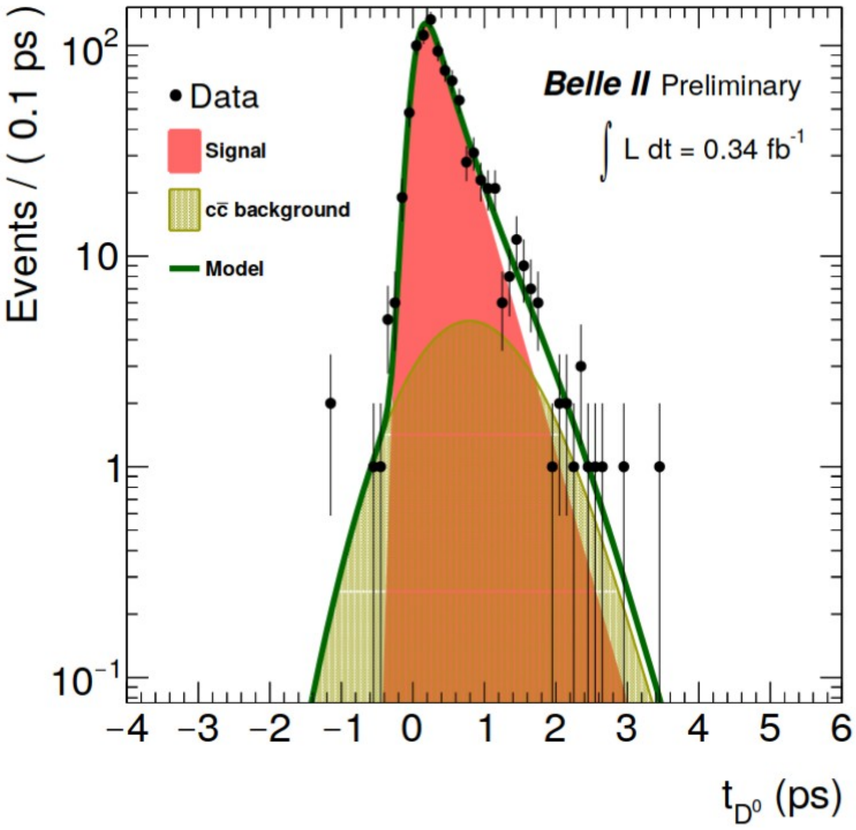


→ Belle 2 “physics commissioning” : D^0 lifetime in D* decays

$$\tau_{D^0} = (380 \pm 40)\ \text{fs}$$

Requires the reconstruction of 2 vertices:





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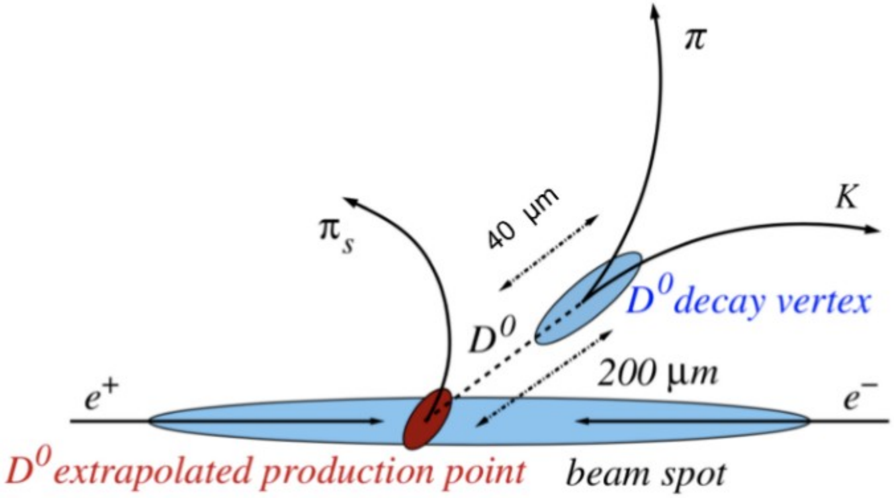
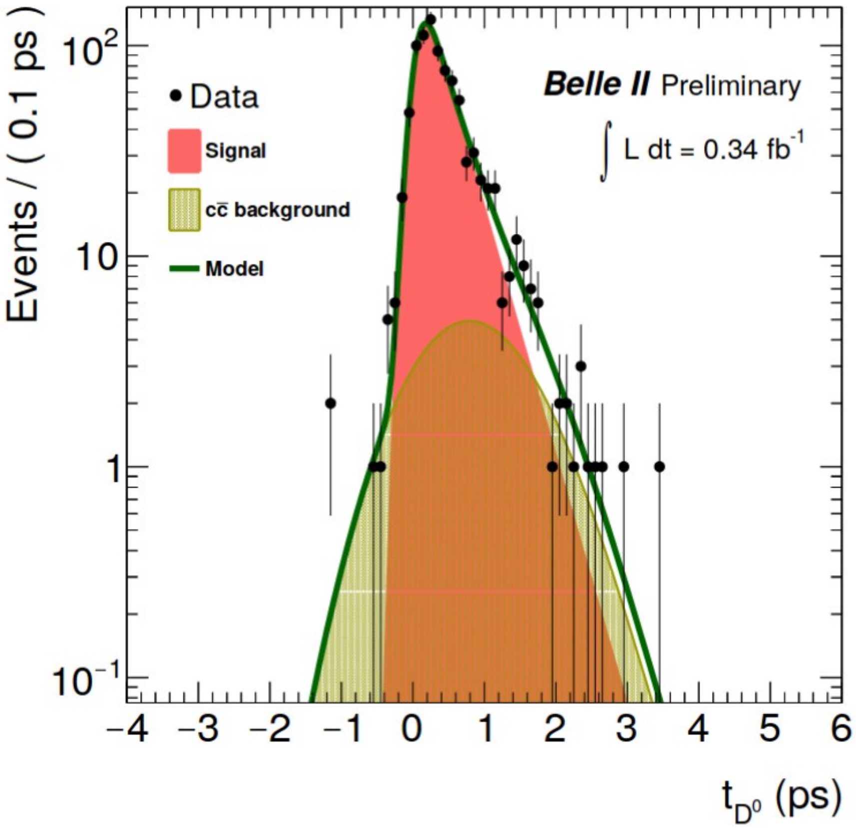




0.5 fb^{-1} (now)

→ ~5 ab^{-1} (~2022/3)

→ 50 ab^{-1} (2027)

New particle searches
(LHC, Dark matter experiments)

Limit, limits, limits

Extra dimensions

W’, Z’

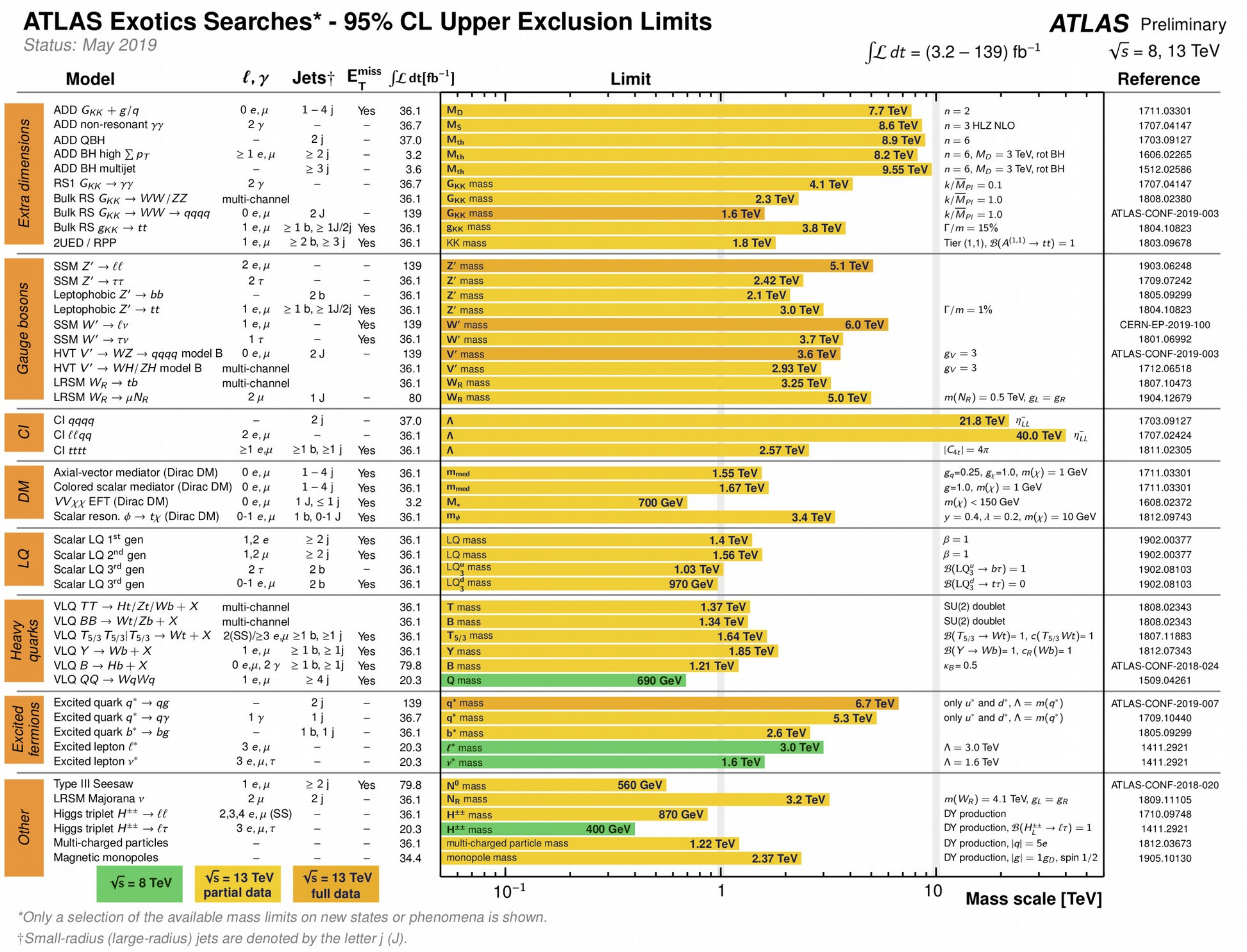
Contact int.

Dark matter

Leptoquarks

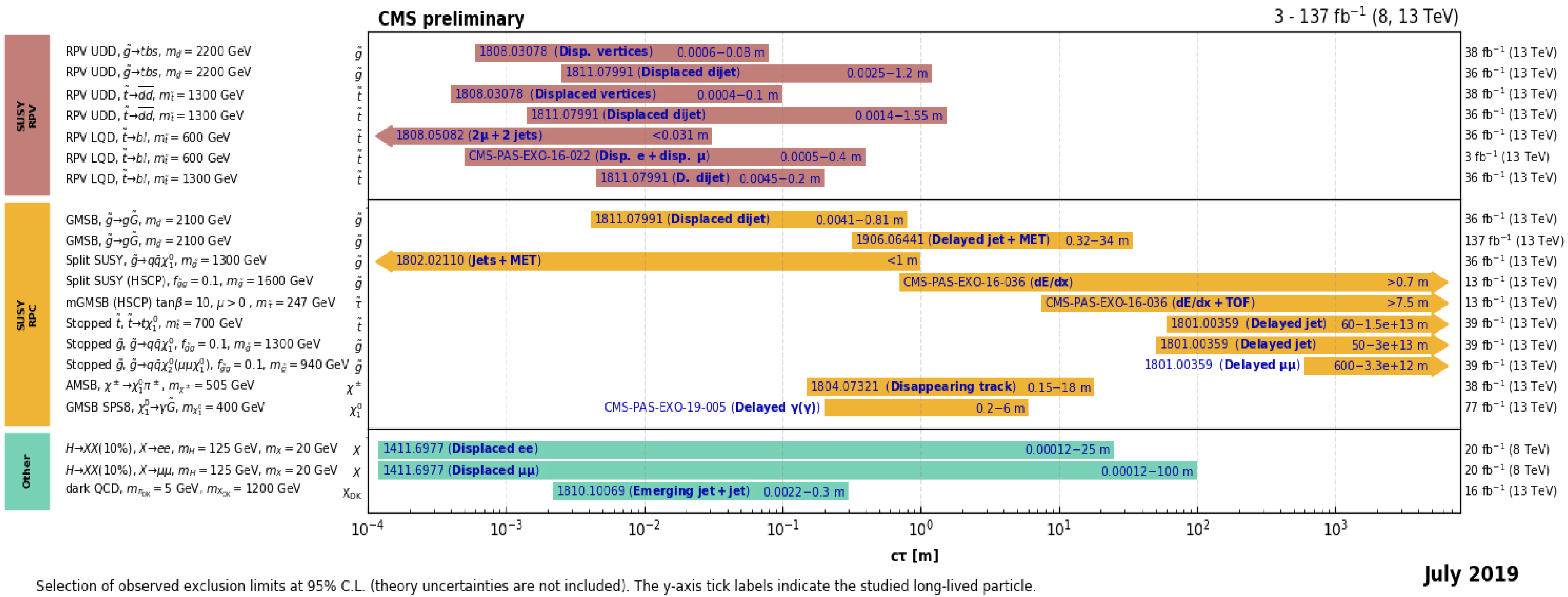
Heavy quarks

Excited fermions



Limit, limits, limits

Overview of CMS long-lived particle searches

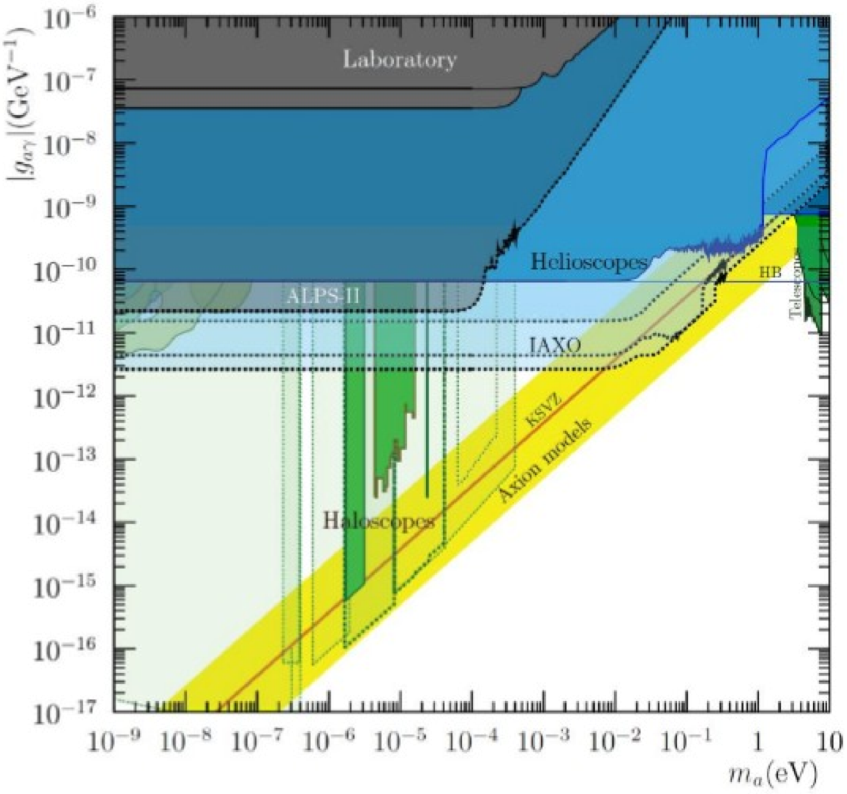


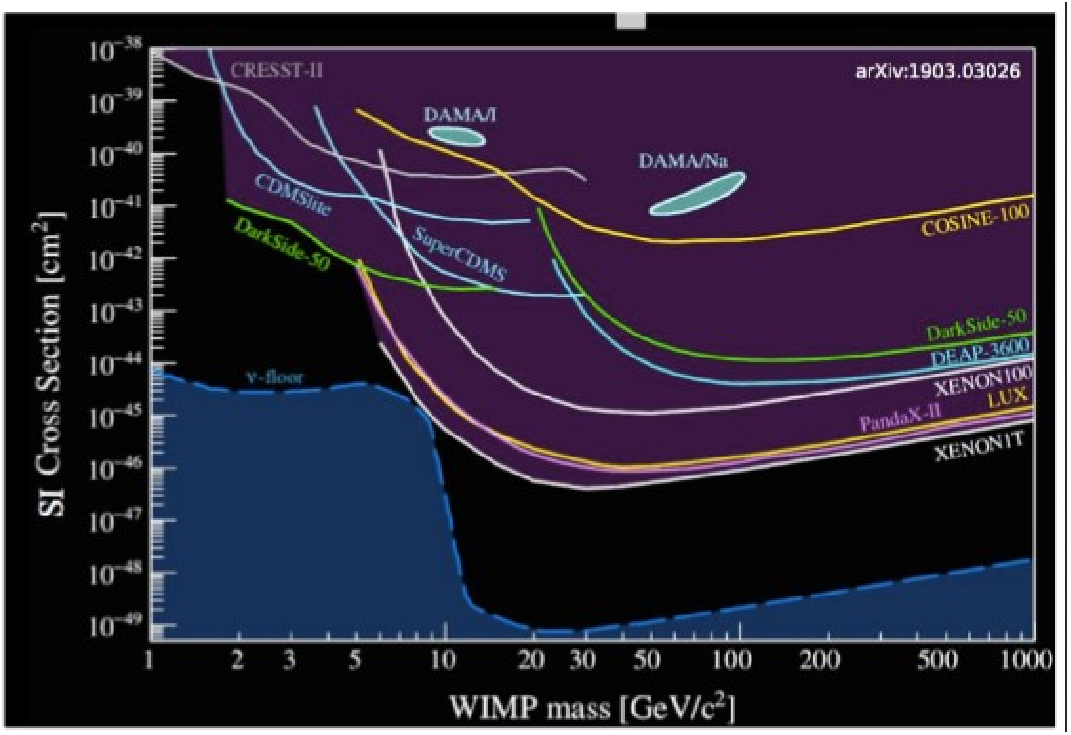
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Generally require inventive reconstruction / analysis algorithms, or good control of E_T^{miss}

Dark matter (more limits)

- Axions (~eV and lighter), WIMPs (GeV – TeV)

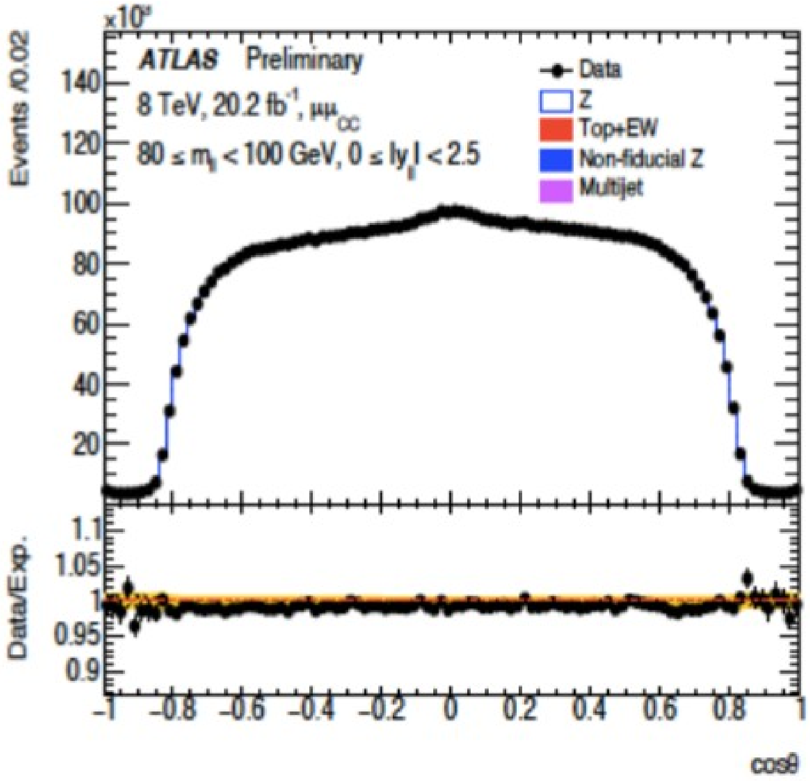




(in Xenon, the recoil energy spectrum of a WIMP with mass 6 GeV and SI cross section 5×10^{-45} cm^2 matches that of ^{8}B Solar neutrinos)

Electroweak symmetry breaking (LHC)

Precision electroweak observables – $\sin^2\theta_{eff}$



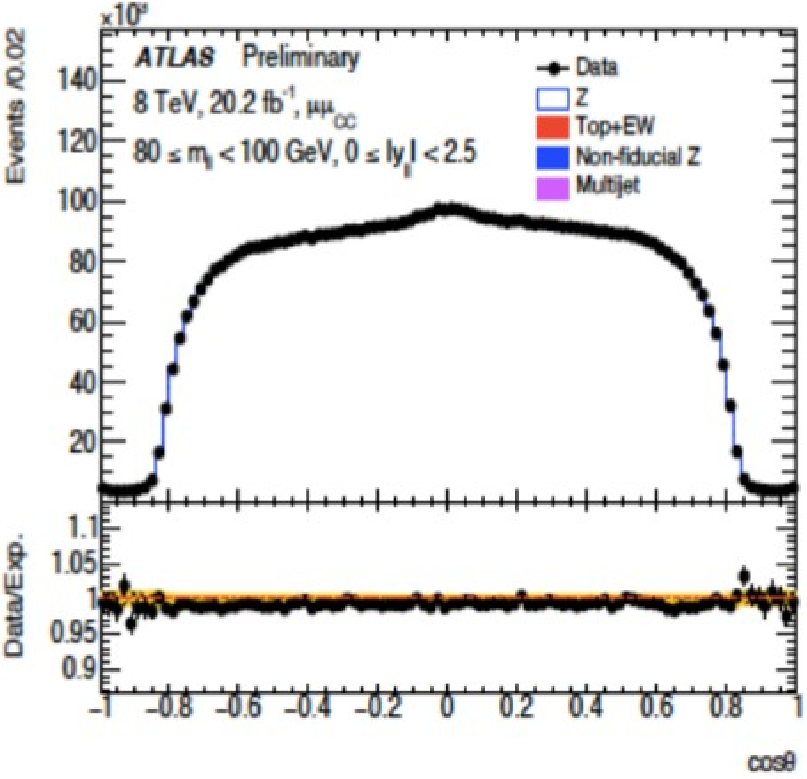
From forward/backward asymmetry
In Z → ee, μμ decays

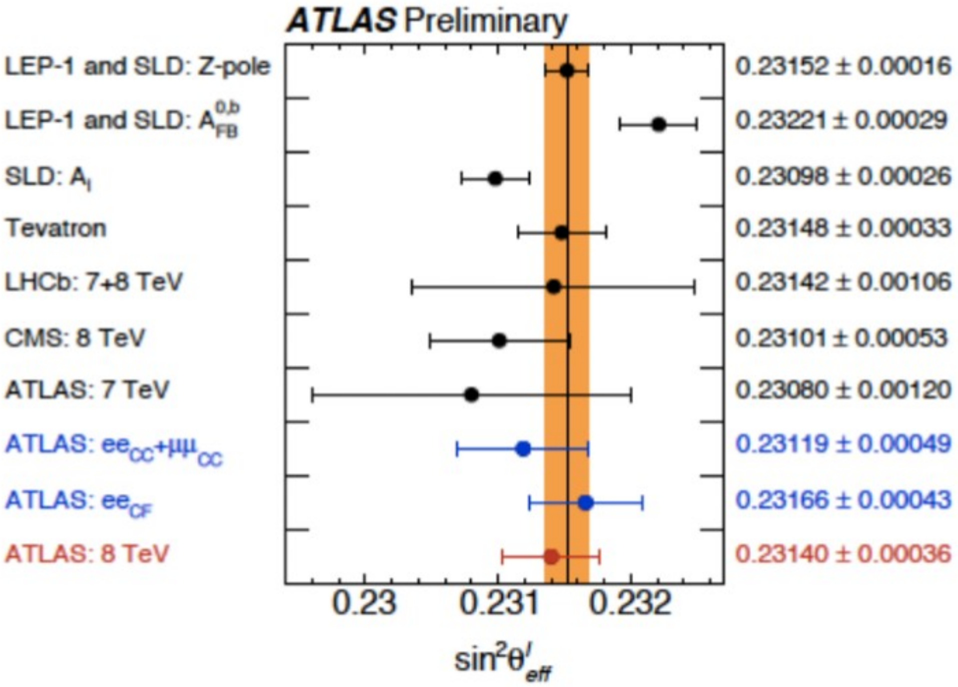
Issues :

direction of initial quark/antiquark?
→ PDFs

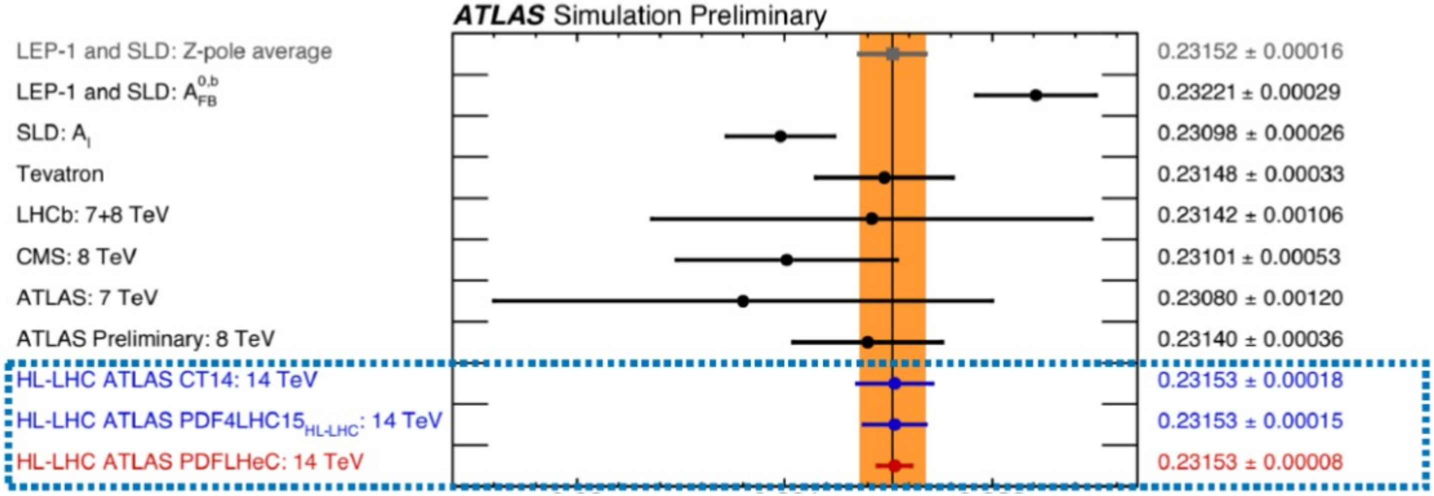
theoretical framework. The LEP paradigm (factorized corrections, form factors Δρ, Δκ…)
→ work only on the Z pole; pp experiments "integrate" over a large mass window
→ full NNLO corrections needed; only NLO available off-peak this far.

Precision electroweak observables – $\sin^2\theta_{eff}$



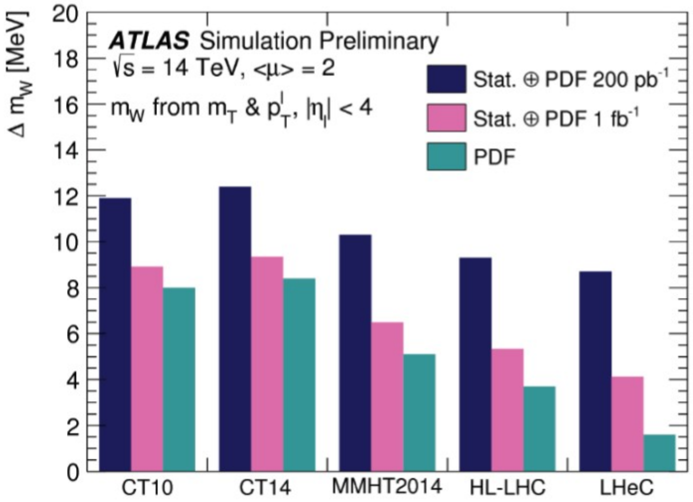


Precision electroweak observables – prospects for $\sin^2\theta_{eff}$, m_W

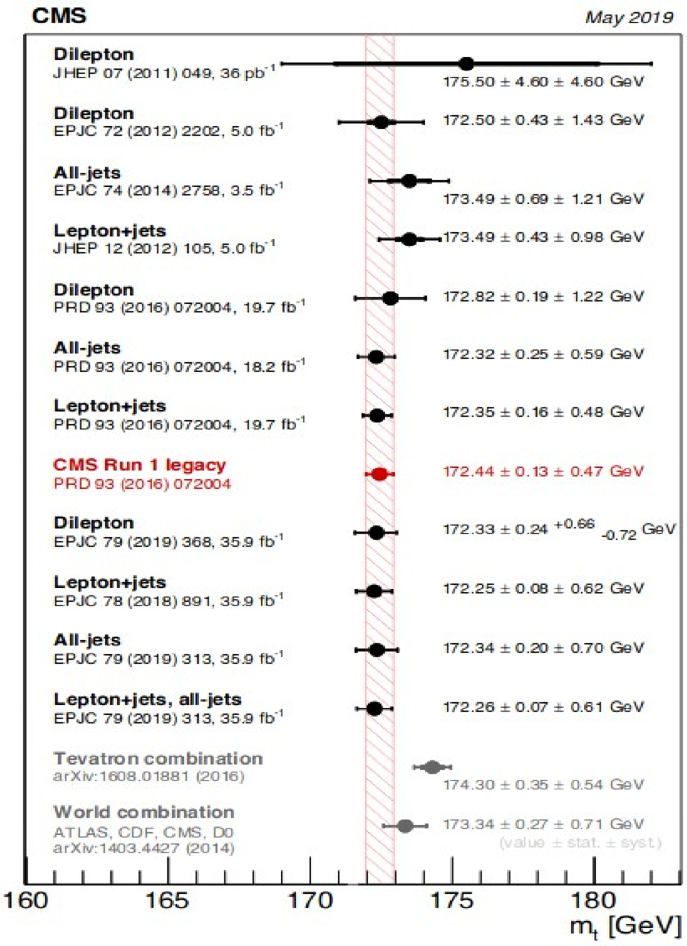


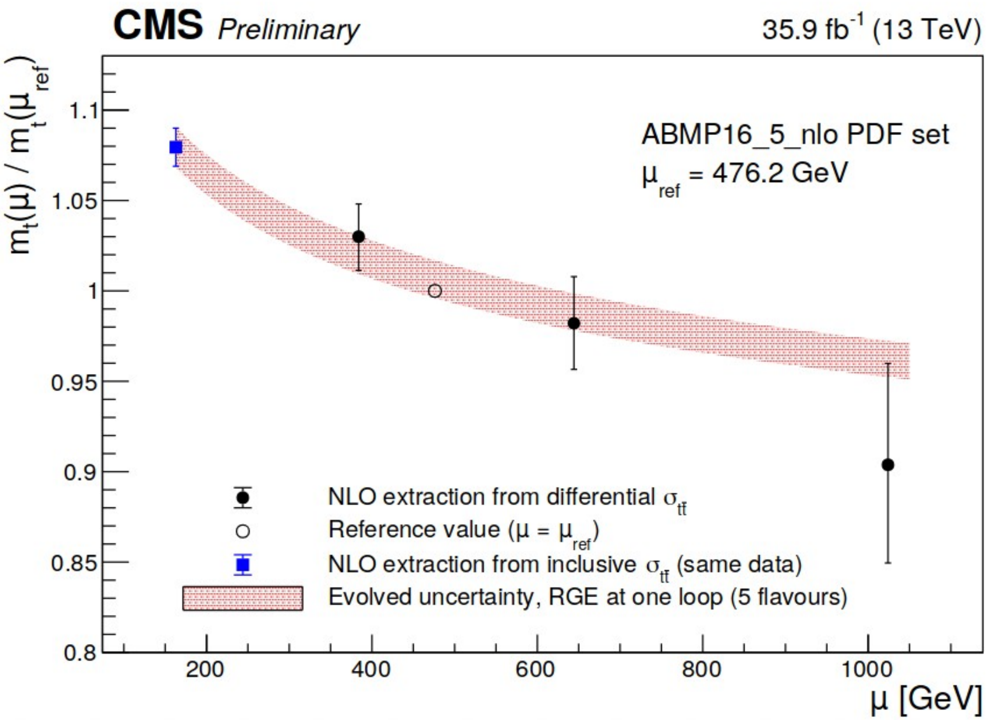
These two very strongly PDF-dominated measurements will greatly benefit from improved constraints on the proton structure.

New DIS data in particular could "remove" this source of uncertainty almost completely.

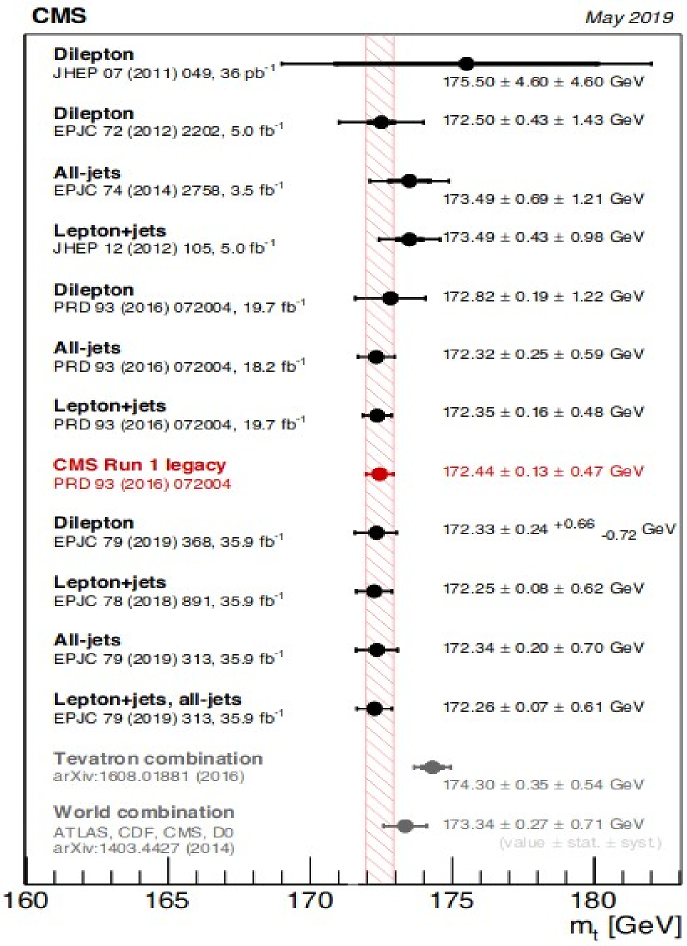


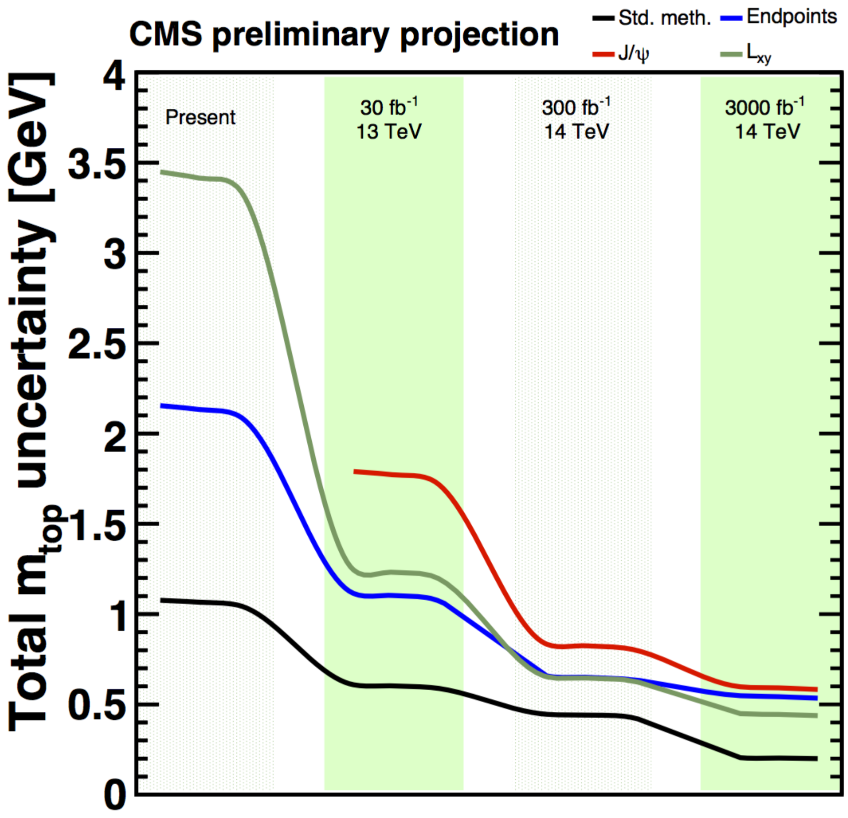
Top quark mass



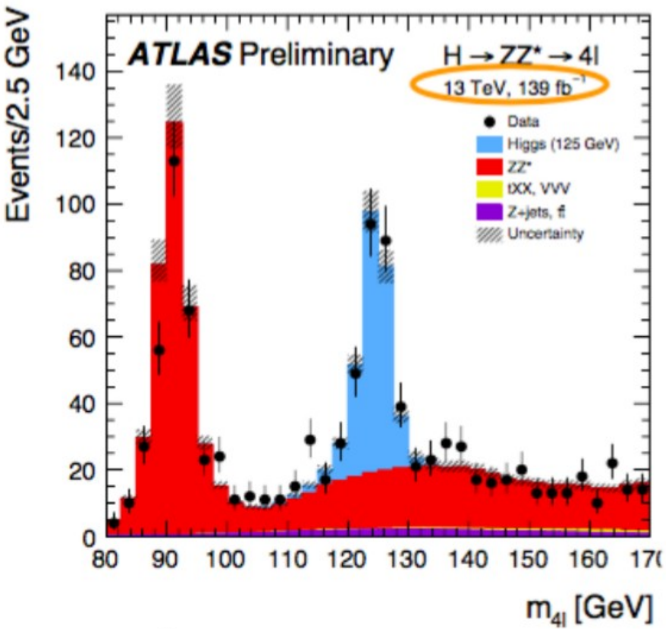


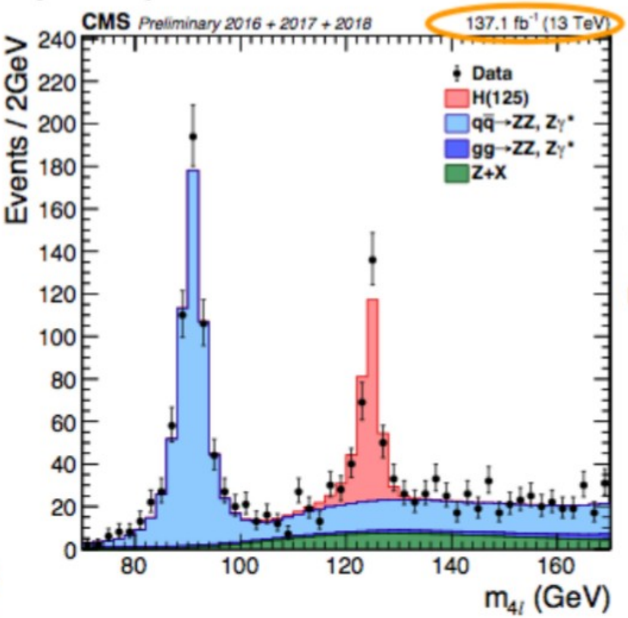
Top quark mass

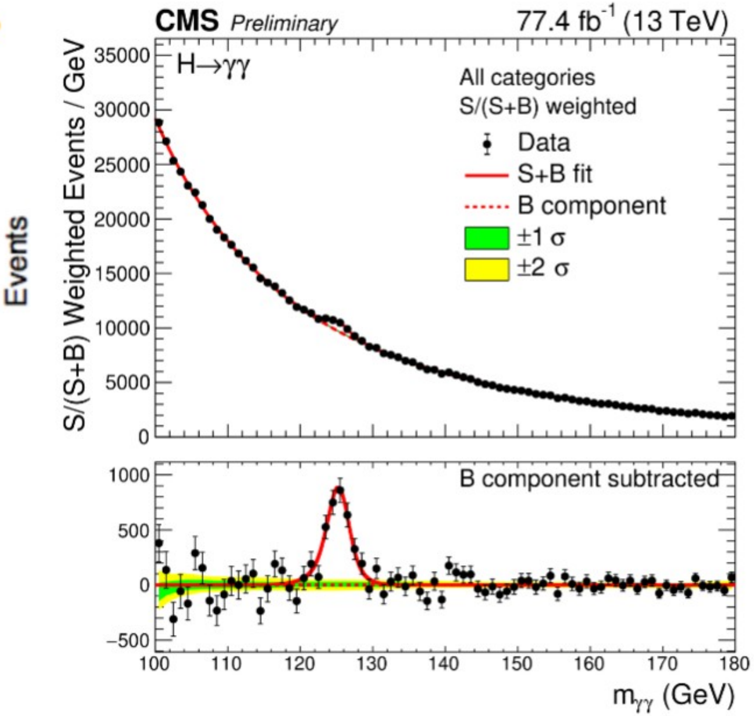




Higgs boson properties : m_H



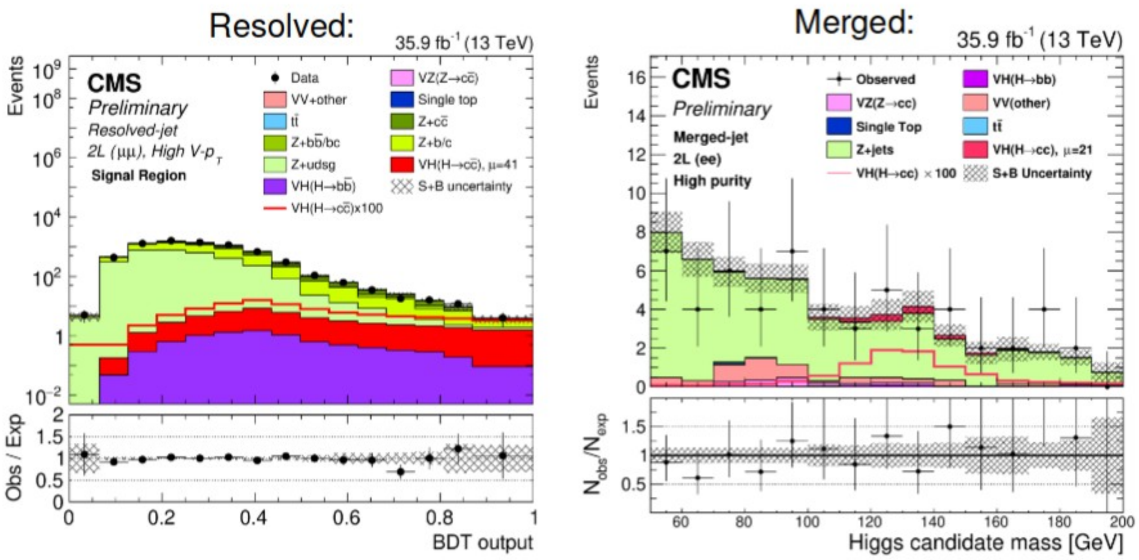




Mass known to <0.2% today; will reach <0.1% with the complete Run2 dataset

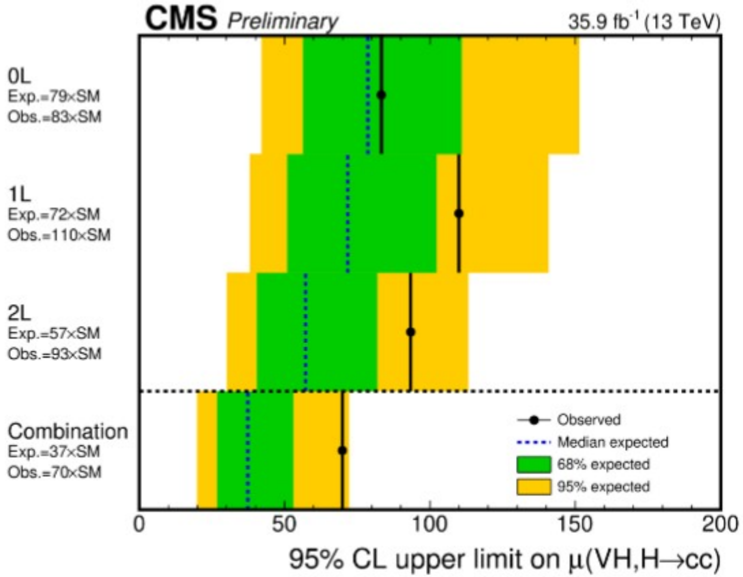
Higgs boson properties : H → cc

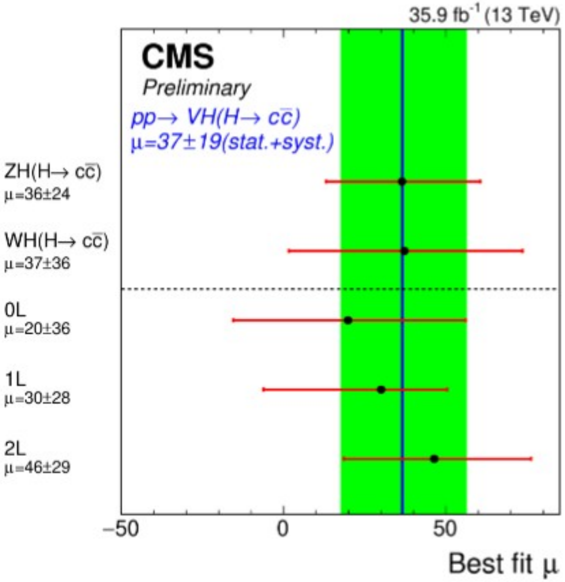
- Charm tagging based on deep neural networks (DNN)
  - calibration with various control data sets
- Signal extraction by simultaneous fit to signal and control regions
  - analysis variables
    - BDT discriminant (resolved)
    - Higgs candidate mass (merged)
- Validated by measuring $VZ(\rightarrow c\bar{c})$ process



- For the overall result, combine resolved ($p_T^V < 300\ GeV$) and merged ($p_T^V > 300\ GeV$)

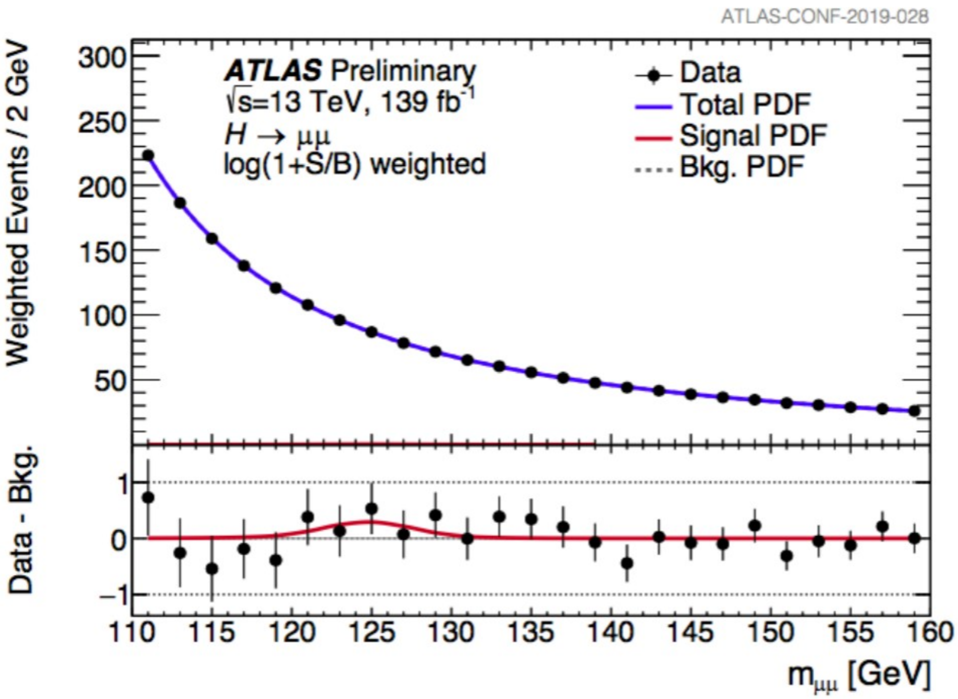
Higgs boson properties : H → cc





- ➔ Combined upper limit relative to SM expectation: $\mu < 70\ obs.\ (37\ exp.)$ at 95% CL
- ➔ Most sensitive direct measurement to date
- A long way ahead to achieve SM sensitivity. Next step: full Run 2 analysis

Higgs boson properties : H → μμ



σ(obs) / σ(SM) = 0.5 ± 0.7
< 1.7 at 95% CL

Sensitivity: 0.8σ, for 1.5σ expected

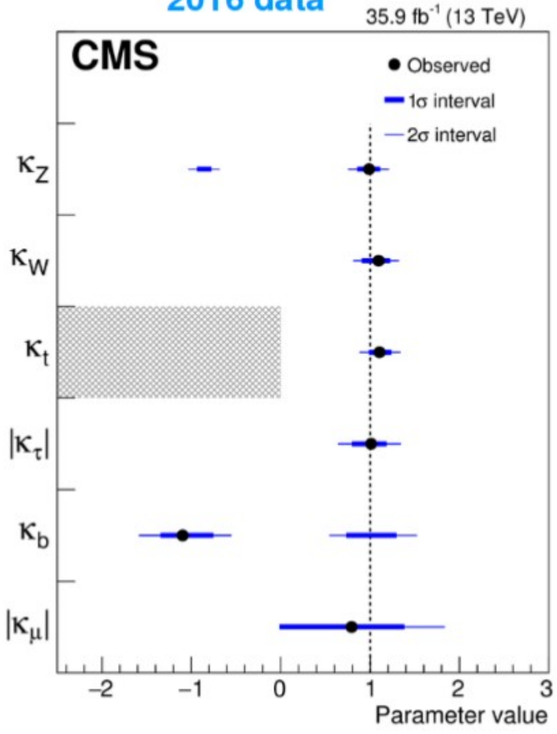
Very reminiscent of the H → γγ search, with less sensitivity, better theory (for background), and better control of reconstruction resolution (using Z → μμ). Still mostly a search; combined LHC results after Run3 should be conclusive.

Higgs boson properties

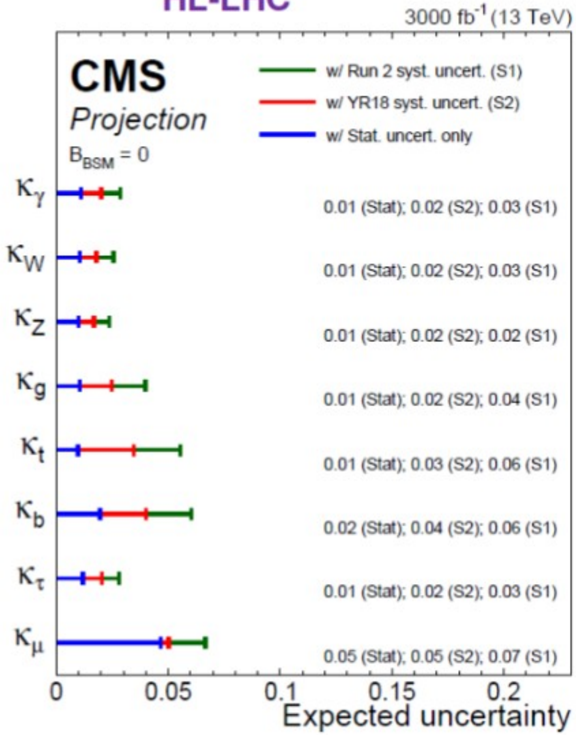
- Coupling modifiers are presented at the level of the 2016 data
  - ggH and $H \to \gamma\gamma$ loop processes resolved
  - ➔ results are in line with SM
  - ➔ precision in 10-30% range, apart from κ_μ
  - stay tuned for full Run 2 result

- Projections have been made for full HL-LHC period (3000 fb^{-1})
  - ➔ precision improves down to 2-5% range (apart from κ_μ)
  - ➔ dominated by signal theory in S1 case (κ_μ dominated by statistics)

2016 data



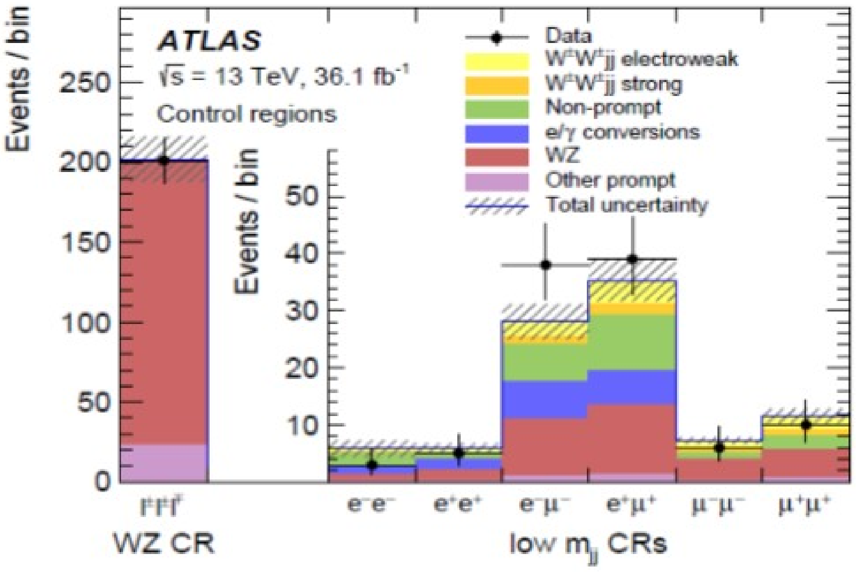
HL-LHC

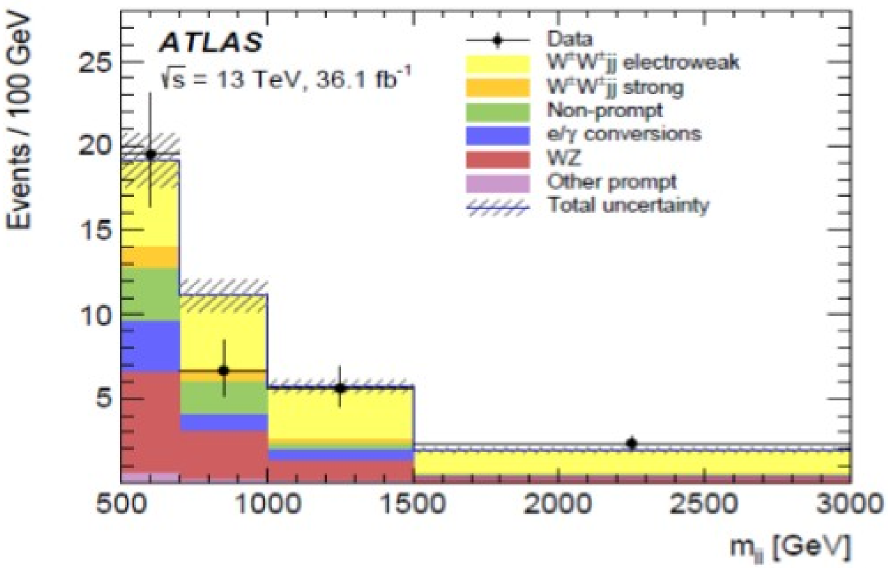


Vector boson scattering at high energies

Observation of Electroweak $W^{\pm}W^{\pm}jj$ Production

arXiv:1906.03203





Control regions at low m_{JJ}
→ normalize backgrounds

Fairly pure signal (all EW)
at high values

Vector boson scattering at high energies

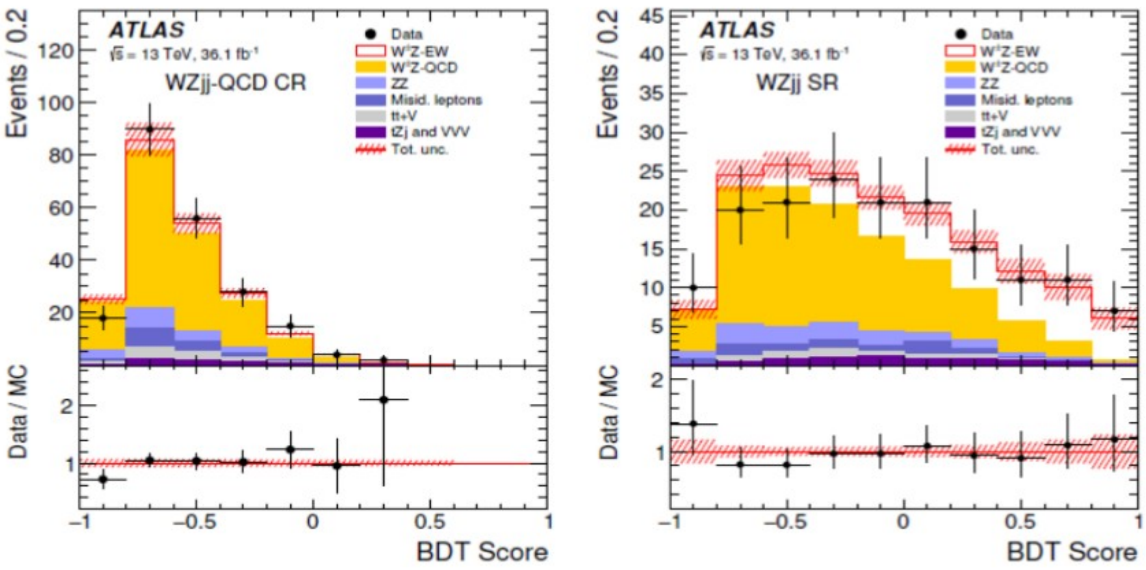
Observation of Electroweak *WZjj* Production

Phys. Lett. B 793 (2019) 469

Signal extracted by fitting a BDT discriminant built from 15 variables

- jet kinematics
  (m_{jj}, p_T^{j1}, p_T^{j2}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, y^{j1}, n_{jets})
- diboson kinematics
  (p_T^W, p_T^Z, η^W, $|y_Z - y_{\ell,W}|$, m_T^W)
- combined jet-diboson
  ($\Delta R(j_1, Z)$, $R_{p_T}^{\text{hard}}$, ζ_{lep})

Background constrained in three control regions



Experimentally clean final state. Challenge : extract EW component (QCD dominates!)

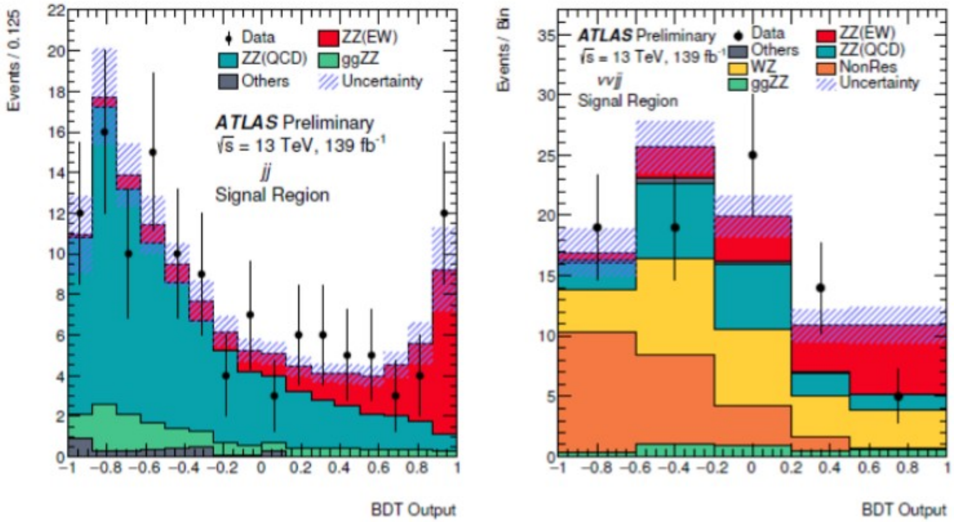
Vector boson scattering at high energies

Observation of *EW ZZjj* Production

ATLAS-CONF-2019-033

The electroweak signal is extracted using a BDT with 12 (4ℓ) or 13 ($2\ell 2\nu$) variables

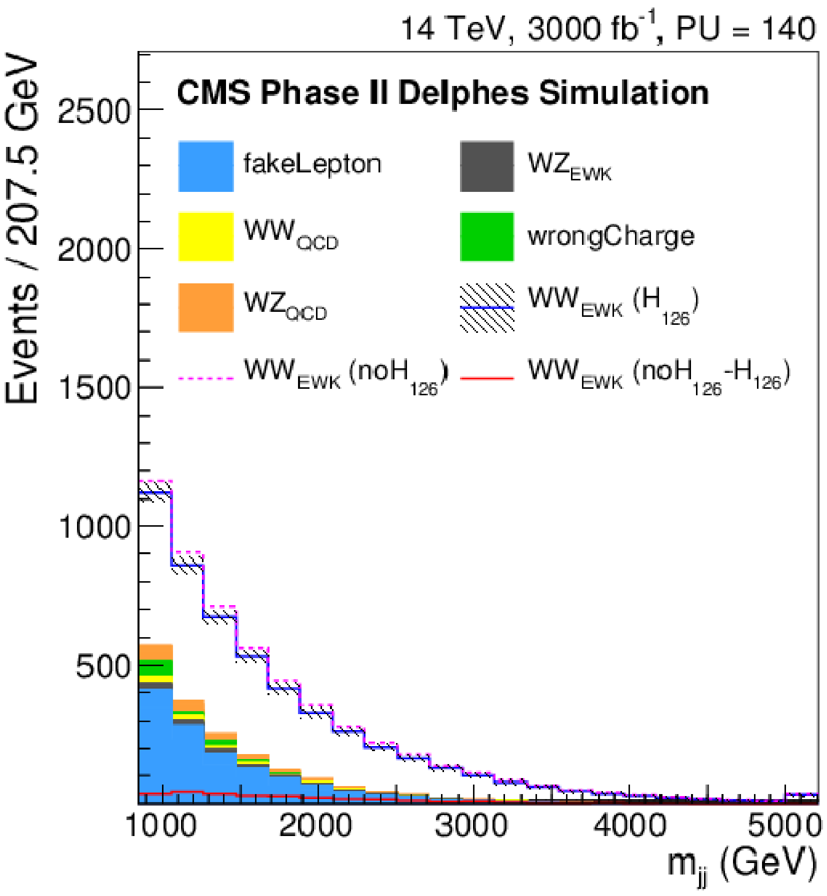
A fit of the BDT discriminant is performed simultaneously in $4\ell jj$ and $2\ell 2\nu jj$ (with a 4ℓ QCD CR defined by events failing Δy_{jj} or m_{jj})

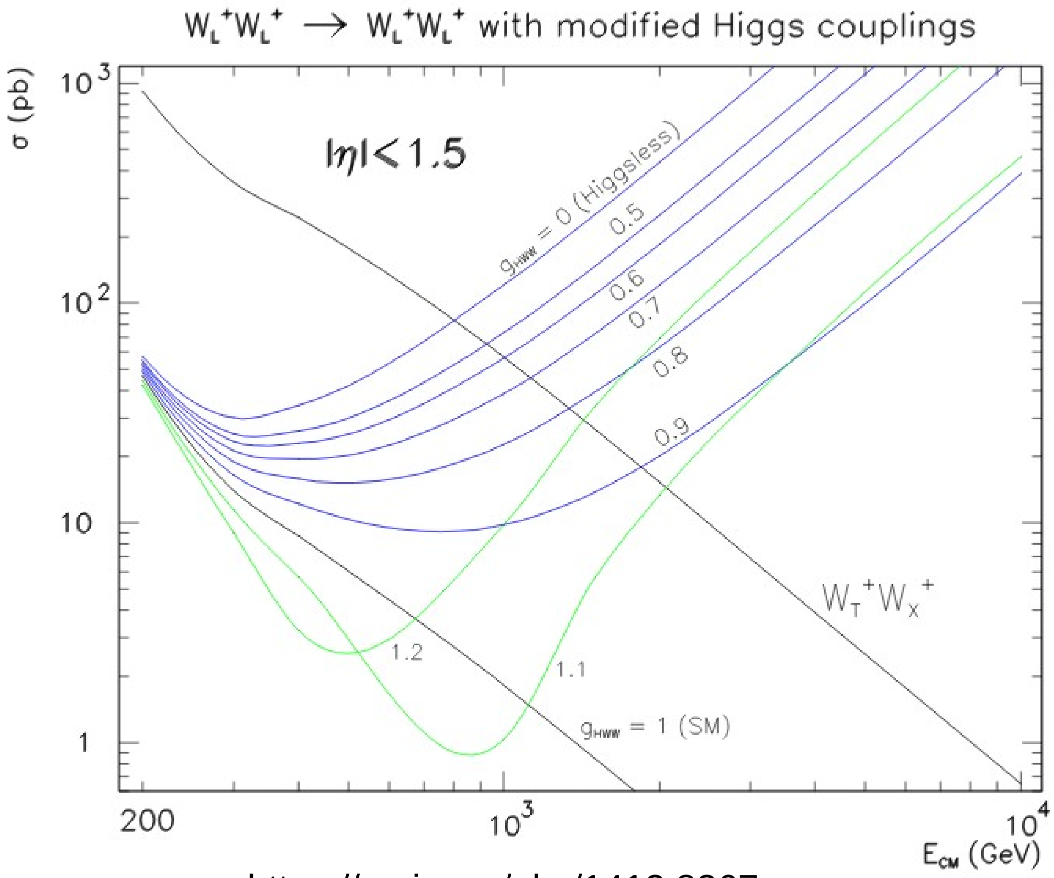


Electroweak *ZZjj* production is observed **for the first time** with the background-only hypothesis rejected with 5.5σ (expected 4.3σ from MG5_aMC@NLO)

Experimentally clean final state. Challenge : extract EW component (QCD dominates!)

Vector boson scattering : prospects and link with Higgs





https://arxiv.org/abs/1412.8367

Summary

- Neutrino physics entered the precision era (or I just realized…)
- Belle II will boost B physics by an order or magnitude, in both precision measurements and searches for rare decays
- The pace of LHC results slows down a little... significant increase in the data sample will now not happen before a long time.
  - Still, precision measurements (W, Z, top, Higgs) have beautiful perspectives on the mid term, and detector/machine preparations for the HL-LHC are in full swing
  - Finally, we close in on the last element of the electroweak “triangle”, namely explicit studies of vector boson scattering at the highest energies and their interplay with the Higgs boson properties, and with EWPO’s in W, Z production.