Anomalies in energy frontier physics

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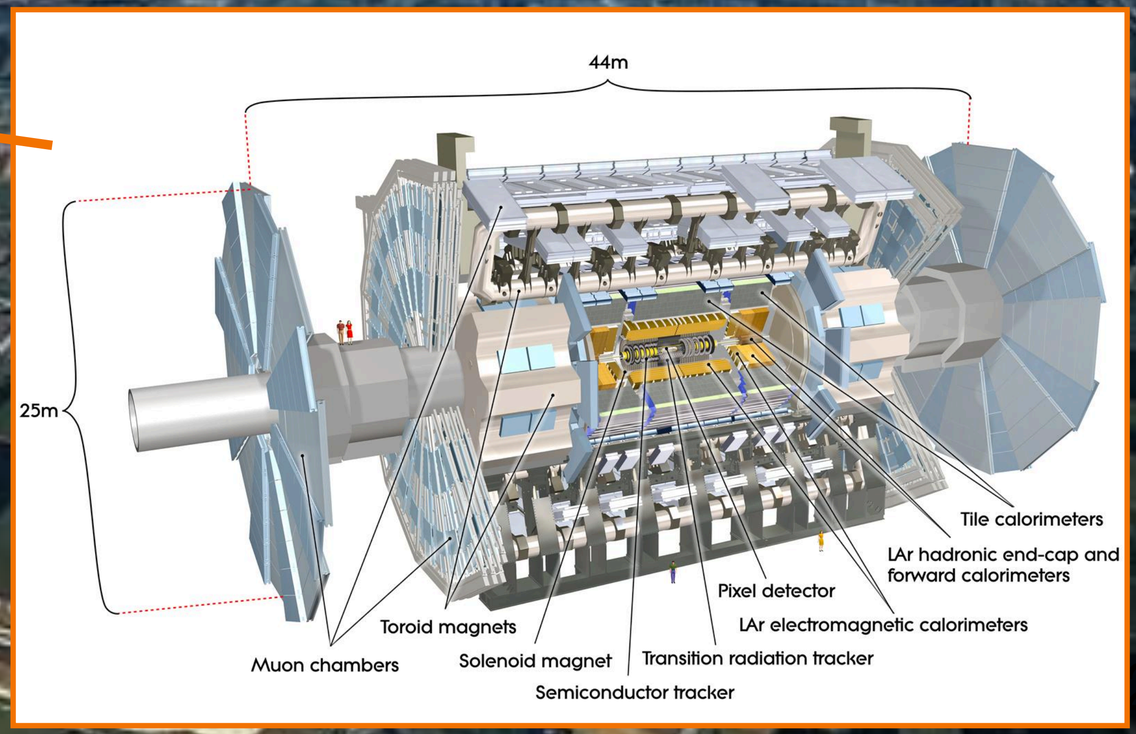
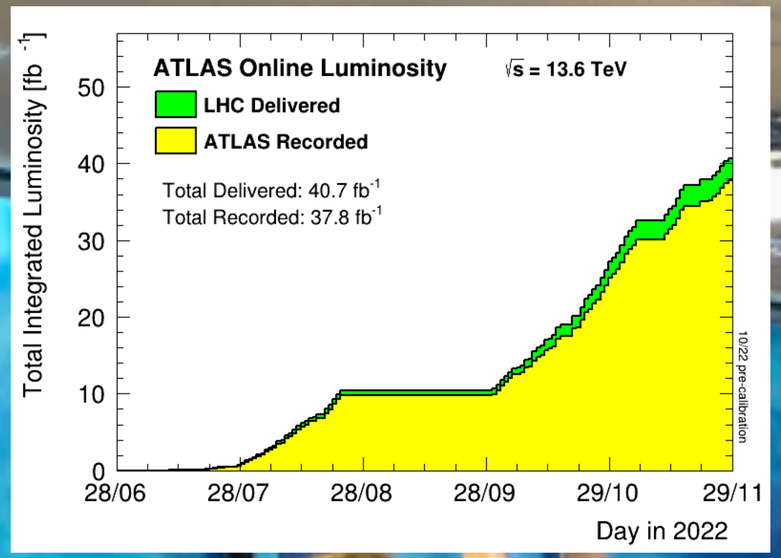
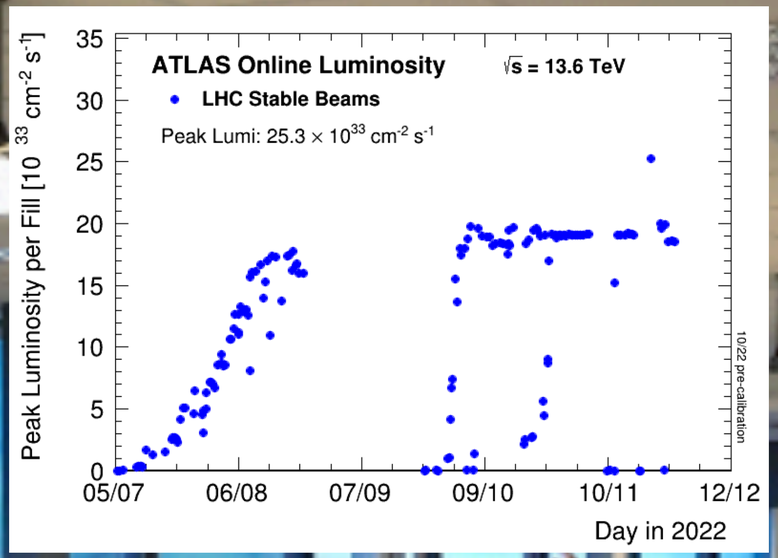
KMI school
16/12/2022

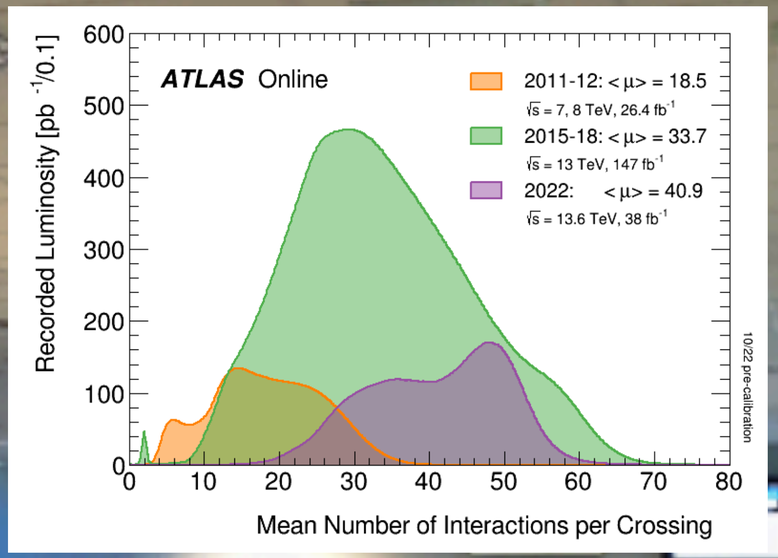
LHC and ATLAS experiment

- Synchrotron with a 27km circumference at CERN
- pp collisions at $\sqrt{s}$=13 TeV (Run2) and 13.6 TeV (Run3)
- SM measurements at very high energy + search for new physics beyond the SM
- ~3000 collaborators from 181 institutes in 42 countries



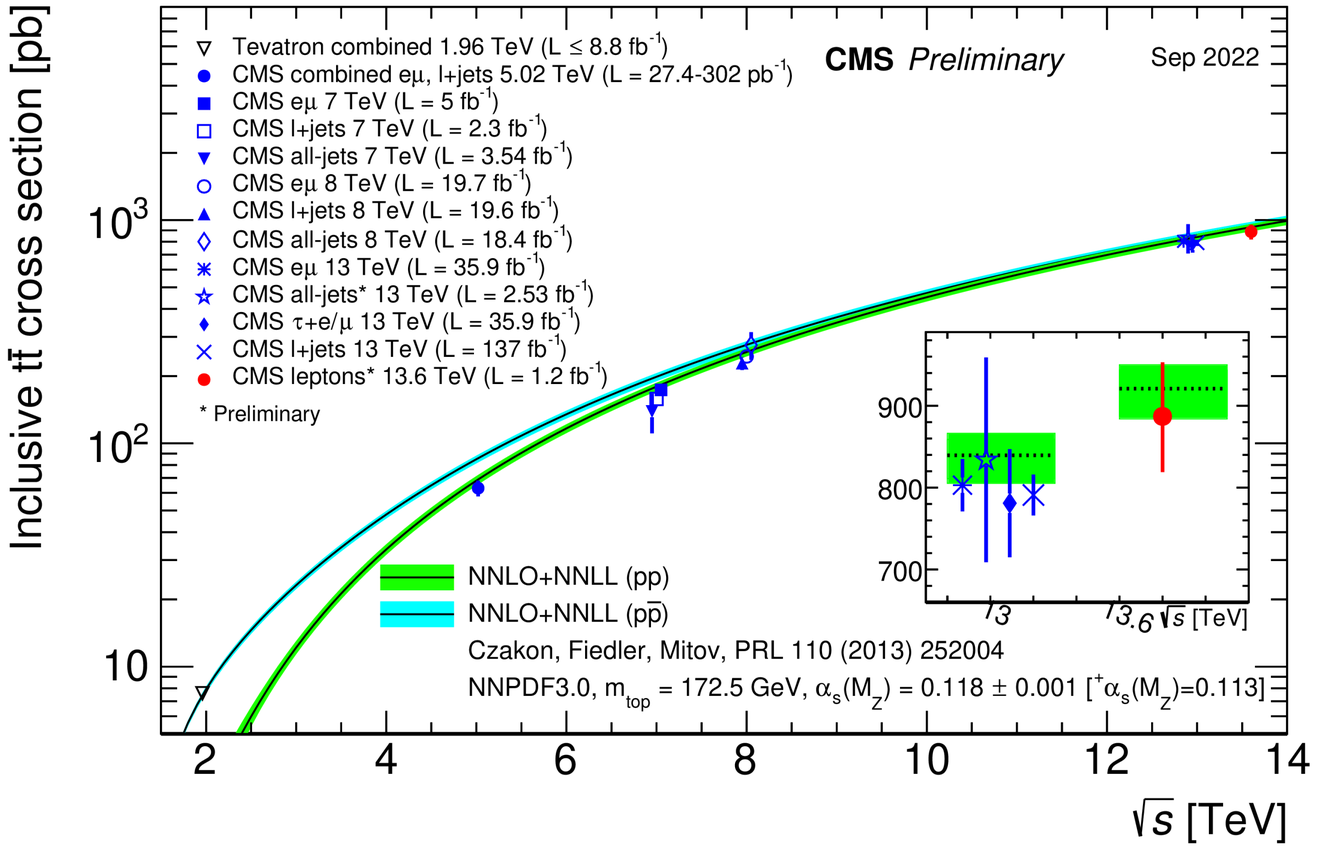


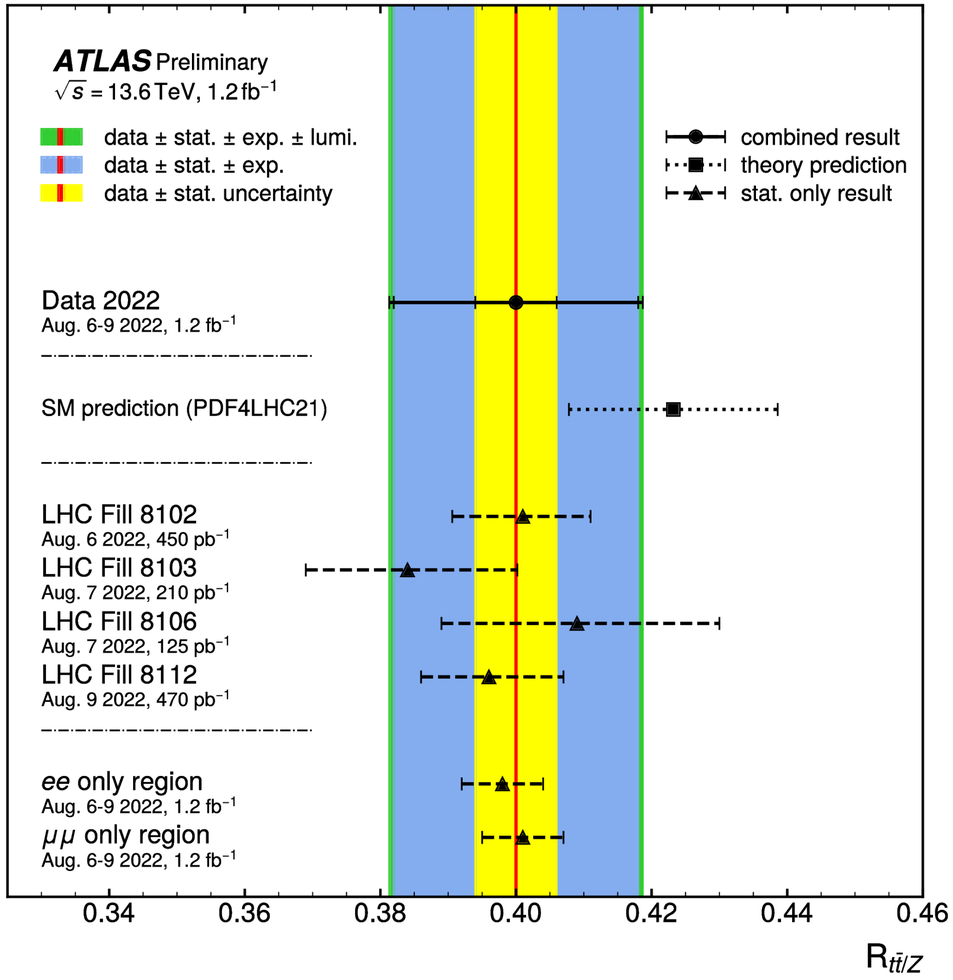




2022: first year of 13.6 TeV collisions

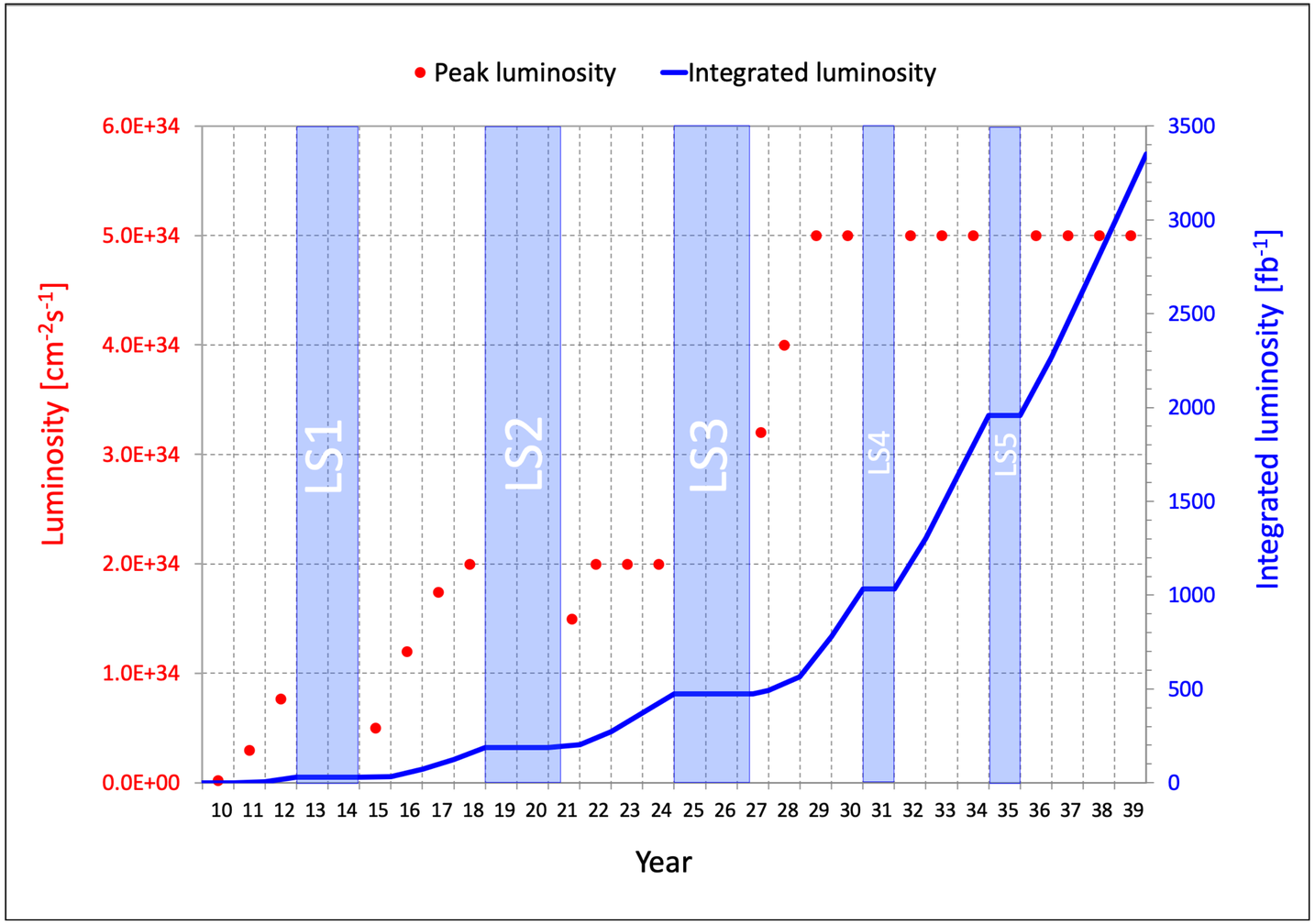
First 13.6 TeV results





- Many other results will be published in early next year!

Long term schedule for HL-LHC



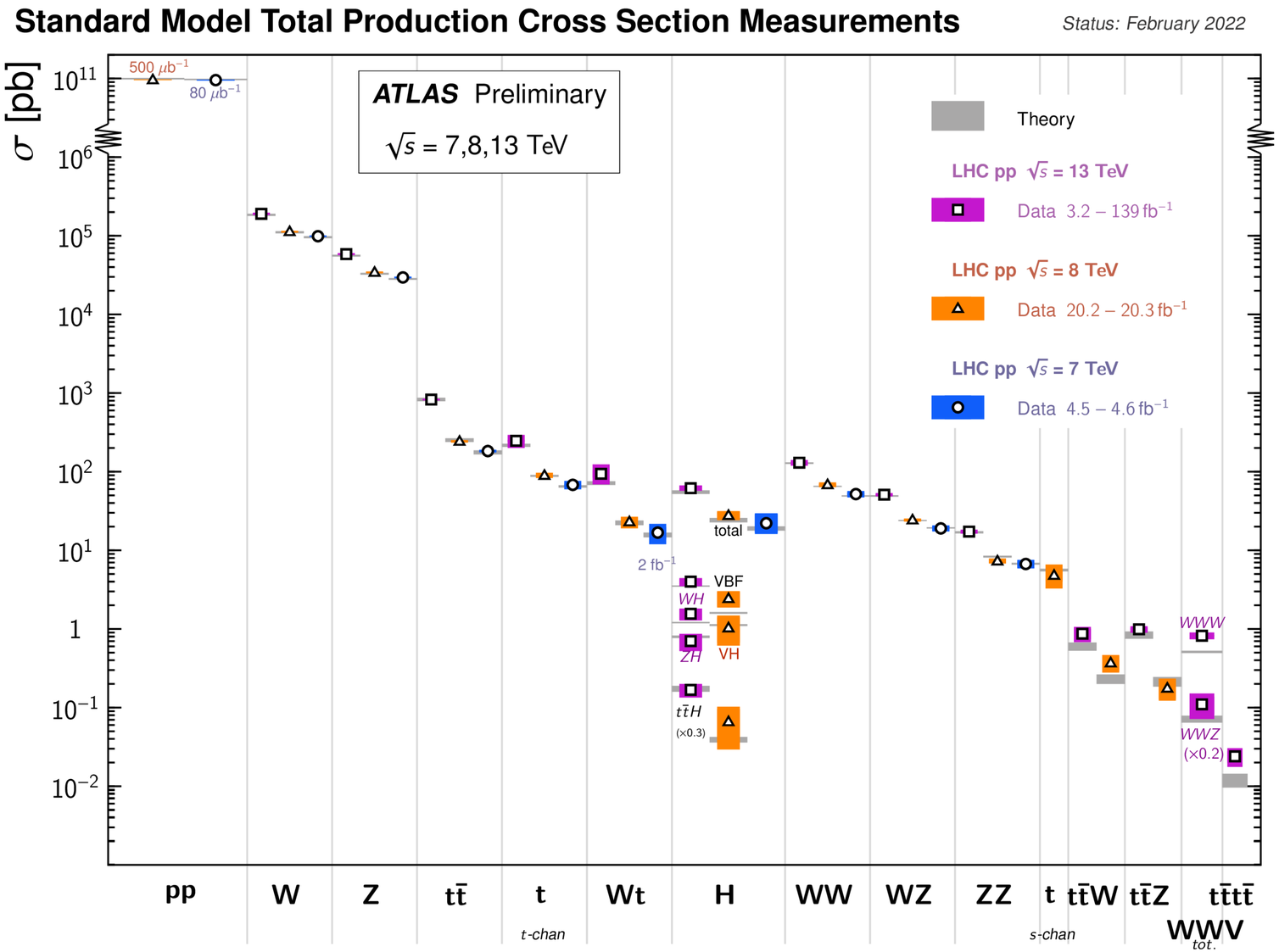
v.s. detector damage, high pileup, computing resource, etc.

Run2 (~150/fb)
* y_t, y_b
* gluino mass <2TeV

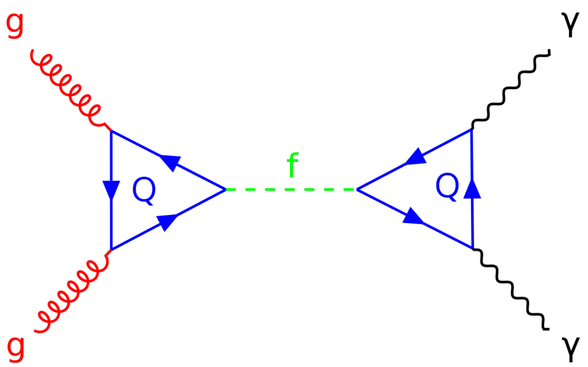
Run3 (~300/fb)
* y_μ, diHiggs x-sec
* gluino mass <2.5TeV

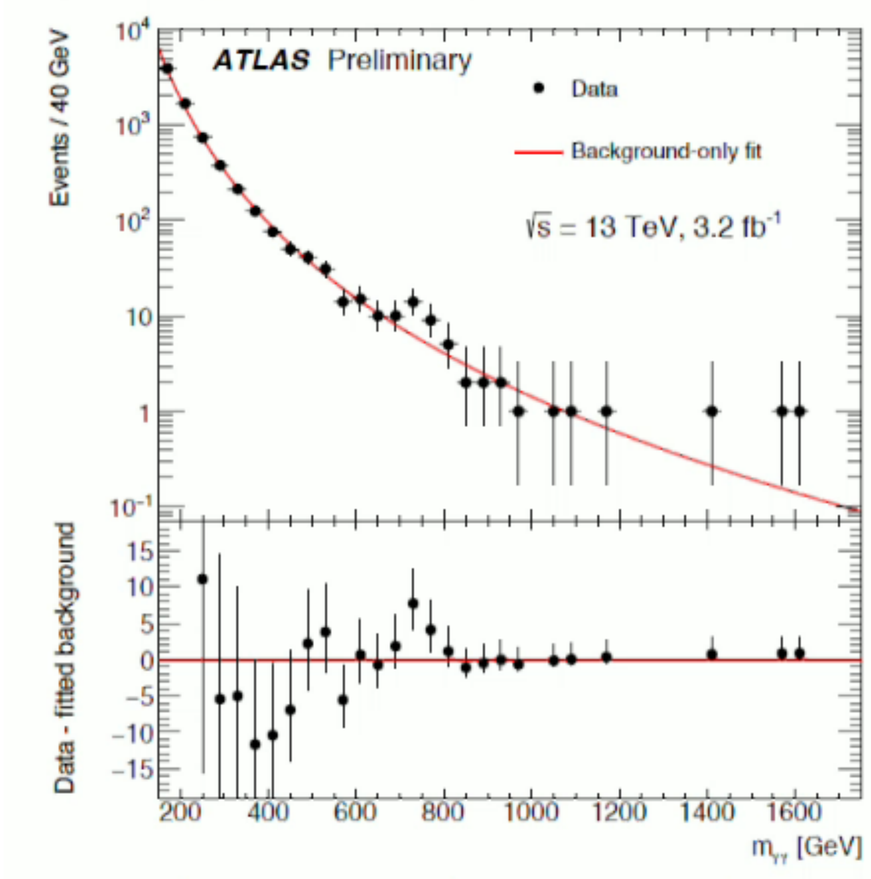
HL-LHC (~3000/fb)
* self-coupling (?)
* gluino mass <3TeV

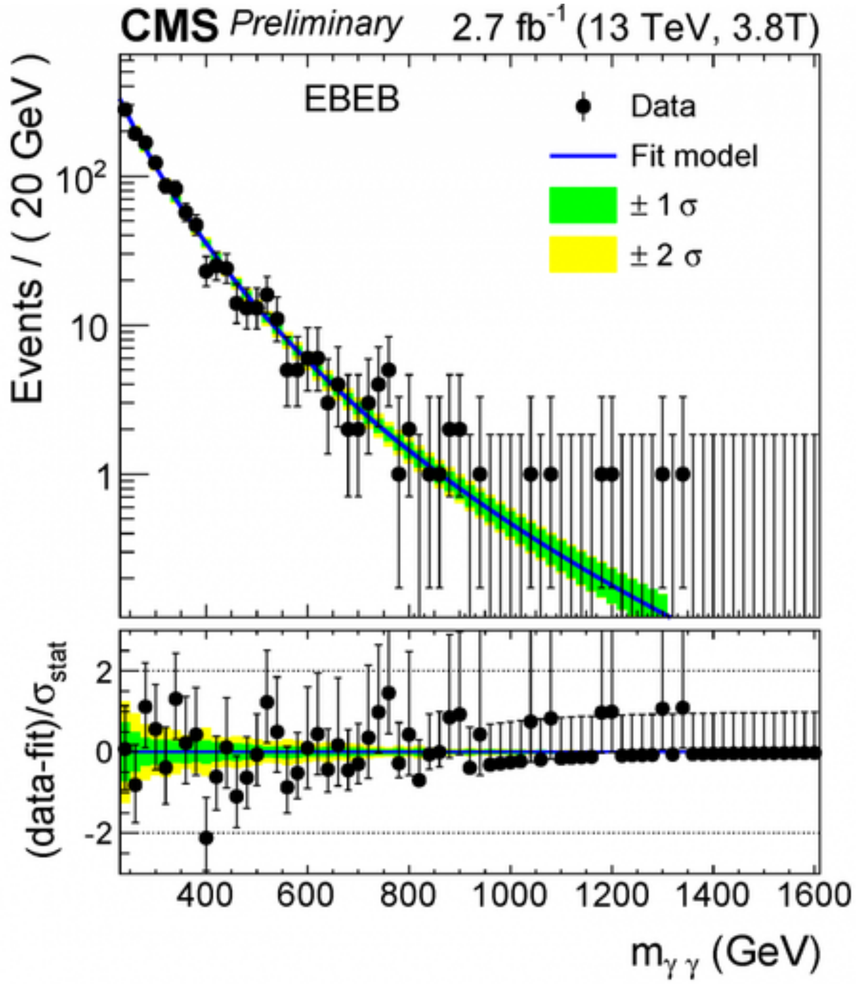
Surprisingly good agreements of the SM with data



750GeV excess?

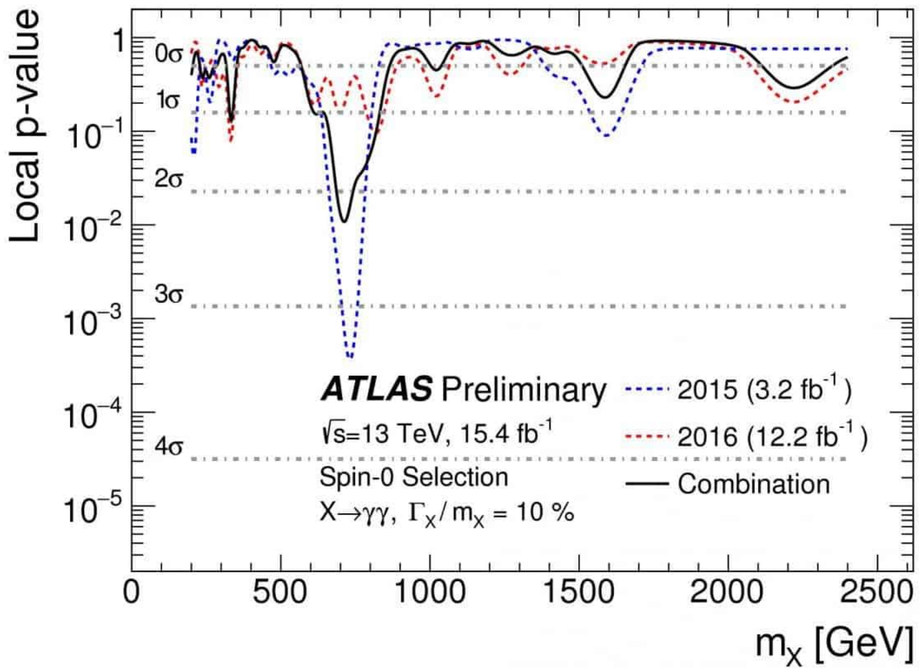


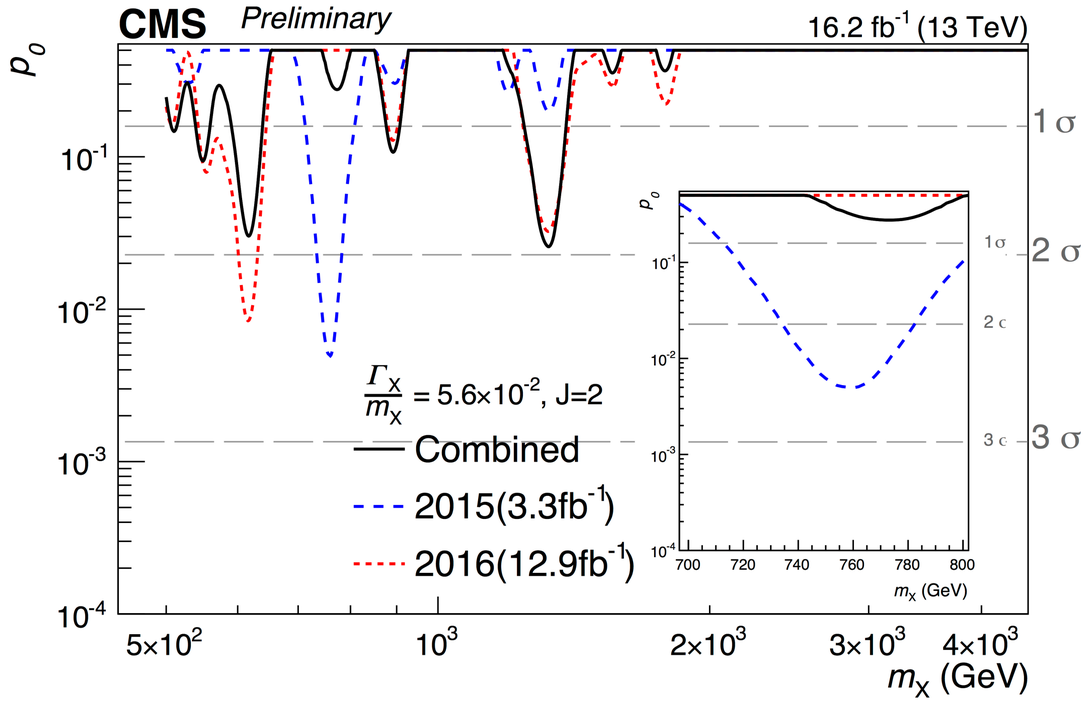




December 2015 >250 pheno papers related to that were submitted to arXiv…

…disappeared by 4x more data





- Lessons learned (?)
  - If hundreds of SRs are used for the search, there could be at least one SR with 3sigma
  - The power of statistics is great
  - Understanding of models with scalar(+VLQ) progressed

What should we do in Run3?

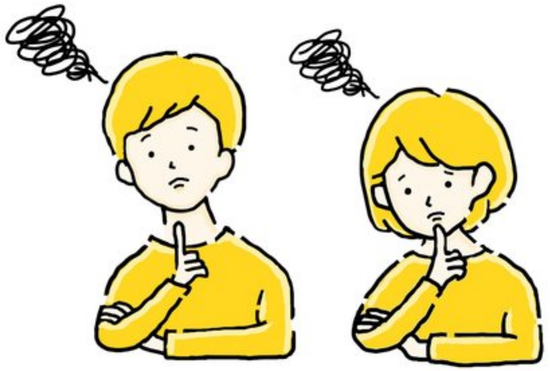
- Data is not increased quickly. 3-4 years to double.

1. Follow up on 2-3σ level excesses, particularly with the **ATLAS and CMS coincidence**

2. Focus on **new techniques** that can improve the sensitivity dramatically, exceeding the increase in data

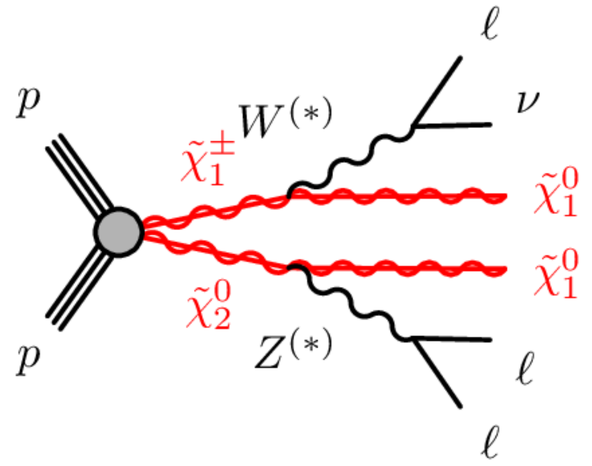
3. Also important to look at the **regions not explored** in Run2 analysis.

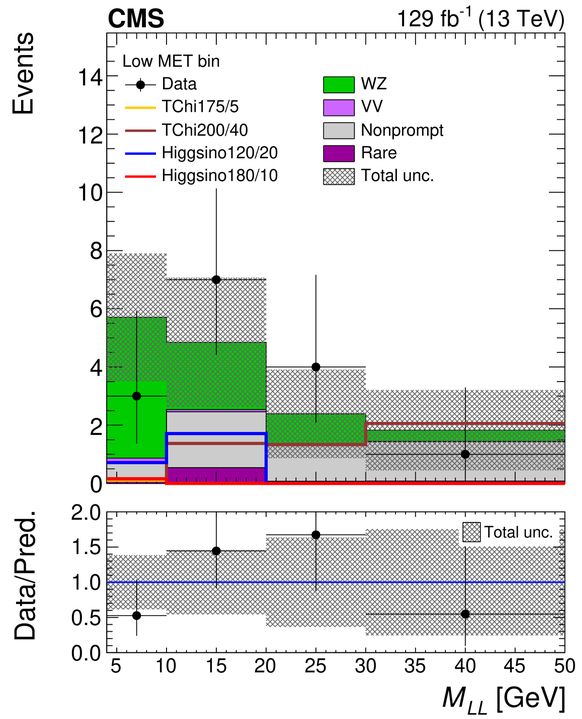
(1) ATLAS/CMS coincidence



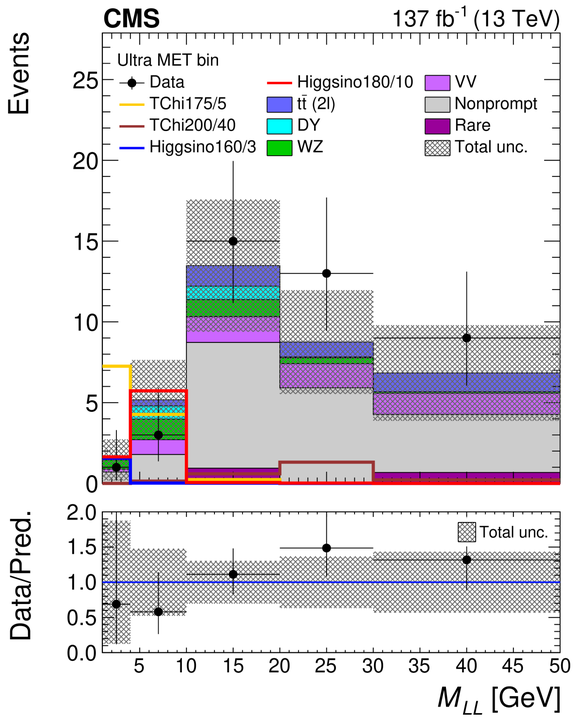
EW SUSY@dM~30GeV

- Analysis requiring low-p_T multilepton
- Dark Matter motivated wino/bino “well-tempered” and pure higgsino scenarios

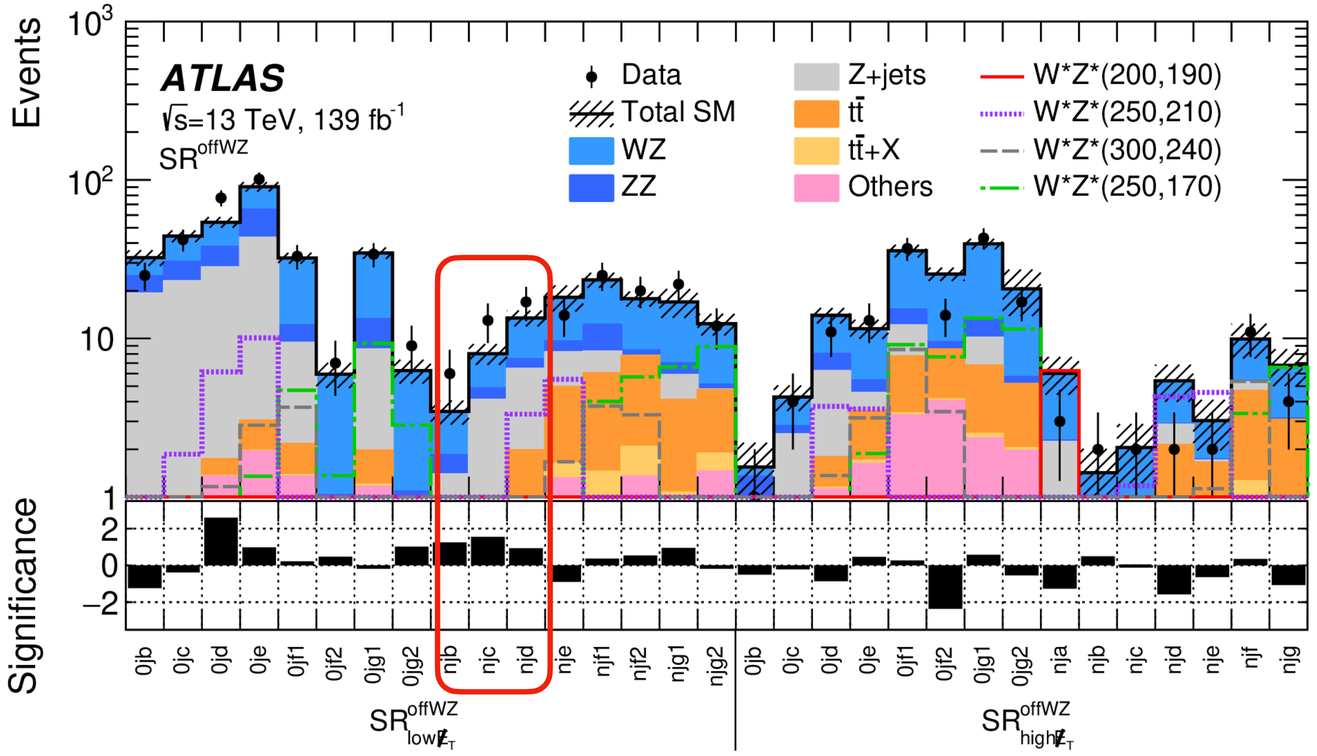




3lep, mEt>125GeV



2lep, mET>290GeV

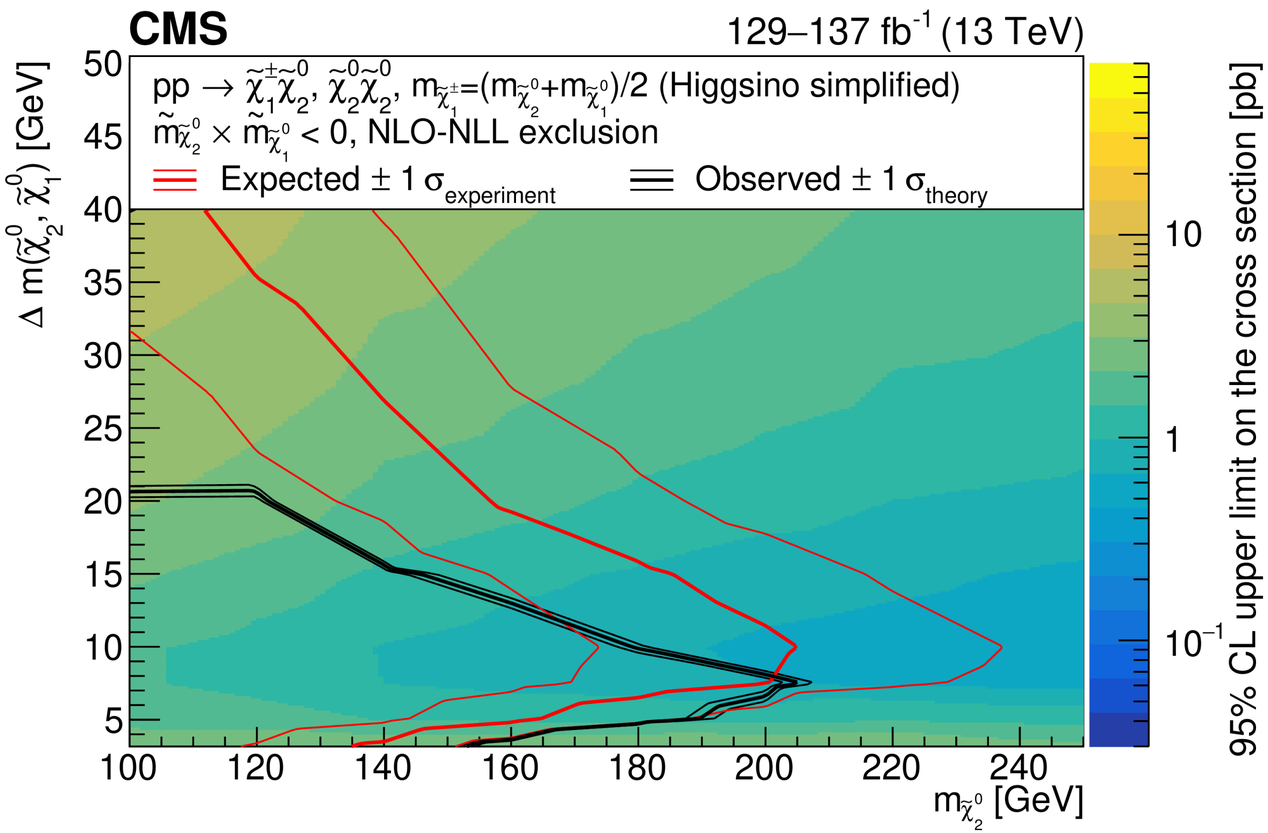


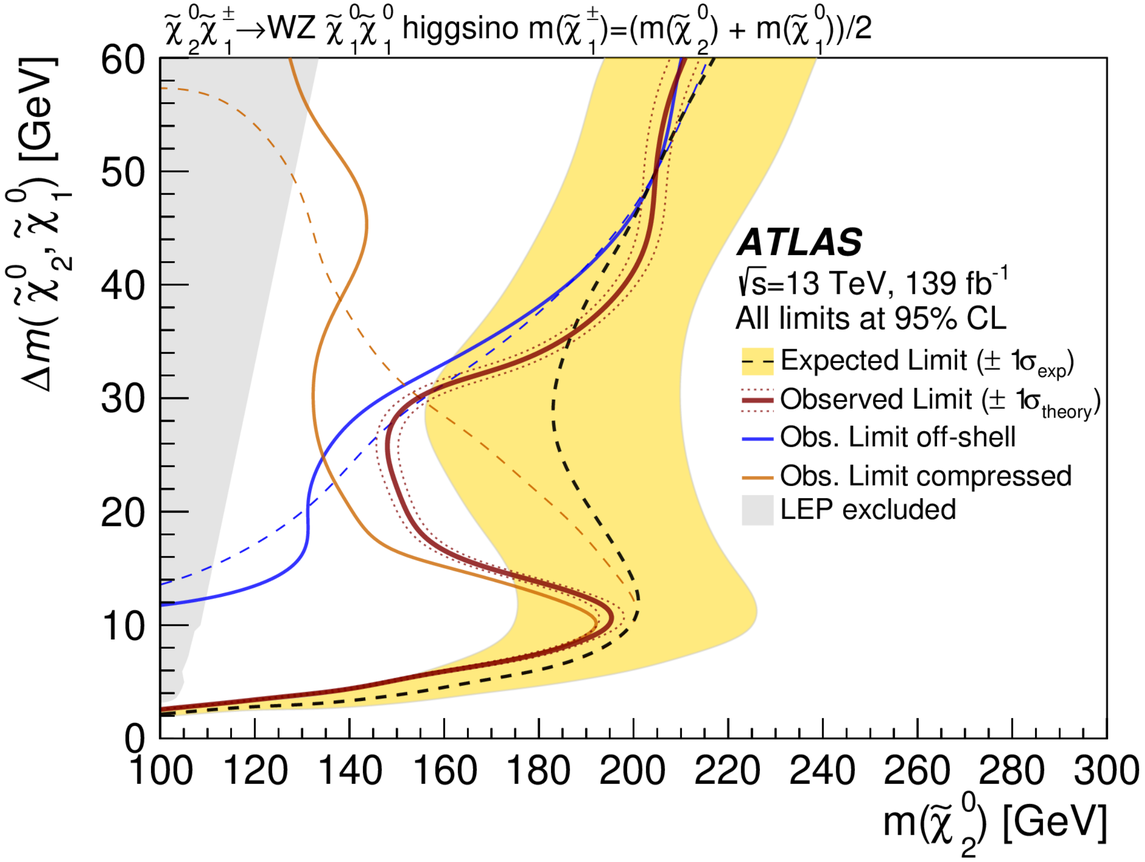
3lep, mEt<200GeV, 12<m(ll)<30GeV

JHEP04 (2022) 091

EPJC 81 (2021) 1118

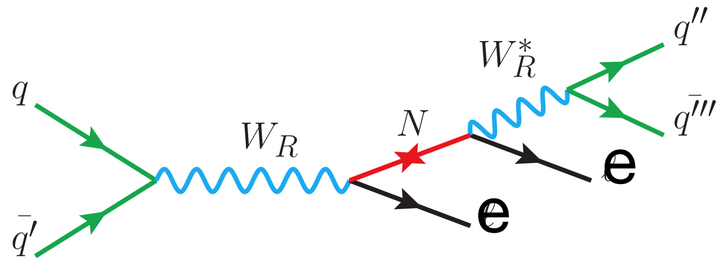
EW SUSY@dM~30GeV



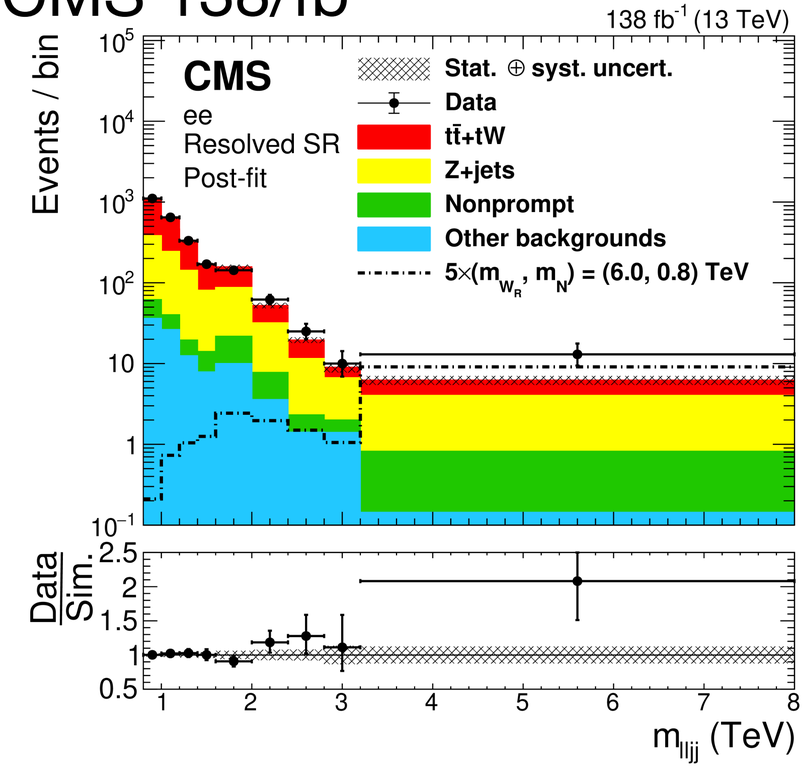


HNL in LRSM

- TeV-scale left-right seesaw model for tiny neutrino mass
- Heavy W_R, Z_R and N_R are introduced

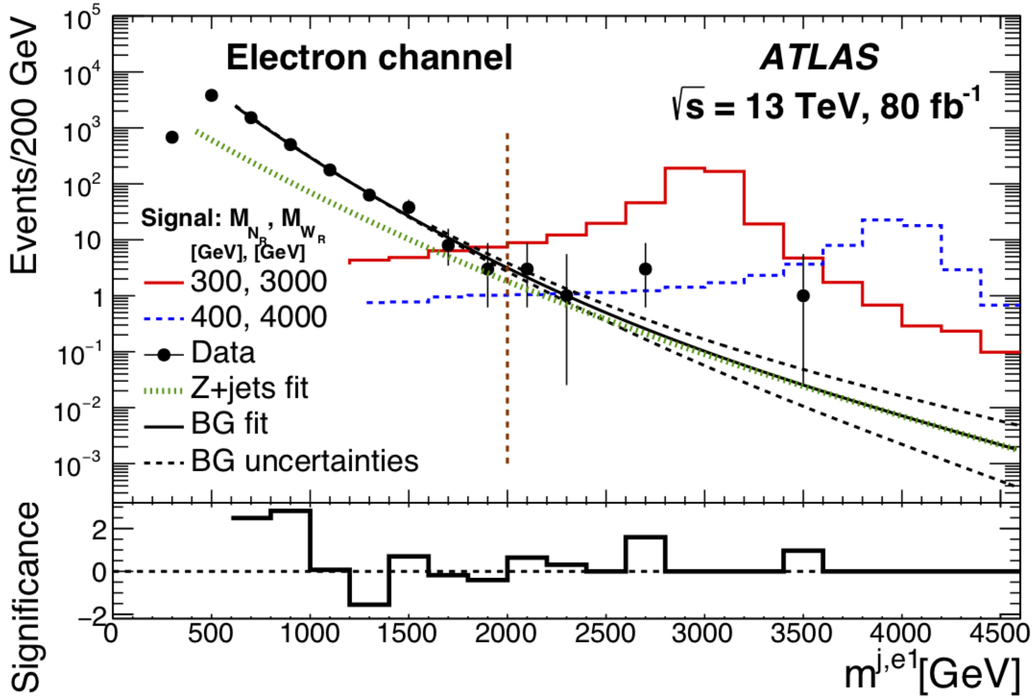


CMS 138/fb



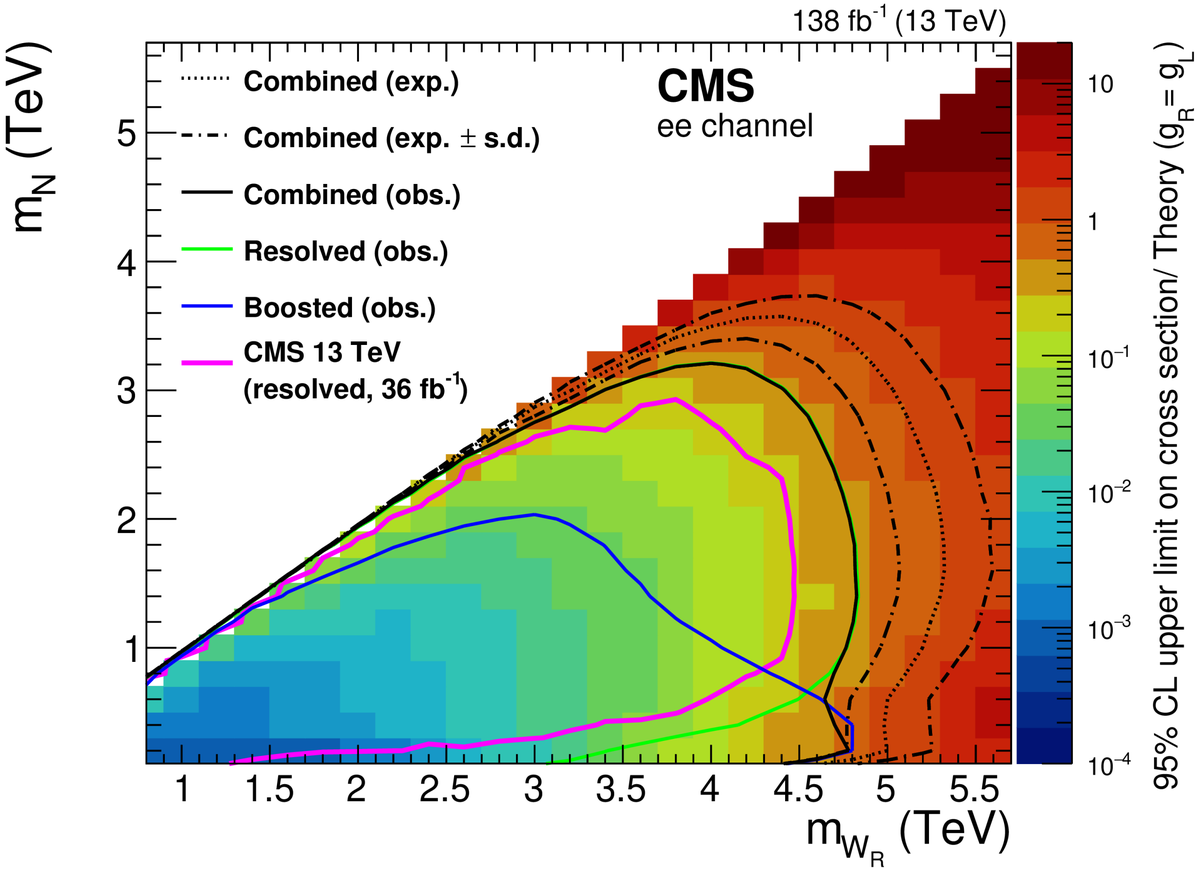
EXO-20-002

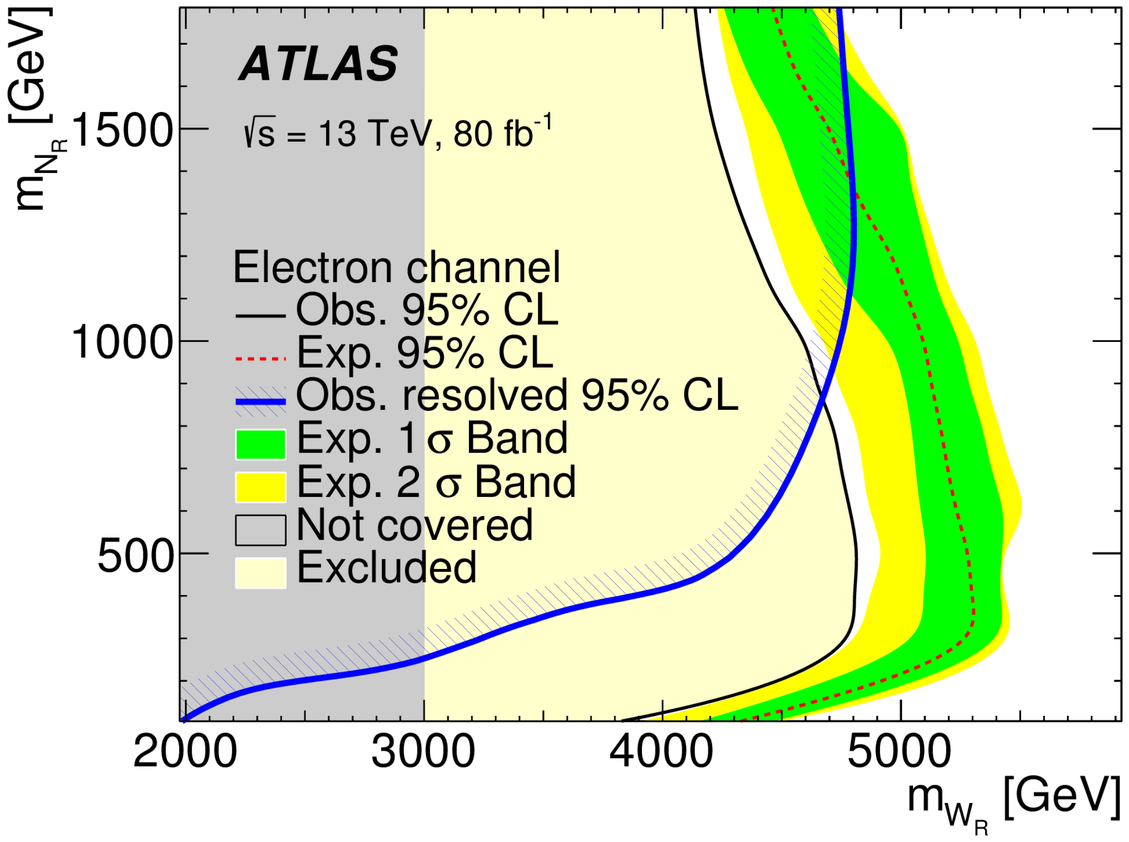
ATLAS 80/fb



PLB798(2019)134942

HNL in LRSM



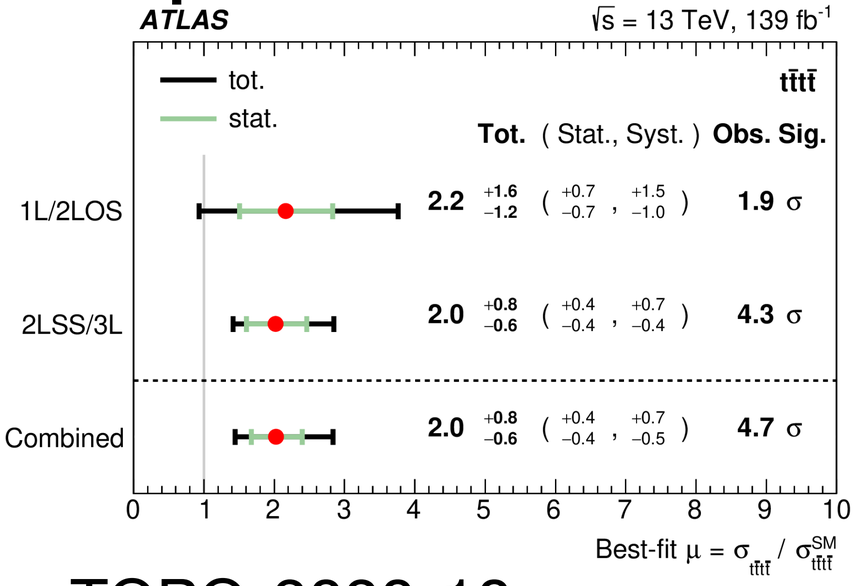


ATLAS full run-2 results coming soon

Others

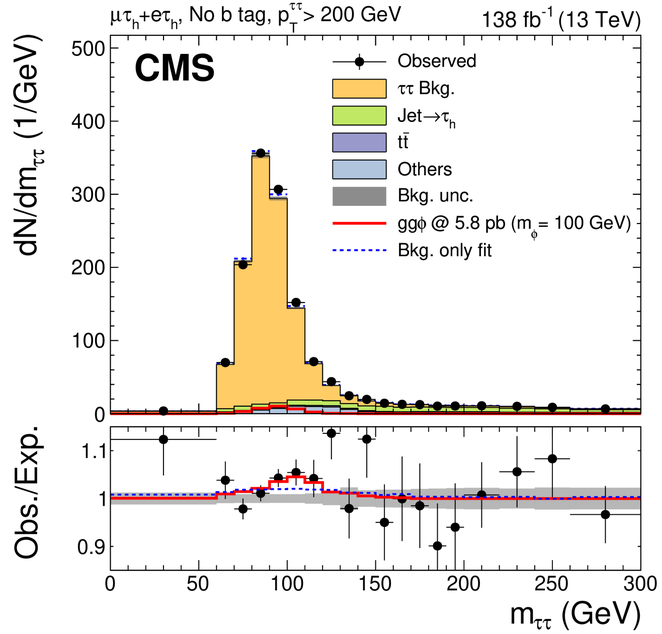
- Only ATLAS or CMS
- Will follow them up in Run3 too

4top x-section

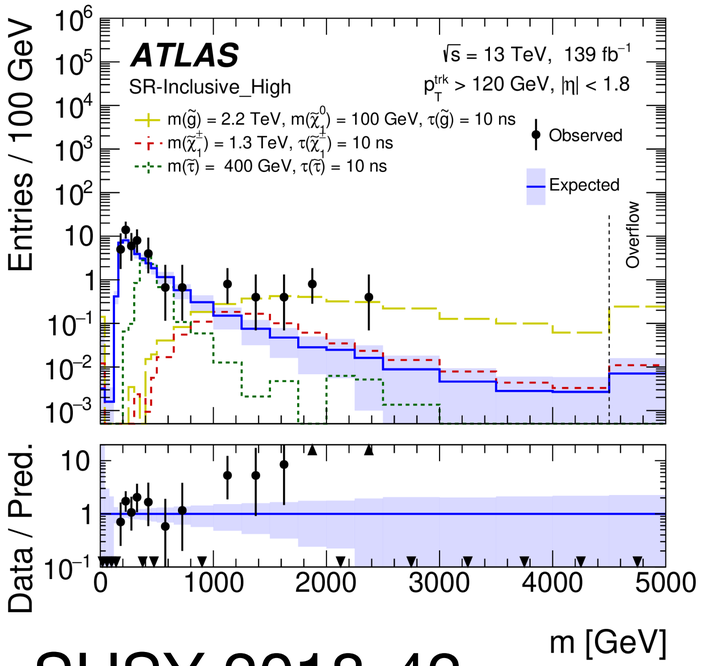


TOPQ-2020-10

ττ resonance

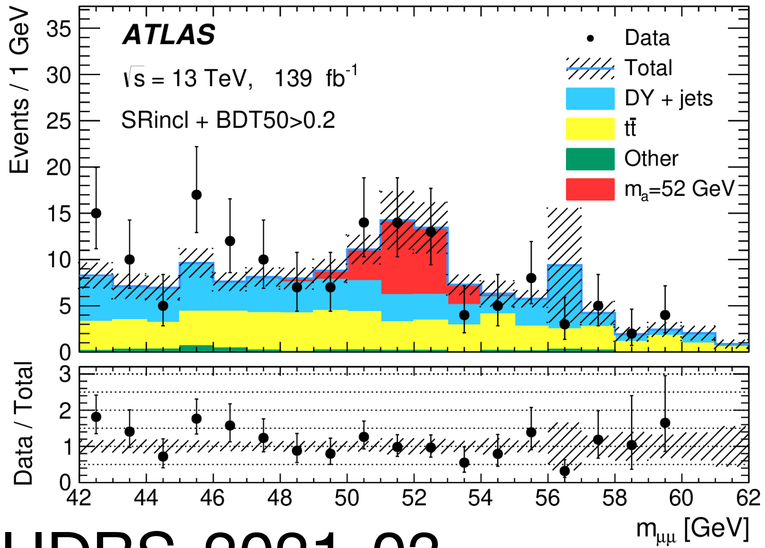


Pixel dE/dx

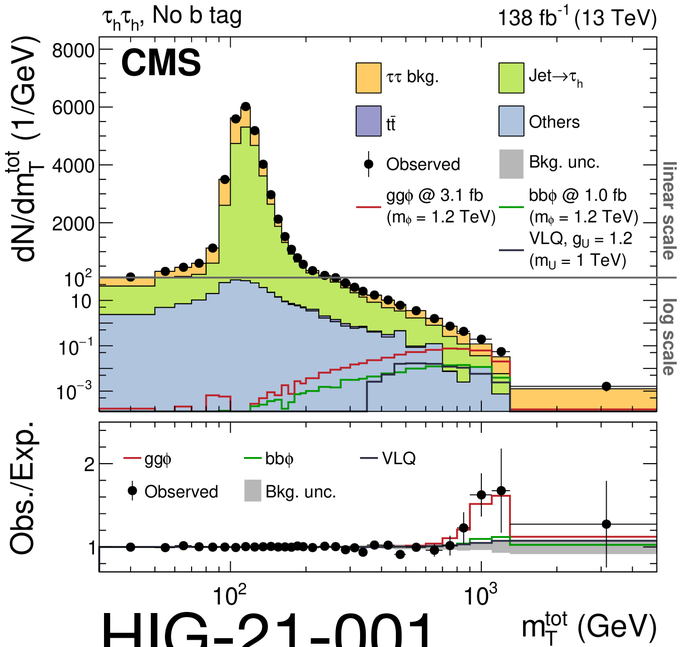


SUSY-2018-42

NMSSM h→ss→bbμμ



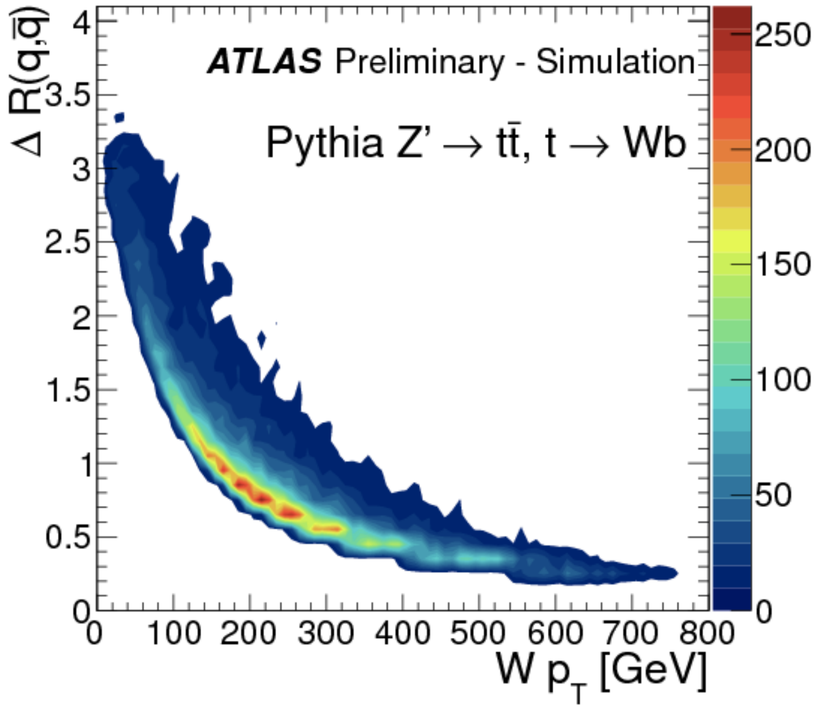
HDBS-2021-03



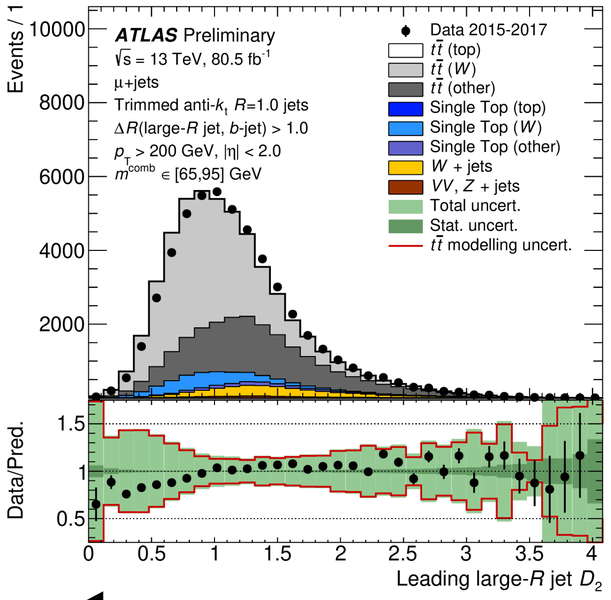
HIG-21-001

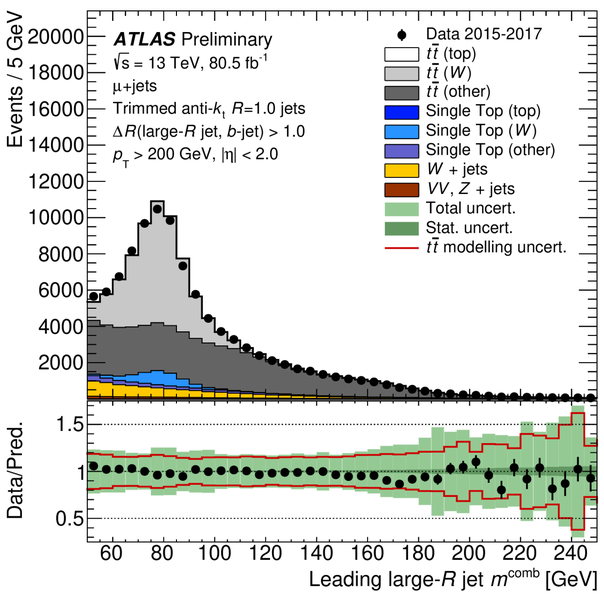
(2) Analysis tool improvements

Boosted object tagging



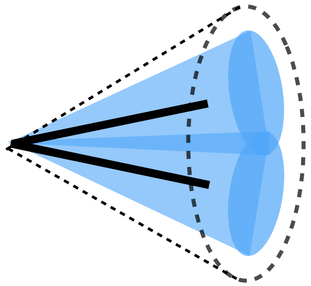
- At very high-p_T range, due to the Lorentz boost, 2 quarks from W/Z/Higgs decay cannot be separated by 2 jets
- Reconstructed as a single large-R jet, and "substructure" information can be used to reduce bkg more



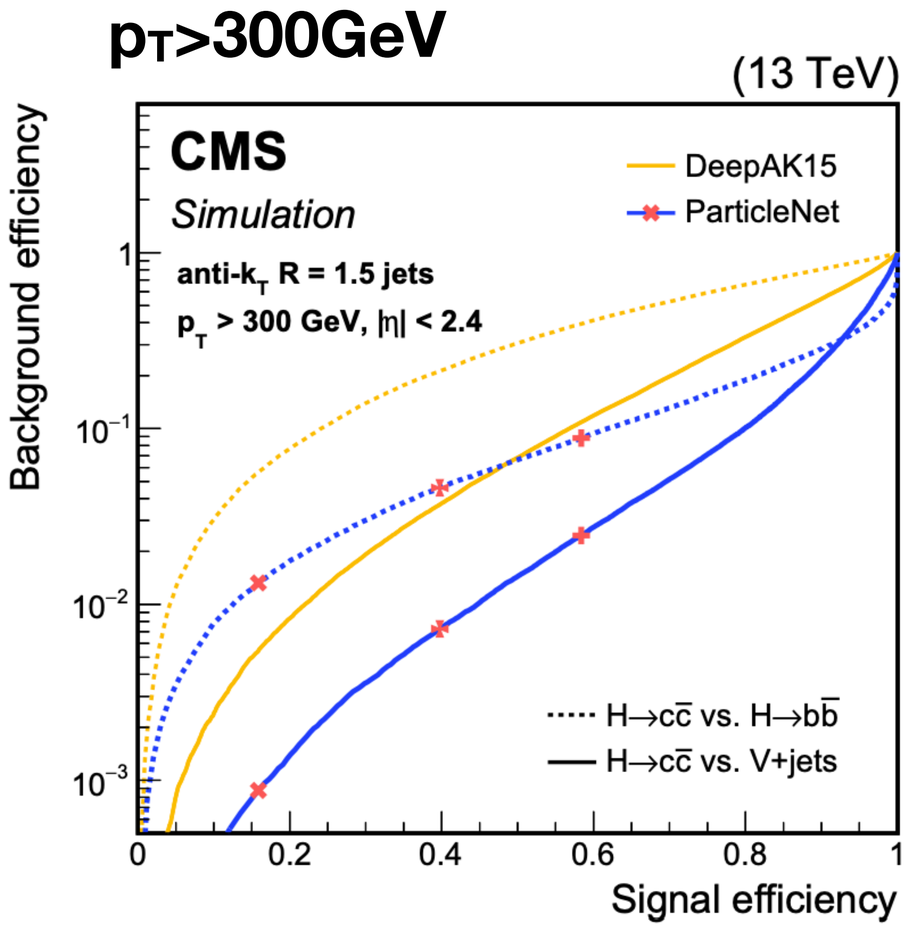


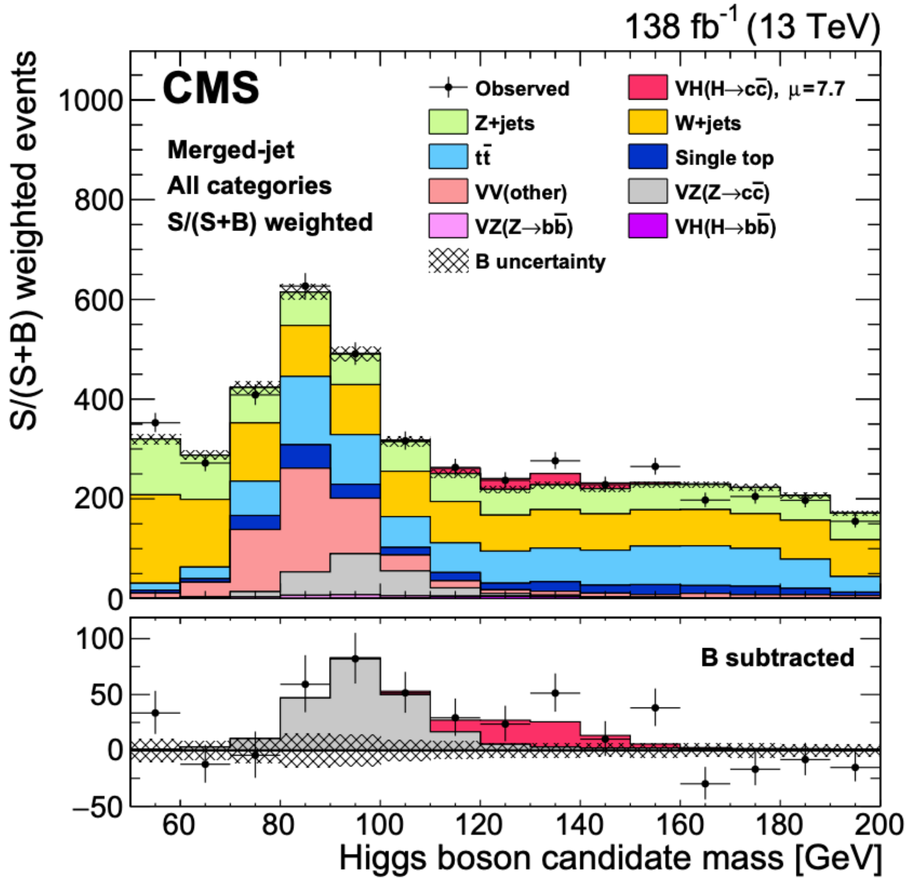
Rest frame

Boosted frame



CMS boosted H→cc tagging



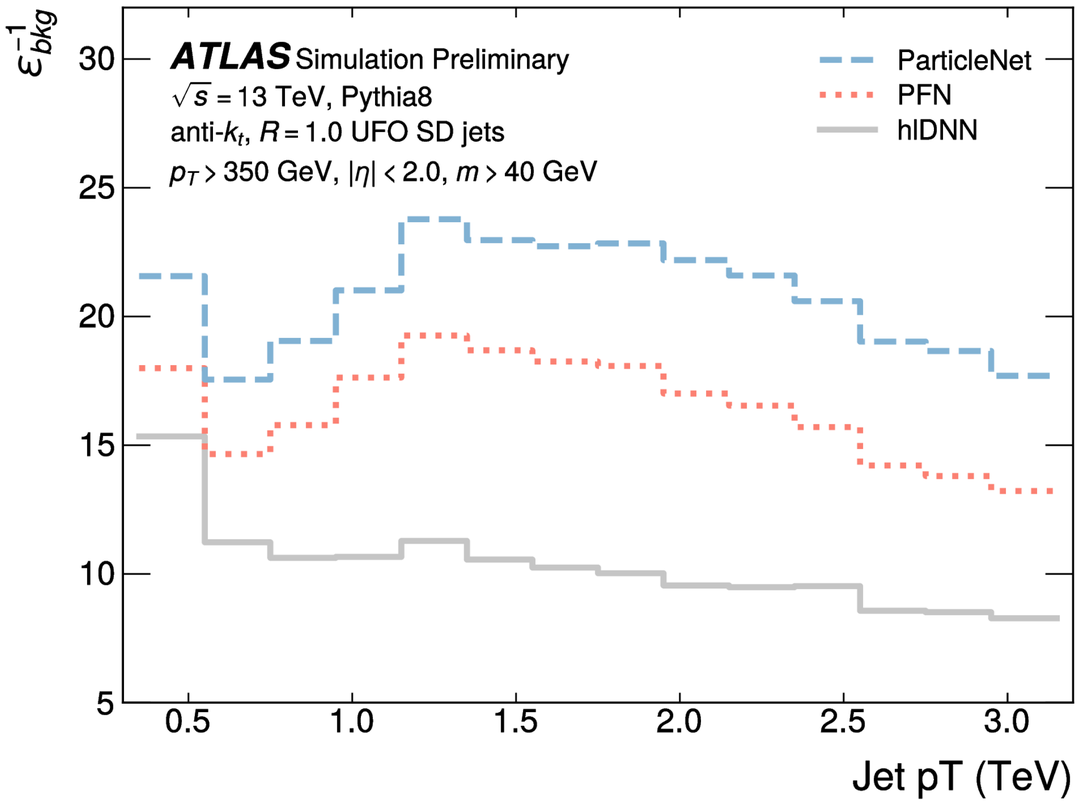


Observed 1.1<|κ_c|<5.5 (expected |κ_c|<3.4)

(c.f. ATLAS expected <12.4)

HIG-21-008

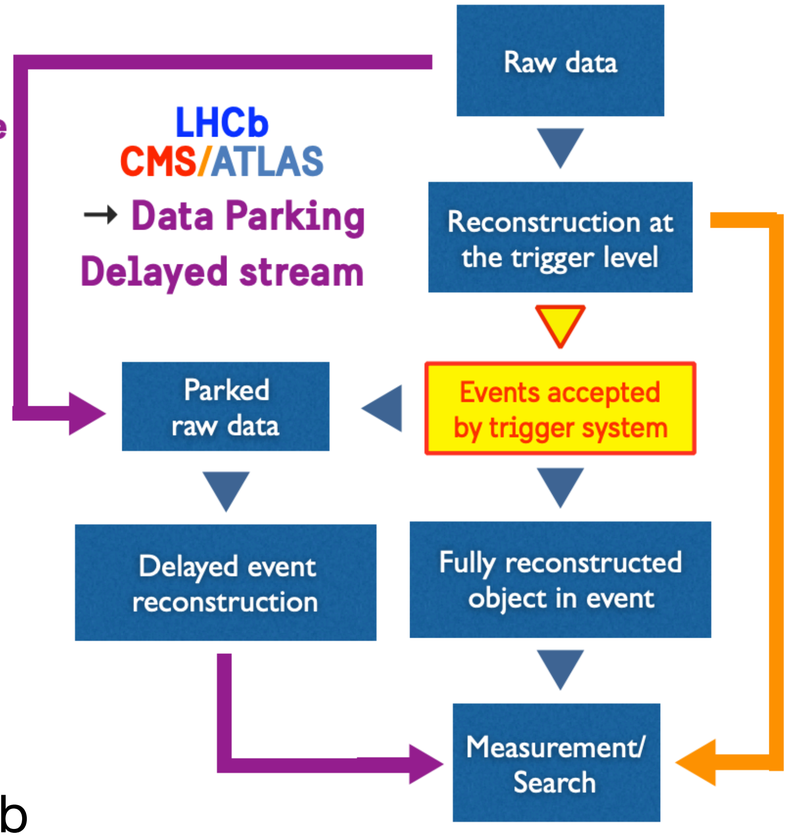
ATLAS constituent-based top tagger



- ParticleNet (graph NN) shows the best result
- The input dataset will be published for the open access

Trigger improvement

- At the hadron collider, a huge online rate reduction (40 MHz→1 kHz) is needed to collect the data
- We basically record the data with high-pT lepton, jet, etc., but many interesting lower-pT physics!
- The data not triggered cannot be analyzed forever



Reduce immediate reconstruction overhead by:
saving data reconstructing it (much) **later**

LHCb
CMS/ATLAS
→ Data Parking
Delayed stream

CMS/ATLAS → Data Scouting
LHCb → Turbo Stream

'Bypass' storage limitation (trigger selection) by:
moving **analysis online**
saving **only selected information**
rather than fewer full events

CMS: optimized B-parking trigger for test of B-anomalies

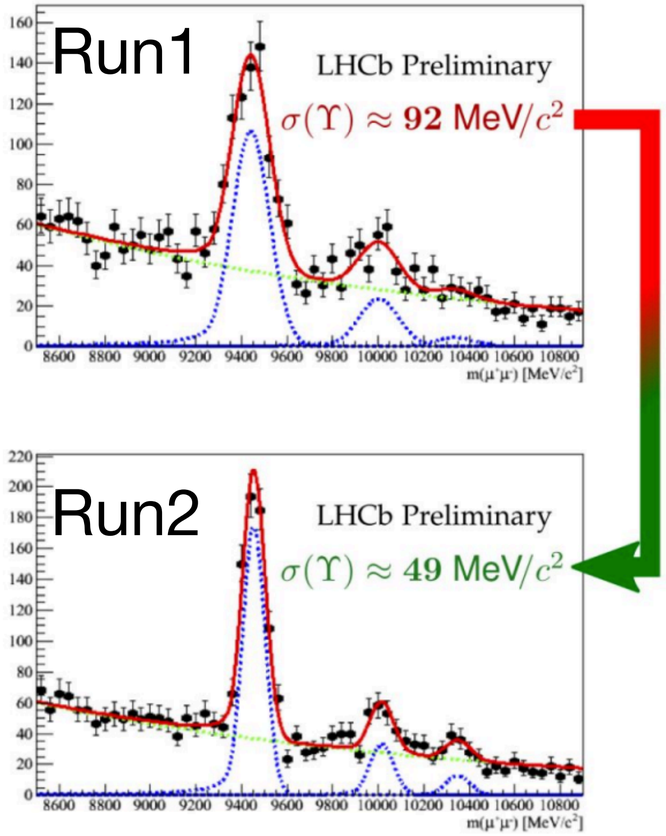
ATLAS: new delayed stream triggers dedicated to diHiggs→4b etc.

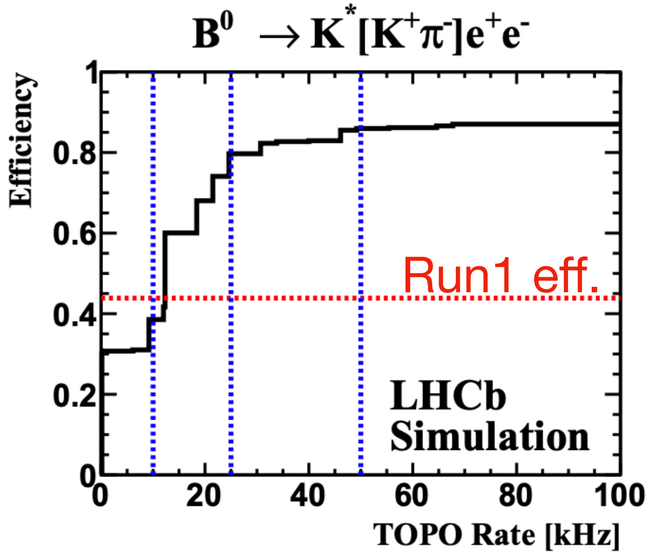
LHCb Run3
>70% of data will be collected in the TURBO stream (!)

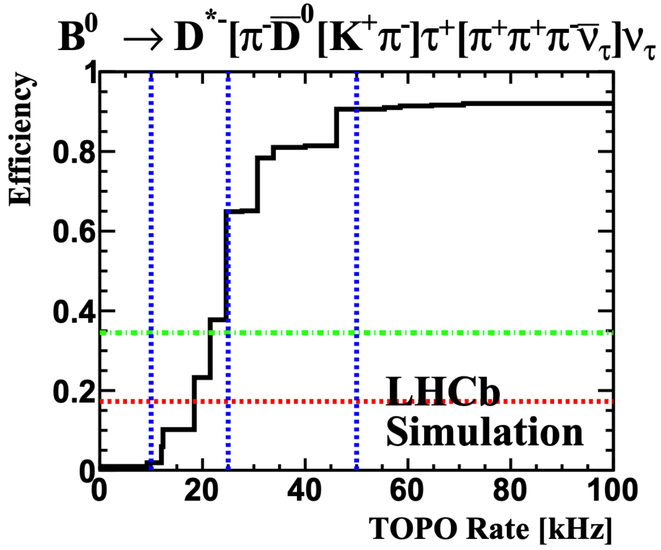
LHCb TURBO + trigger-less DAQ

- TURBO online calibration almost equivalent as the offline
  - Calorimeter calibration for every fills (compare LED monitoring system to a reference and update HV)
  - Tracker alignment calibration for every fills
- “Trigger-less data taking”
  → software trigger only。

  Trigger efficiency will be improved by factor 2--4

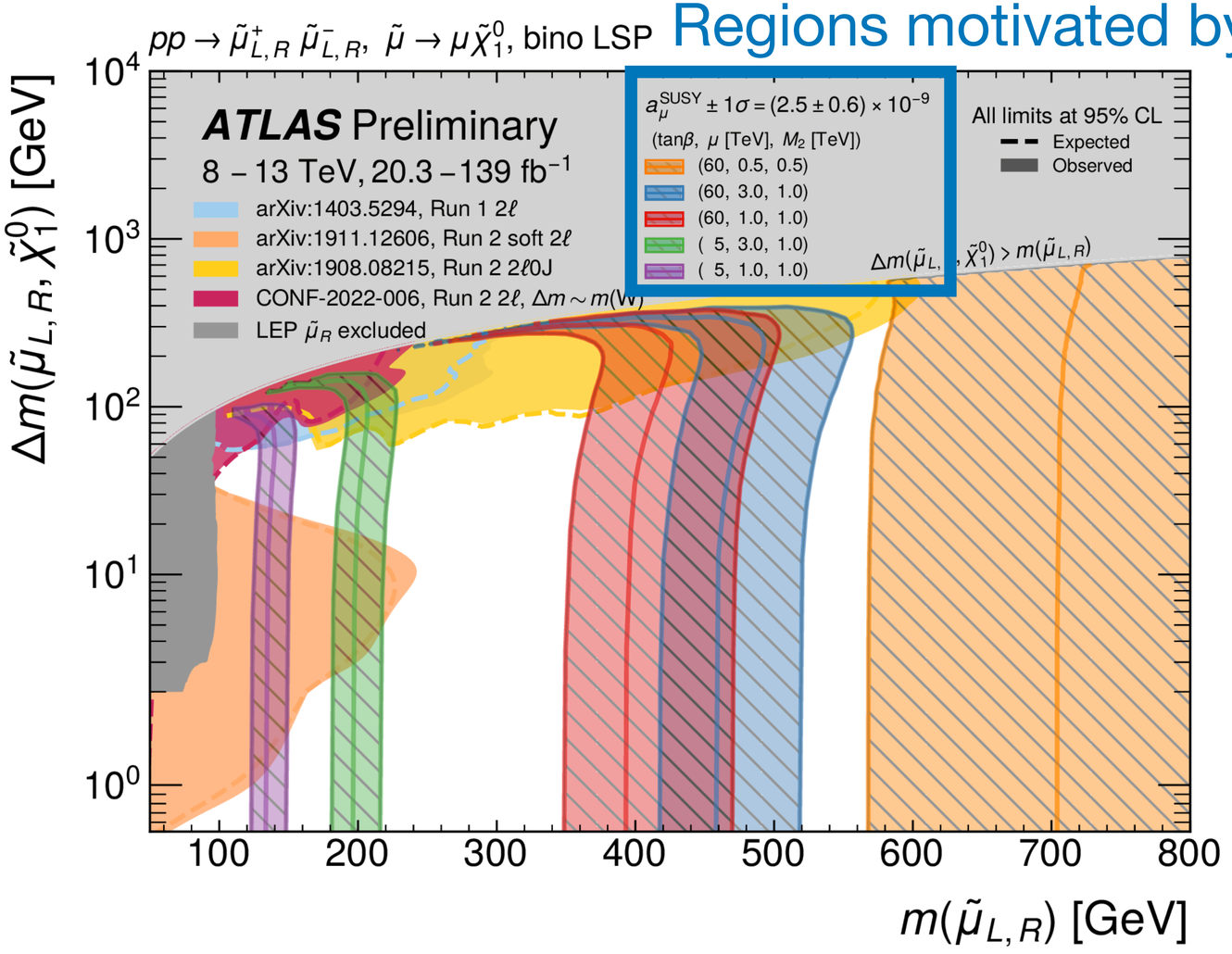




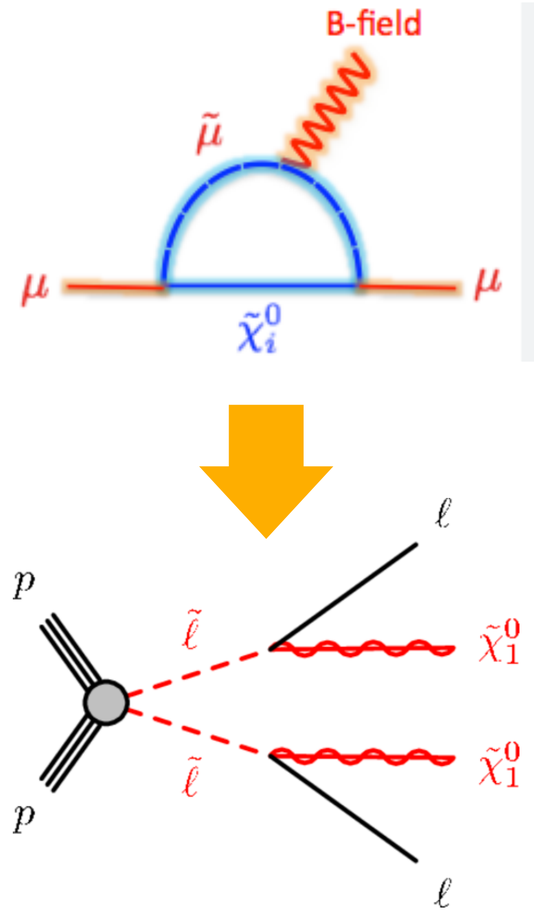


(3) Searches motivated by anomalies

Smuon search current limit



Regions motivated by muon g-2

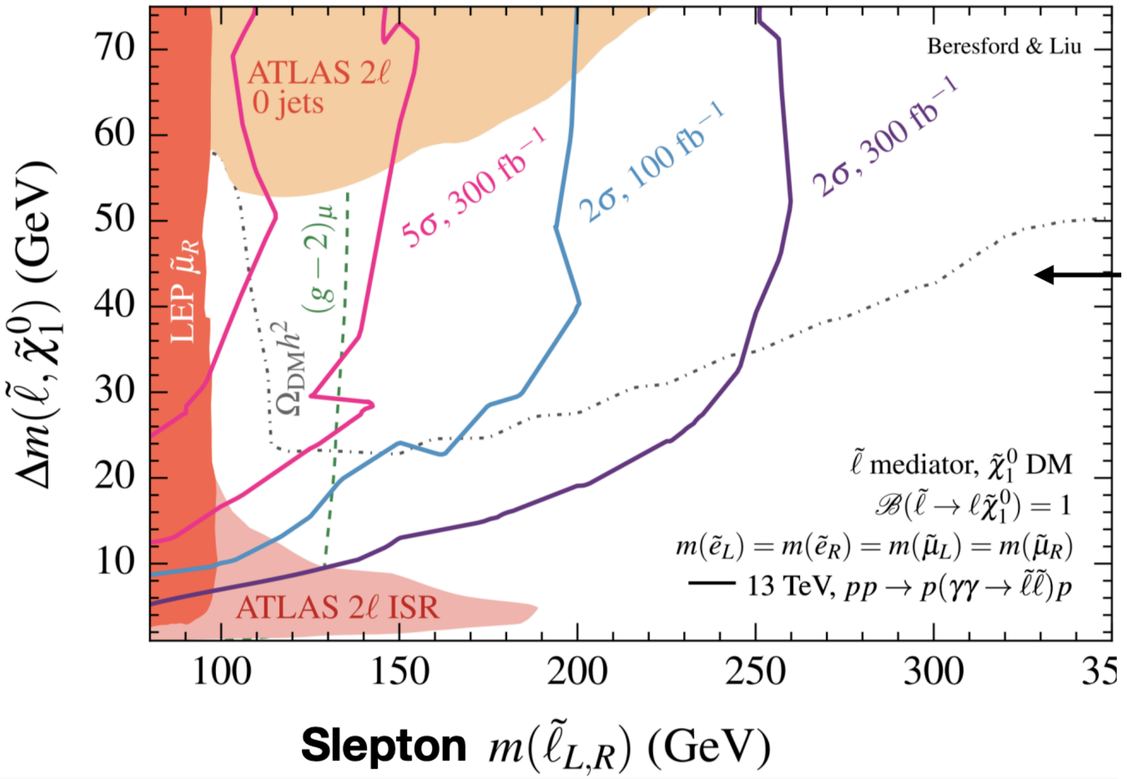


Scalar muon pair decaying to muon and the LSP

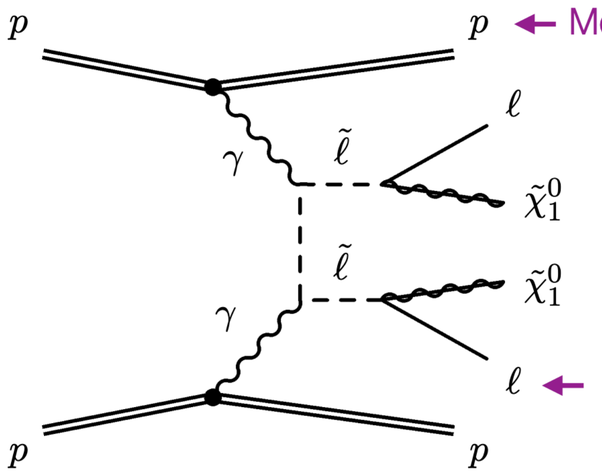
(Idea is to improve the low-pT lepton reconstruction more)

PRL123(2019)141801

LHC as photon-photon collider



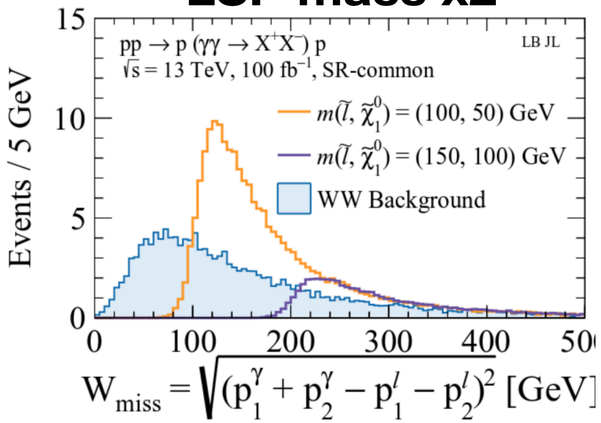
Known proton beam E



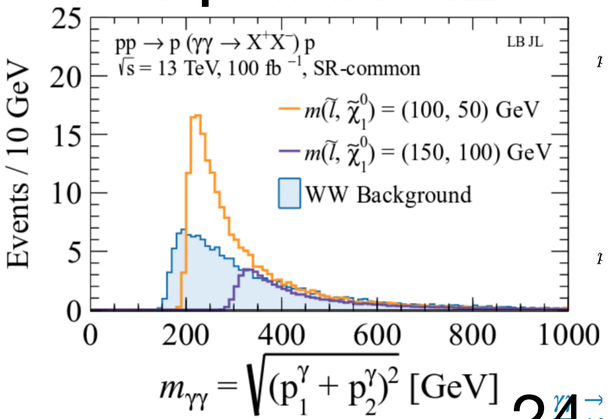
← Measure outgoing proton E with forward detector

← Measure lepton 4-vector with central detector

Missing mass ~ LSP mass x2

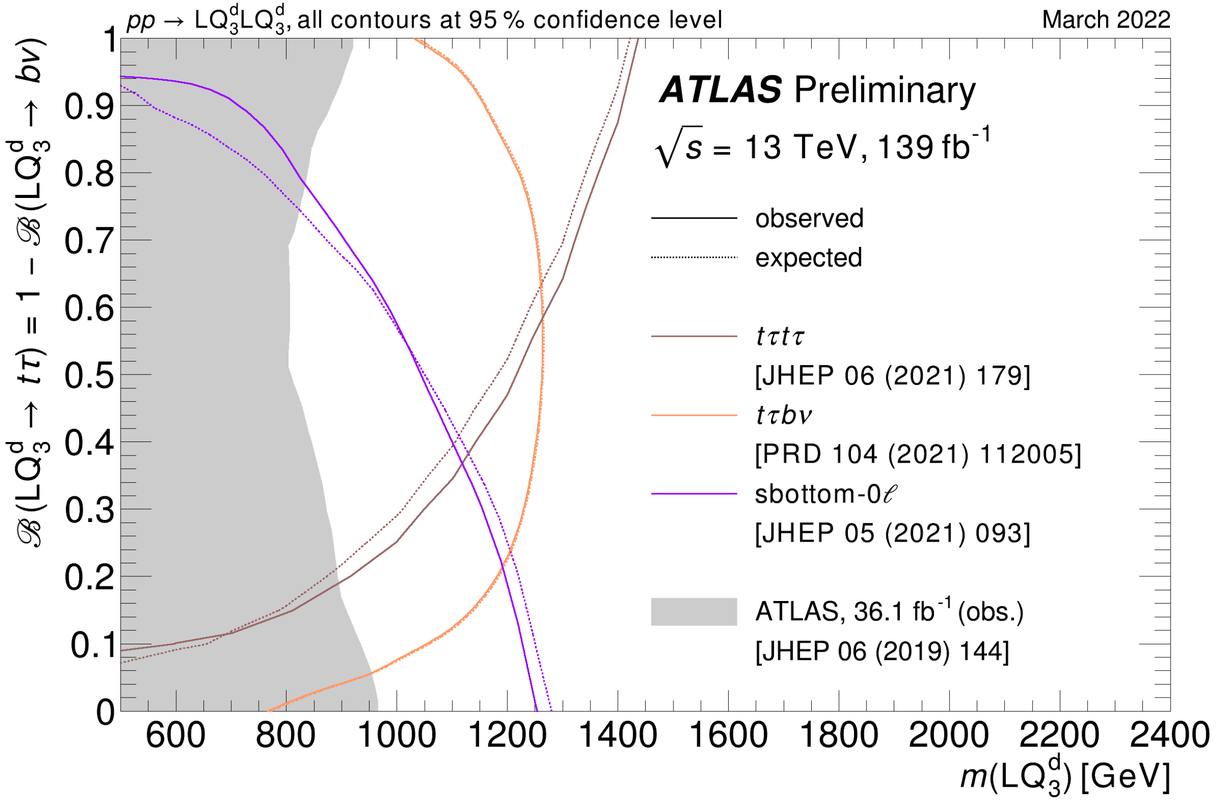


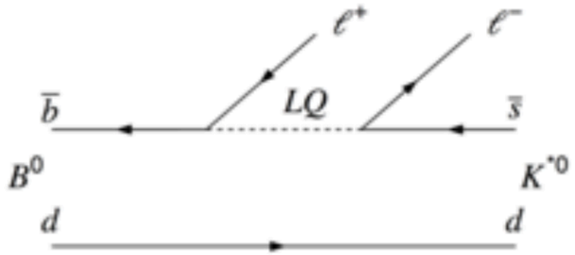
Effective cms energy ~slepton mass x2

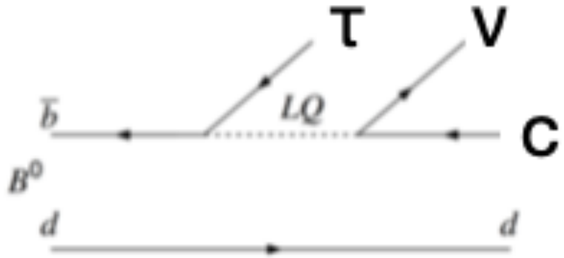


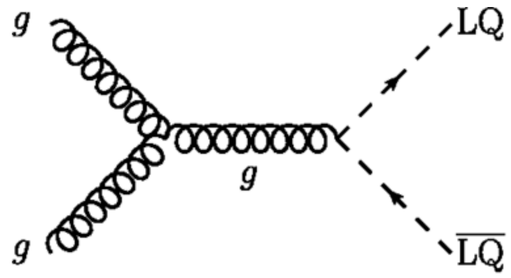
- Challenges:
  - Operation/calibration of the forward proton detector
  - Very large bkg due to diffracted proton
  - Precise timing detector to identify the interaction point to reduce bkg

Leptoquark search





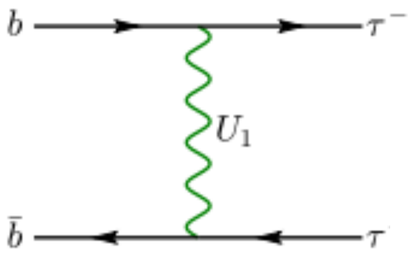




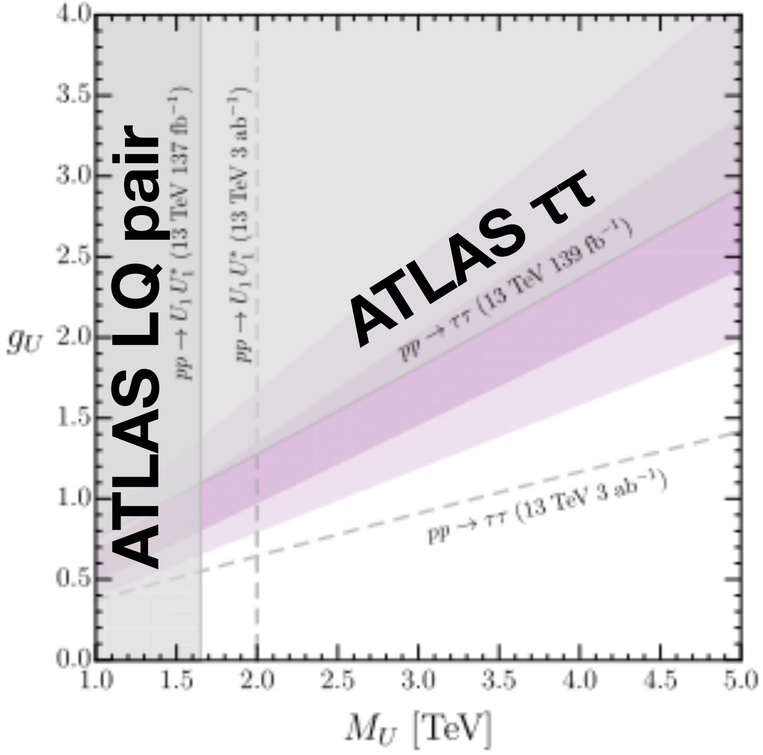
- All possible final states are tested, especially using 3rd gen. particles
- m_{LQ}<~1.4TeV is excluded model independently

$(SU(3)_c, SU(2)_L, Y)$	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
$(\bar{3},1,1/3)$	S_1	✗*	✓	✗*
$(3,2,7/6)$	R_2	✗*	✓	✗
$(3,2,1/6)$	$\widetilde{R_2}$	✗	✗	✗
$(\bar{3},3,1/3)$	S_3	✓	✗	✗
$(3,1,2/3)$	U_1	✓	✓	✓
$(3,3,2/3)$	U_3	✓	✗	✗

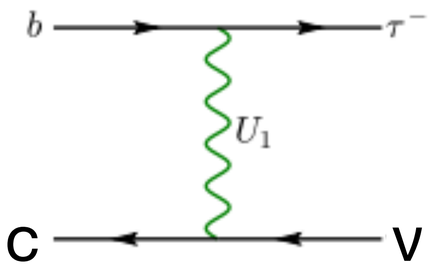
t-channel exchange of LQ



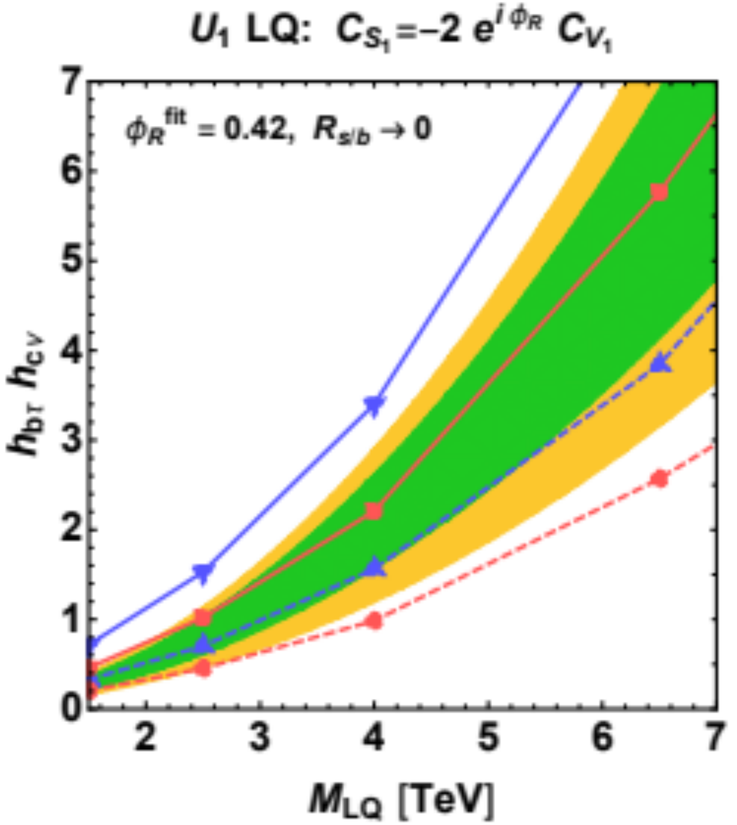
Excess in the tail of $m_{\tau\tau}$



https://arxiv.org/pdf/2103.16558.pdf



Excess in the tail of $m_{T,\tau\nu}$

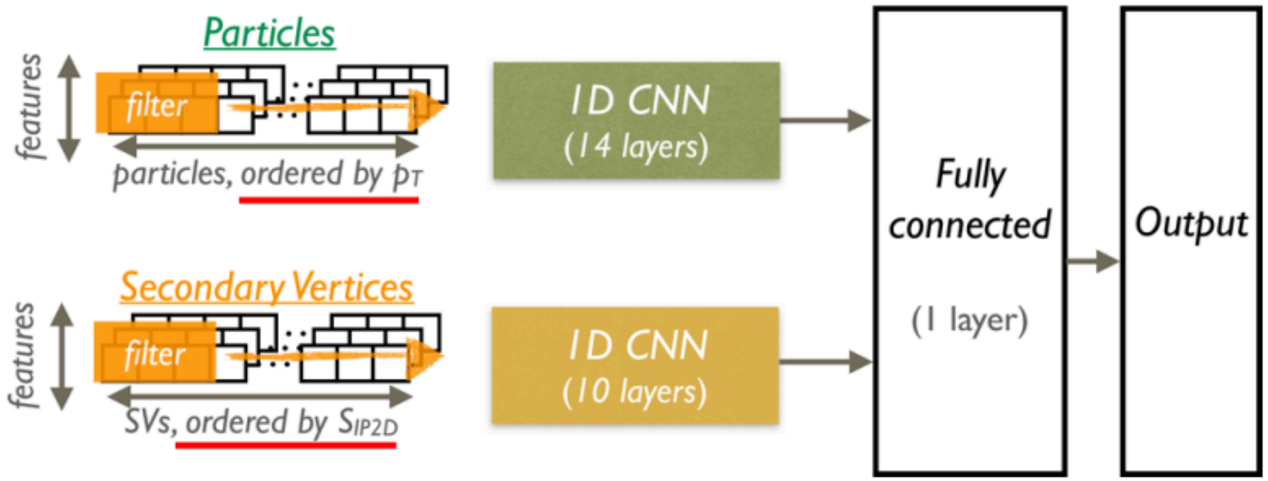


https://arxiv.org/pdf/2111.04748.pdf

Summary

- Let’s say something like this:
  - If there is new physics hidden at the TeV scale, we've got it cornered
  - We must not miss it!
- Strategy in Run3 analysis
  - Keep an eye on 2-3σ excess in Run2
  - Develop new tools to improve the analysis
  - Search for phase spaces/signatures not explored yet
- Of course, increasing the precision of the SM measurements sensitive to NP, e.g. W-boson mass, vector-boson scattering, Higgs couplings, etc.

What are the main improvements?

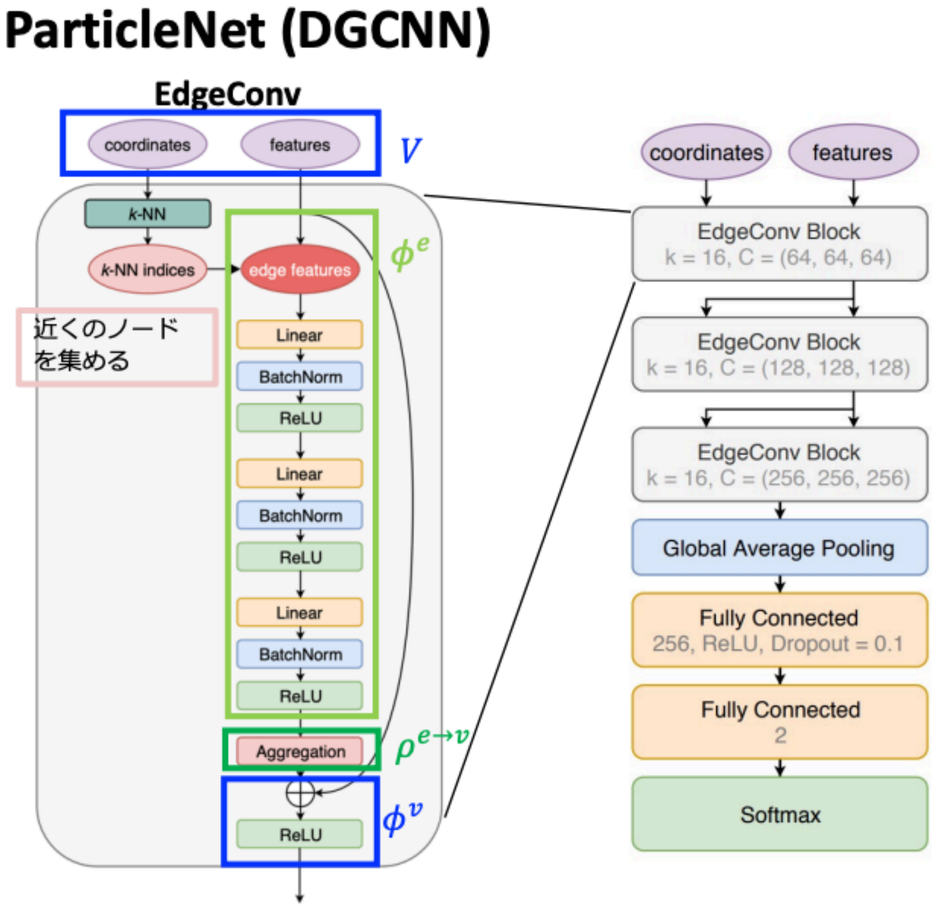


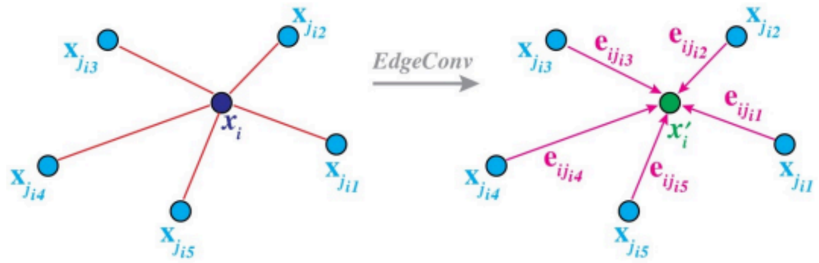
$$x_i' = x_i + NN(x_i, x_{i-1}, x_{i+1}) \quad x_i: \text{粒子の特徴量}$$

- Old “DeepAK” used 1D CNN
- Learn the features of pT-ordered constituents sequentially. Similar to RNN
- In the final step of 1D CNN, substructure and SV info are combined
- Mass decorrelation: tagging results should not depend on the jet mass observable, so that we can validate the performance by using Z→cc

What are the main improvements?

- Looks input variables are not changed (p-flow objects and SVs). No description about how to combine these info





$$x_i' = NN\left(x_i + \sum_{j \in \mathrm{kNN}} \overbrace{NN(x_i, x_j)}^{e_{ij}}\right)$$

2粒子間の特徴量を学習

- Constituents = node
- Correlation between constituents are learned as the edge info

DeepAK15

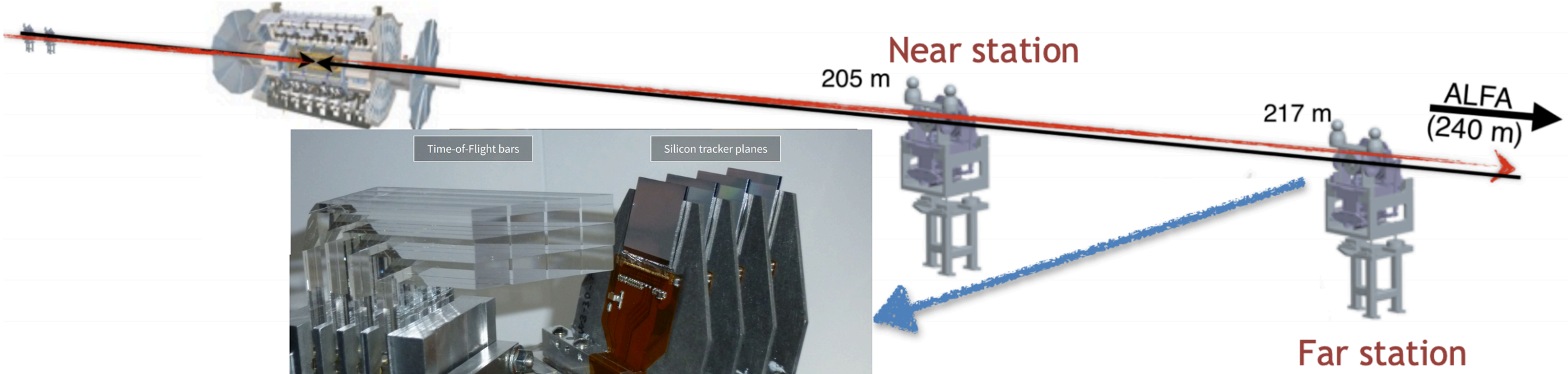
$$x_i' = x_i + NN(x_i, x_{i-1}, x_{i+1})$$

- c.f. DeepAk can learn the correlation between two with closer pT only

- Mass decorrelation method is also updated.

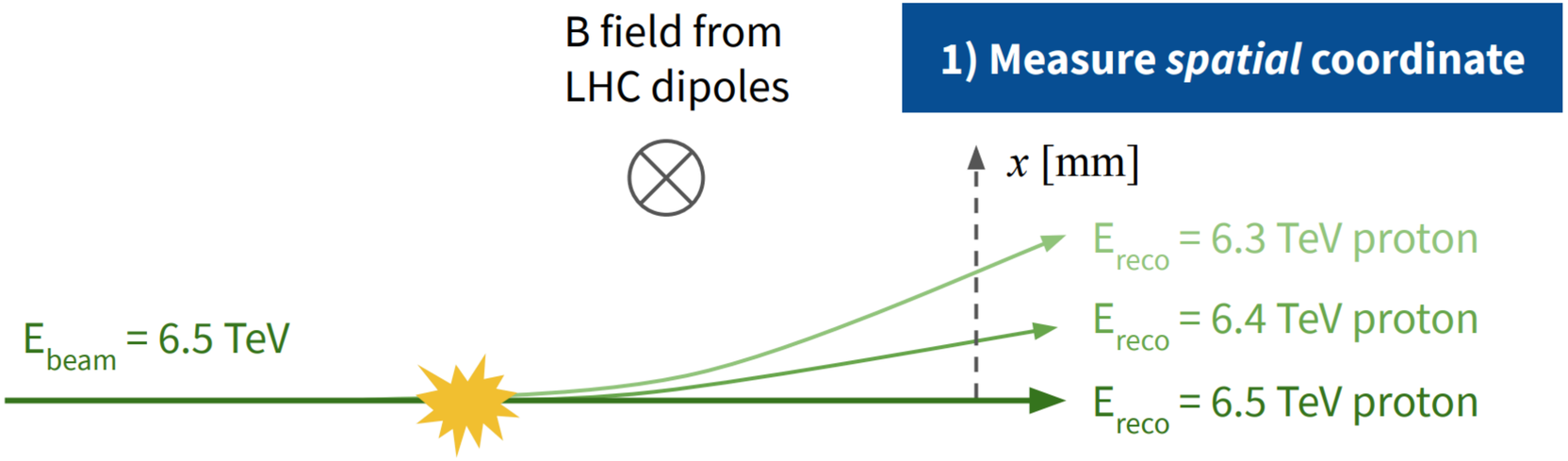
AFP (ATLAS Forward Proton) detector

- Near station: Silicon tracker, track efficiency~100%
- Far station: Silicon tracker(＋ToF from run3), ~96%
- ToF is used to measure the vertex position from the timing difference between A/C sides. Aiming for dt ~ O(10)ps



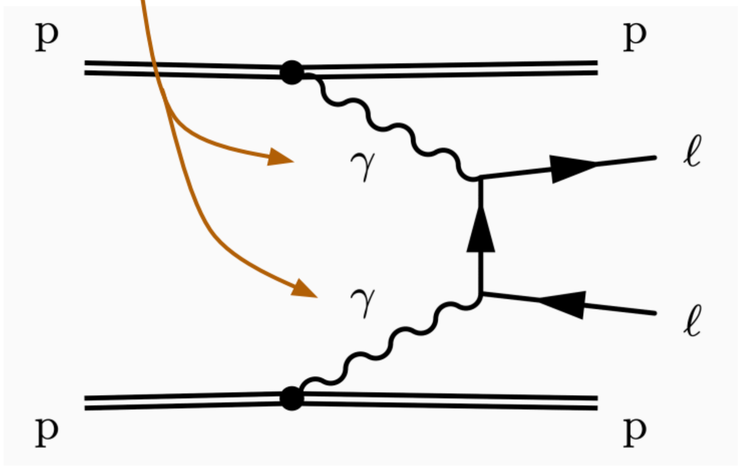
曲率から陽子のエネルギー損失を測定

LHC as photon-photon collider



$$\xi^{A,C}_{AFP} = 1 - E_{reconstructed}/E_{beam}$$

2) Infer *energy* lost by proton



3) Know initial photon energy

Novelty: reconstruct γγ system
without central ATLAS detectors