Outlook

[and partial summary]

Zurich Phenomenology Workshop
The Higgs boson and the Top quark
January 2020

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Rudolf Peierls Centre for
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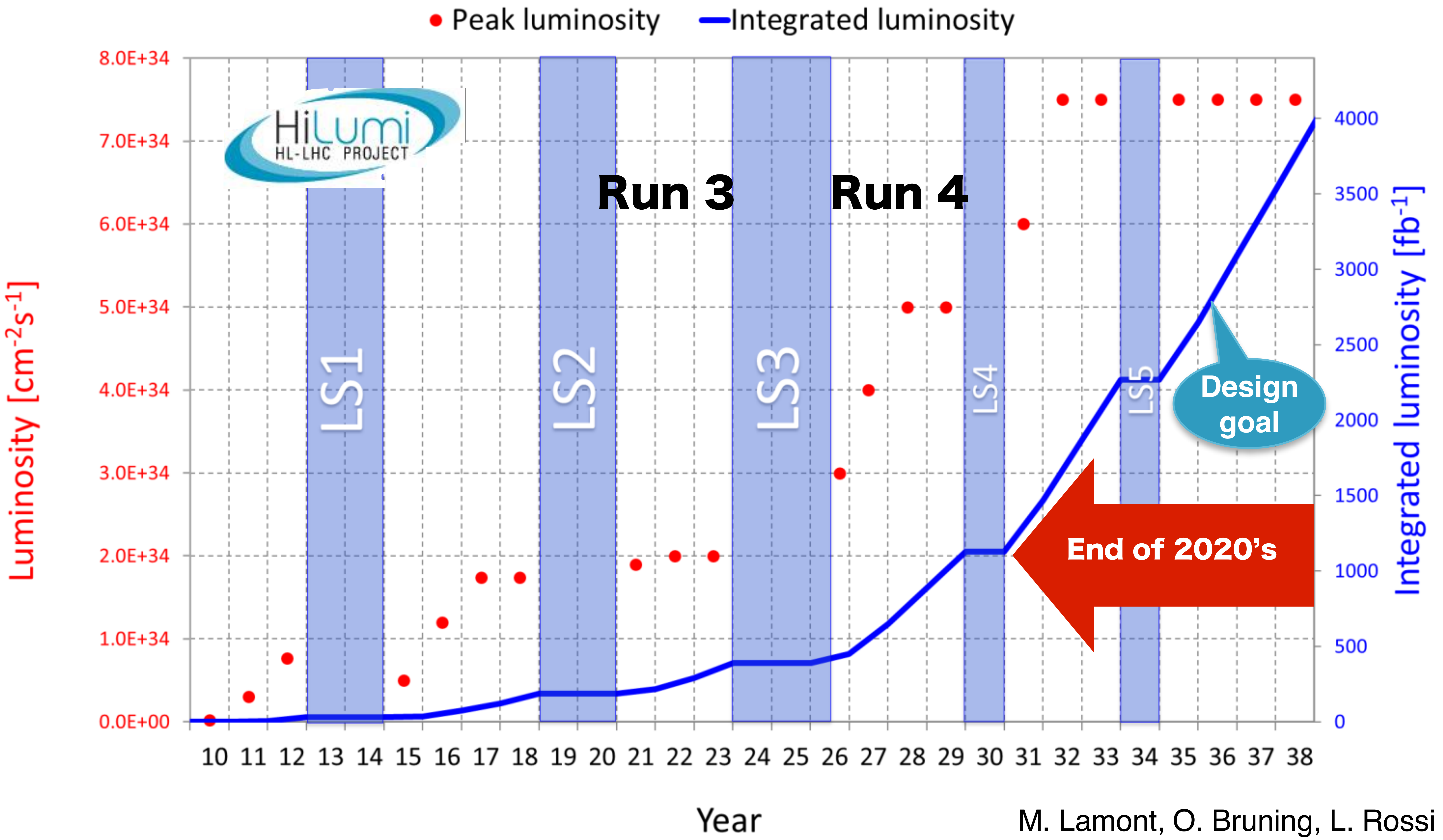
& All Souls College, Oxford
** on leave from CERN and CNRS*

experiments in the 2020s

HL-LHC lumi: 5-7x today's int.lumi by 2030, 20-30x by 2036



M. Lamont, O. Bruning, L. Rossi

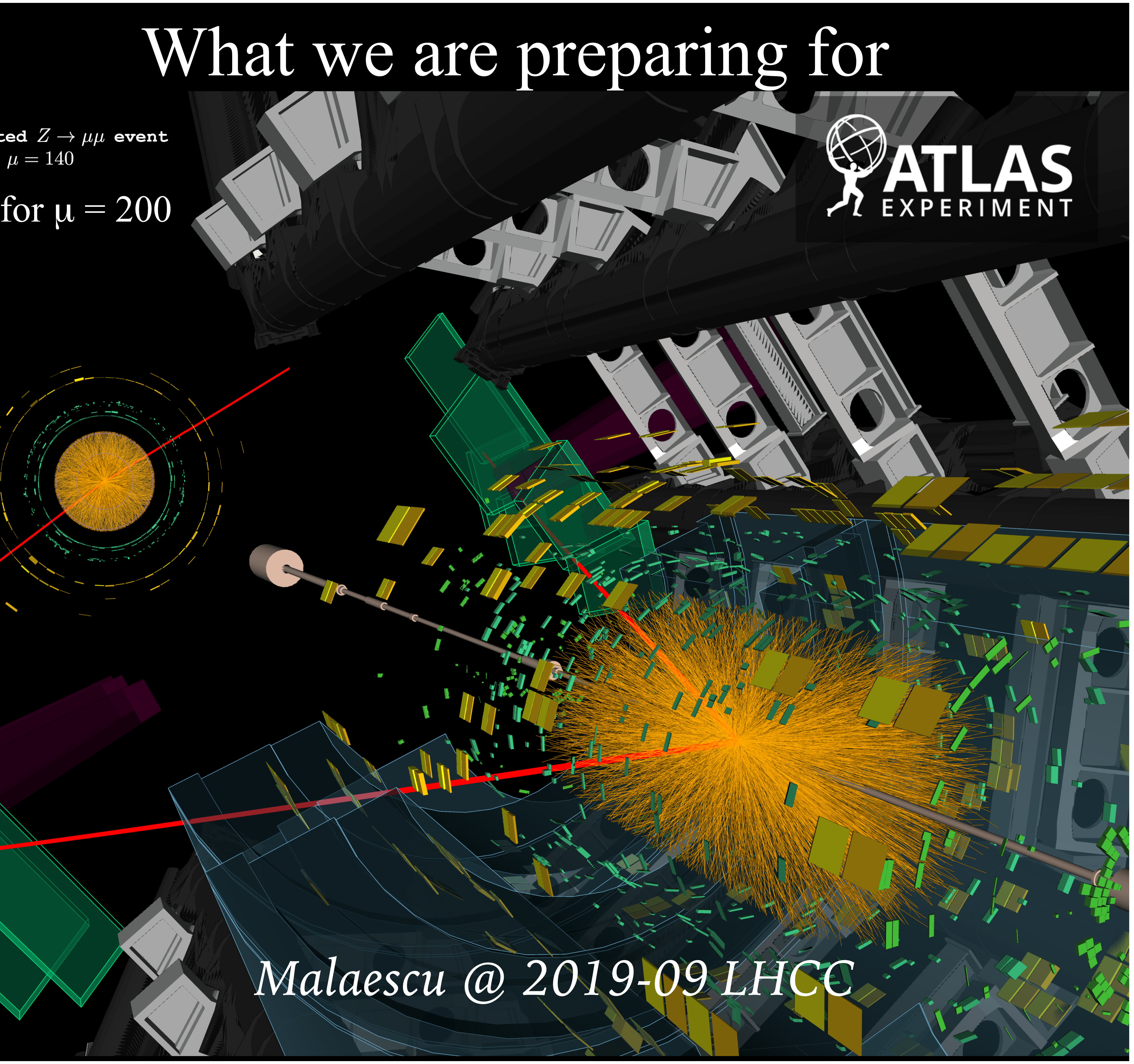
ATLAS and CMS

Run 3	Run4	HL-LHC total
300 fb^{-1}	1 ab^{-1}	3 – 4 ab^{-1}

LHCb

Run 3	Run4	HL-LHC total
23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

huge experimental advances

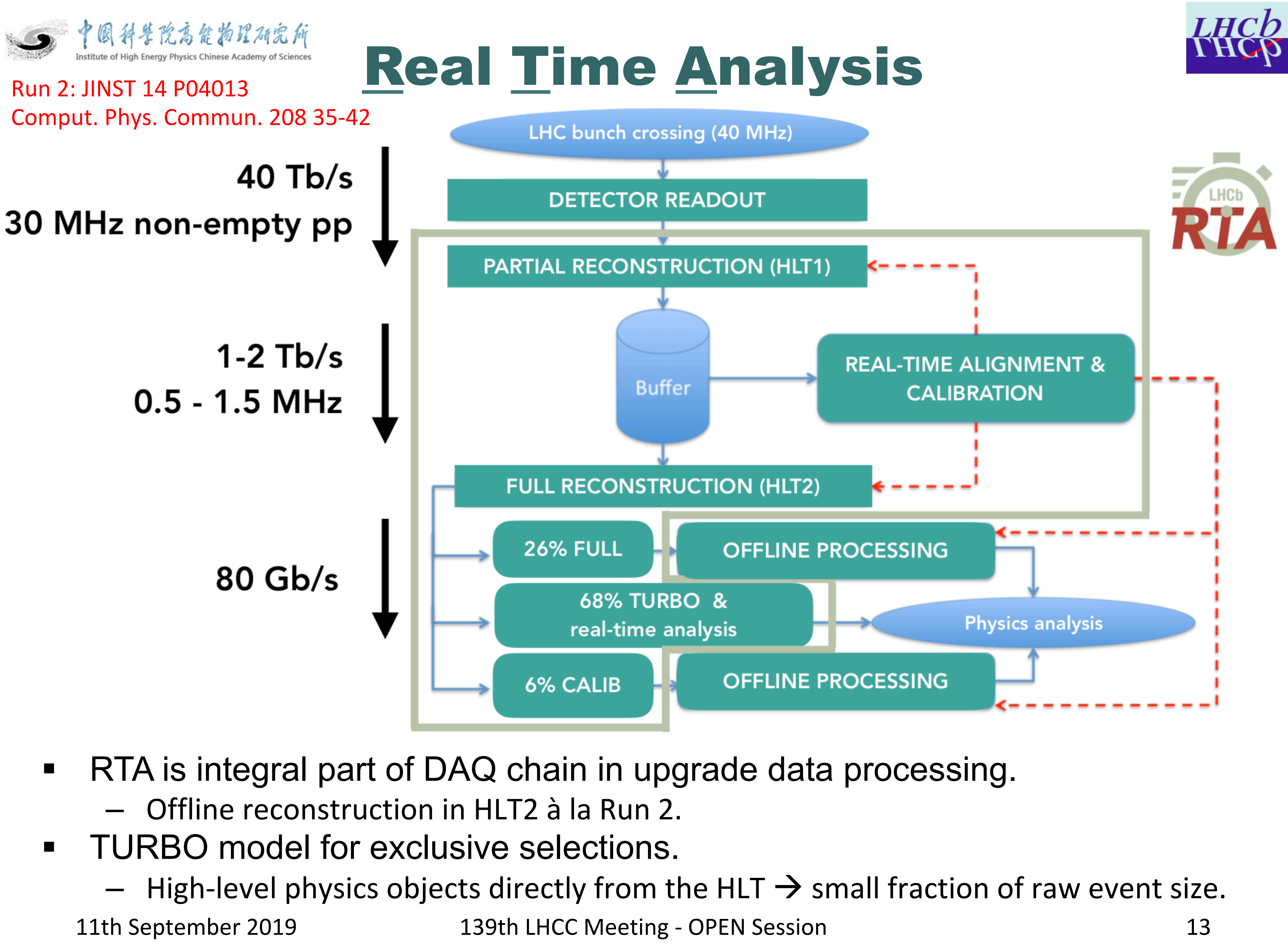


What we are preparing for

ced $Z \to \mu\mu$ event
$\mu = 140$

for $\mu = 200$

Malaescu @ 2019-09 LHCC



Run 2: JINST 14 P04013
Comput. Phys. Commun. 208 35-42

Real Time Analysis

40 Tb/s
30 MHz non-empty pp

1-2 Tb/s
0.5 - 1.5 MHz

80 Gb/s

LHC bunch crossing (40 MHz)

DETECTOR READOUT

PARTIAL RECONSTRUCTION (HLT1)

Buffer

REAL-TIME ALIGNMENT & CALIBRATION

FULL RECONSTRUCTION (HLT2)

26% FULL

68% TURBO & real-time analysis

6% CALIB

OFFLINE PROCESSING

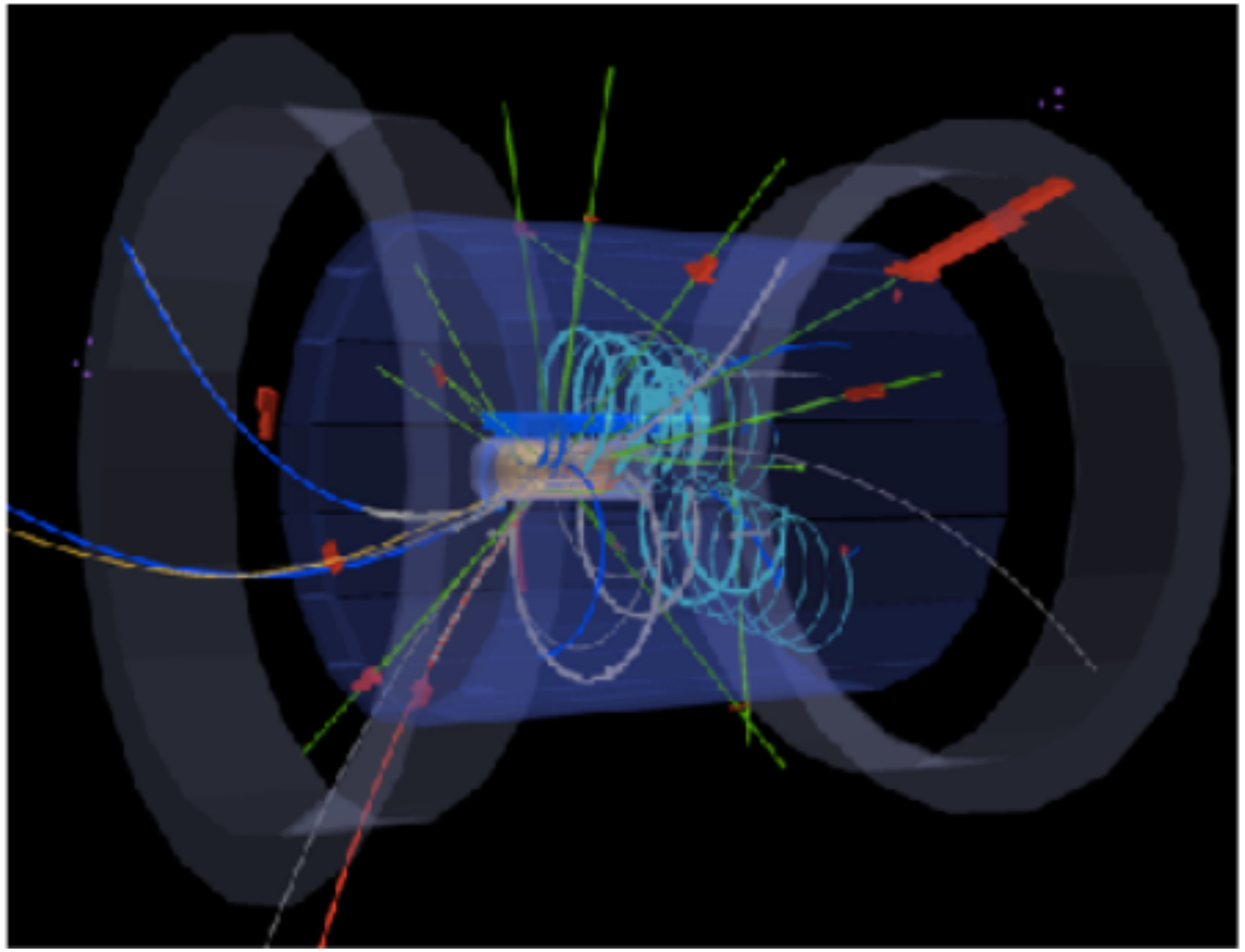
Physics analysis

OFFLINE PROCESSING

- RTA is integral part of DAQ chain in upgrade data processing.
  - Offline reconstruction in HLT2 à la Run 2.
- TURBO model for exclusive selections.
  - High-level physics objects directly from the HLT → small fraction of raw event size.

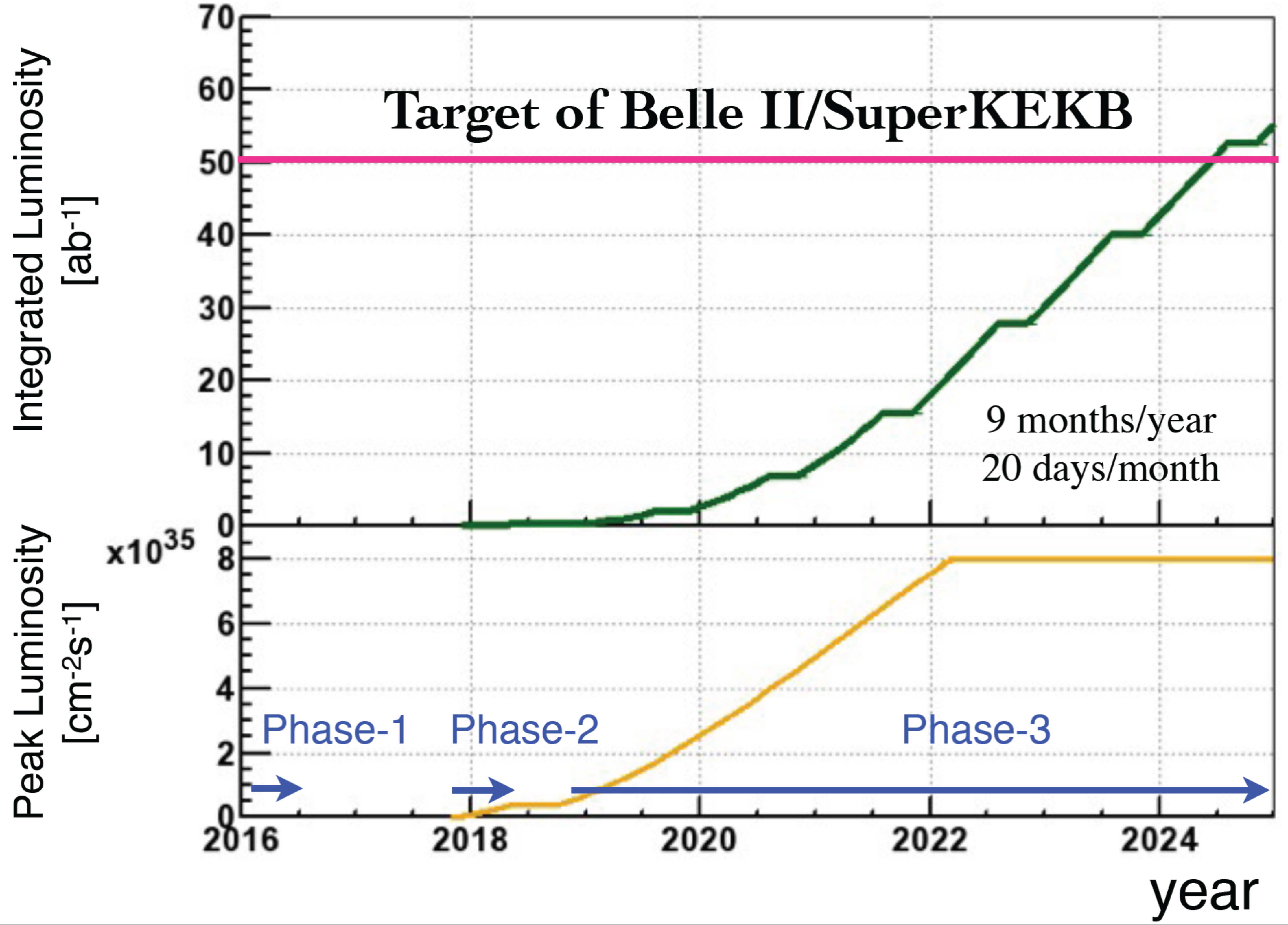
11th September 2019 139th LHCC Meeting - OPEN Session 13

Belle II: 40-50x increase relative to Belle



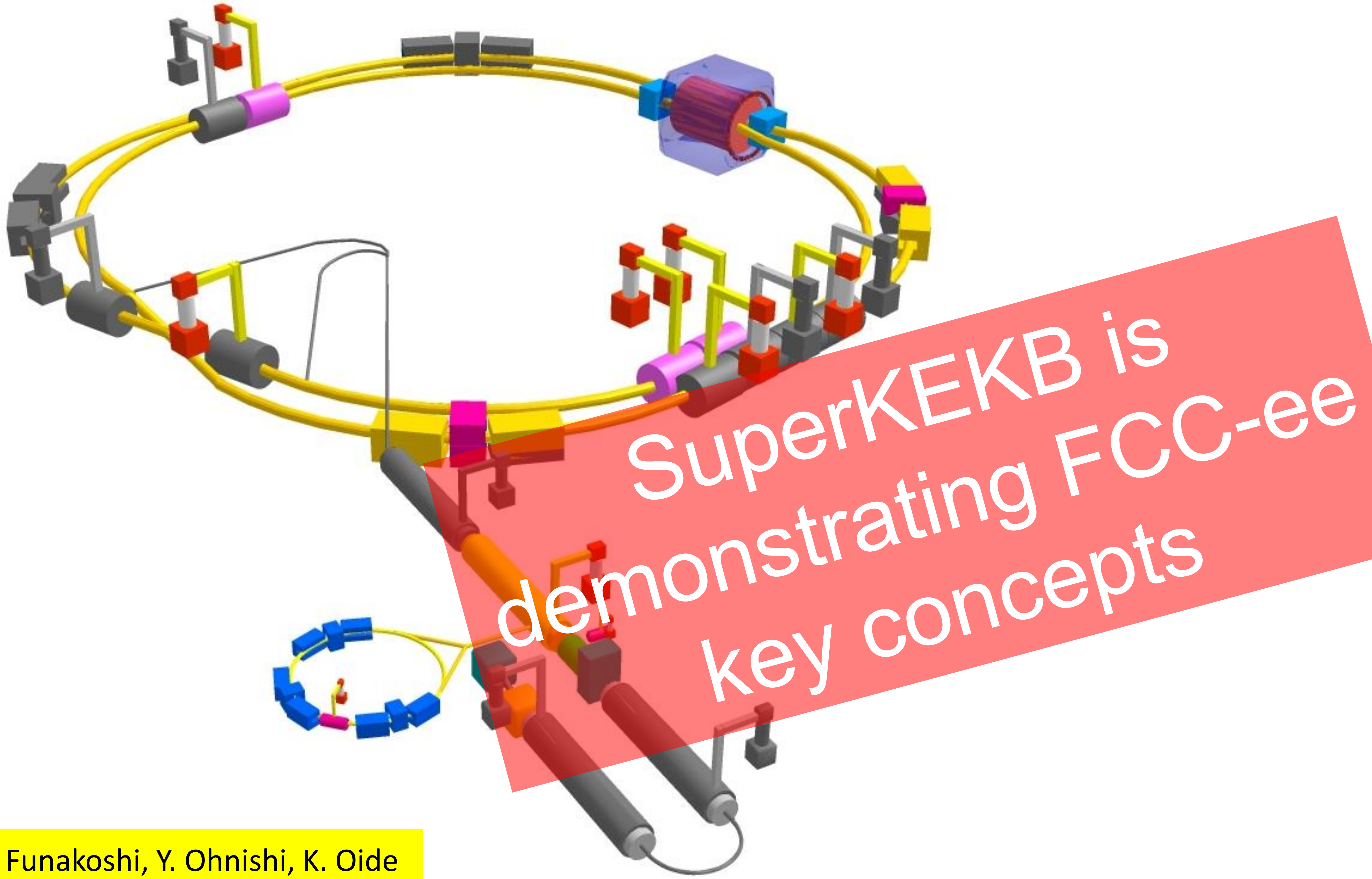
Zupanc (2017)

SuperKEKB luminosity projection



SuperKEKB – pushing luminosity and β*

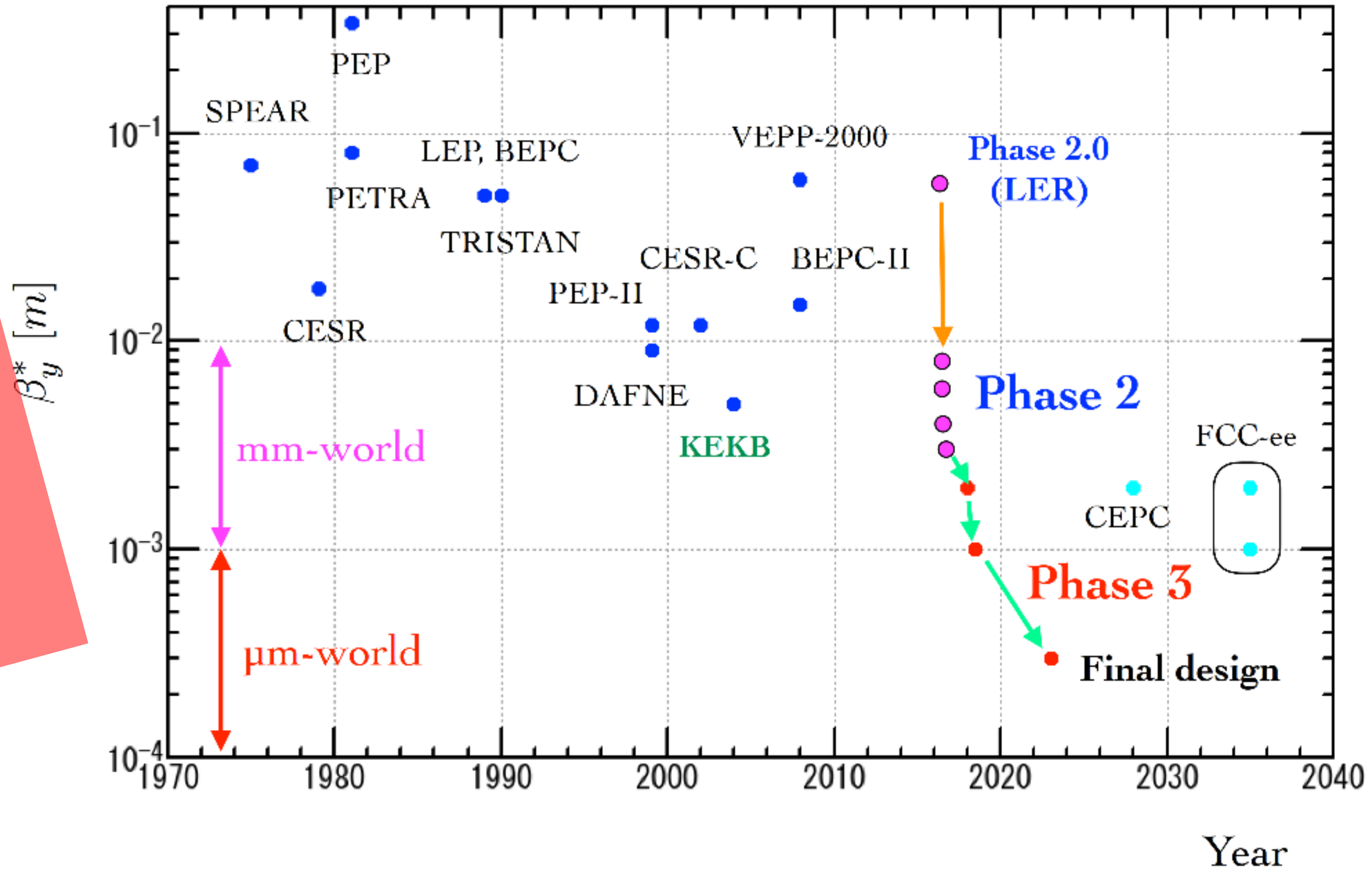
double ring e^+e^- collider as *B*-factory at 7(e^-) & 4(e^+) GeV; **design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$**; **$\beta_y^* \sim 0.3$ mm; nano-beam – large crossing angle** collision scheme **(crab waist w/o sextupoles)**; **beam lifetime ~5 minutes**; **top-up** injection; **e^+ rate up to ~ 2.5 10^{12} /s** ; **under commissioning**



SuperKEKB is demonstrating FCC-ee key concepts

Y. Funakoshi, Y. Ohnishi, K. Oide

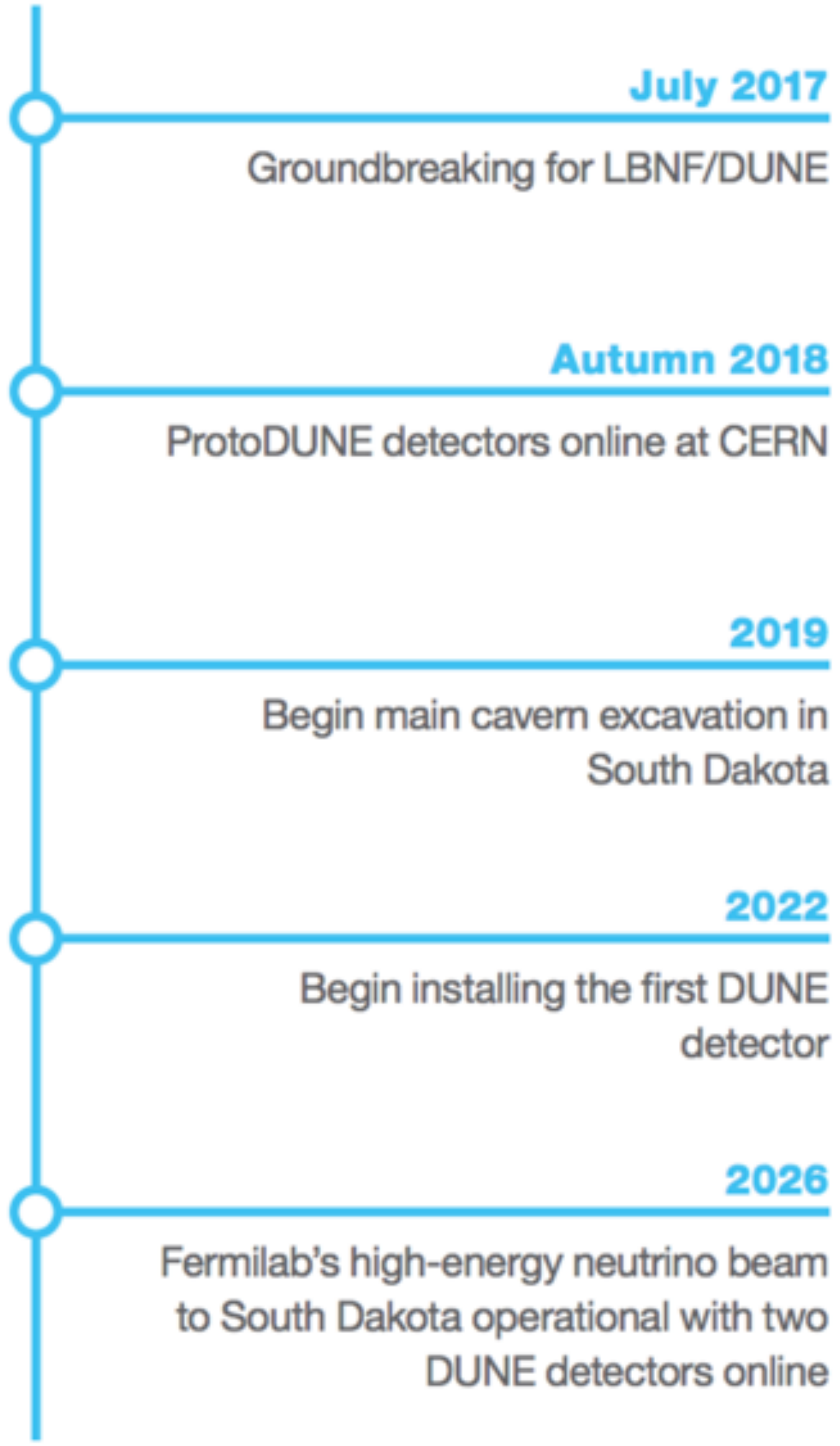
Strategy of beta squeezing for Phase 2 and Phase 3



β_y^* ≤2 mm achieved!

Nova + T2K running; DUNE & Hyper-K starting ~2027

DUNE



July 2017
Groundbreaking for LBNF/DUNE

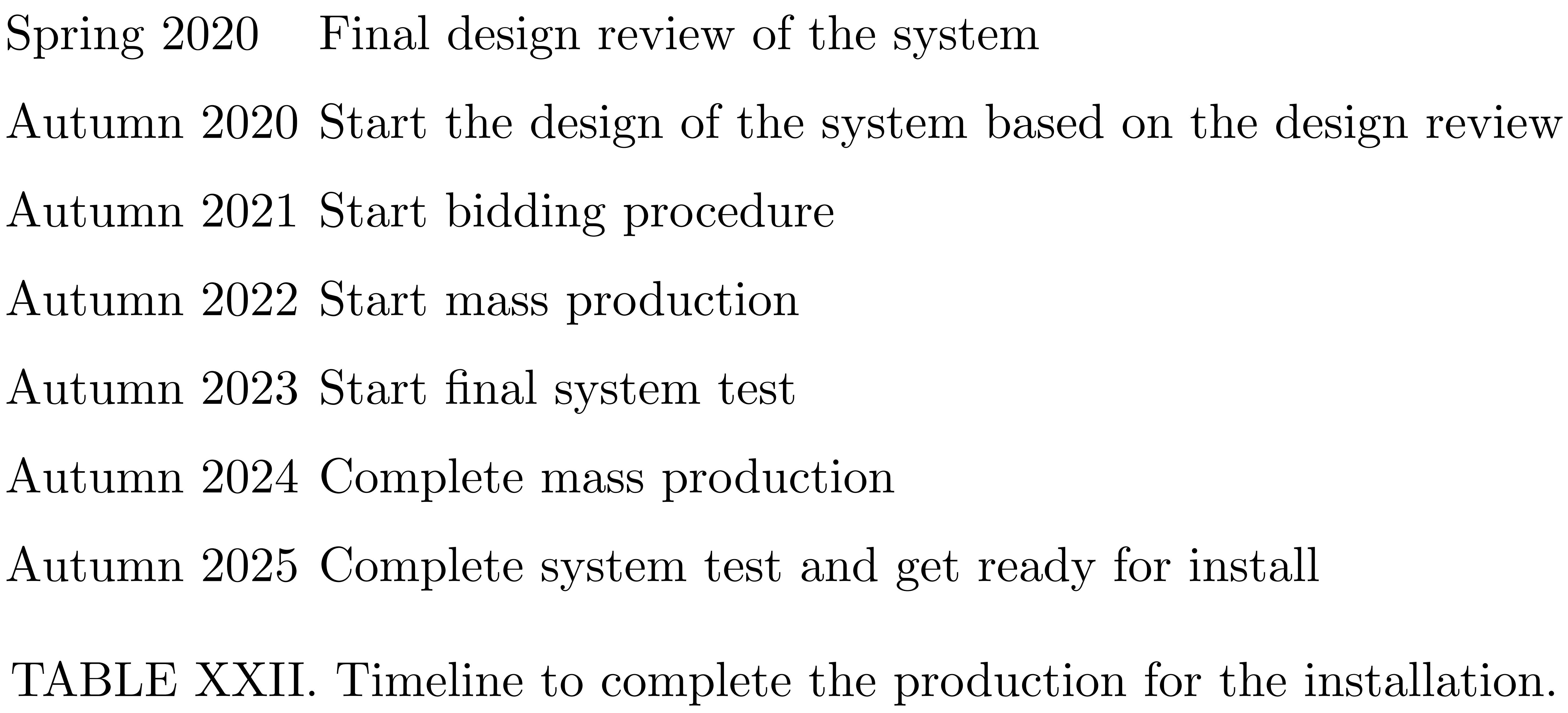
Autumn 2018
ProtoDUNE detectors online at CERN

2019
Begin main cavern excavation in South Dakota

2022
Begin installing the first DUNE detector

2026
Fermilab's high-energy neutrino beam to South Dakota operational with two DUNE detectors online

HYPER-K



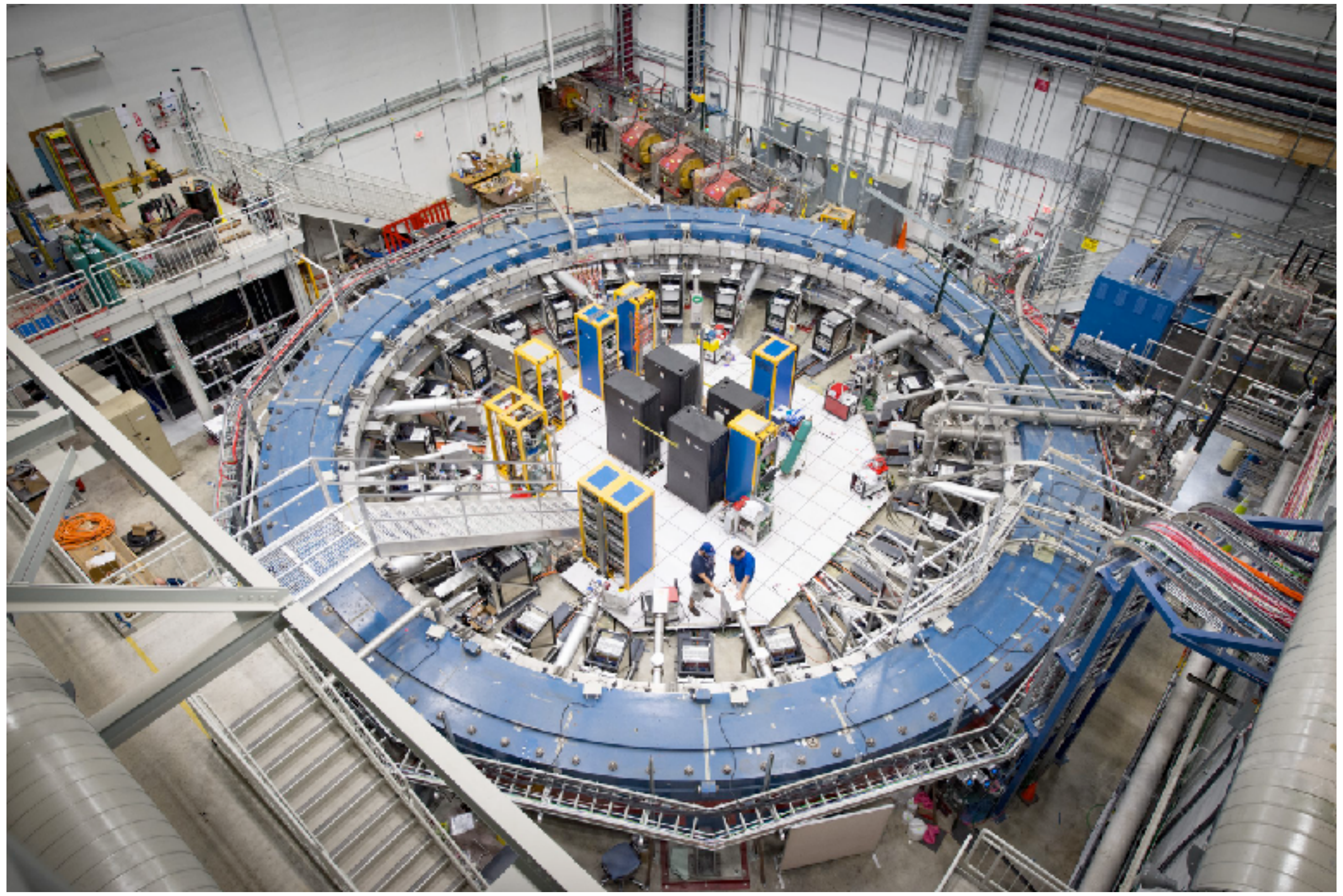
Spring 2020	Final design review of the system
Autumn 2020	Start the design of the system based on the design review
Autumn 2021	Start bidding procedure
Autumn 2022	Start mass production
Autumn 2023	Start final system test
Autumn 2024	Complete mass production
Autumn 2025	Complete system test and get ready for install

TABLE XXII. Timeline to complete the production for the installation.

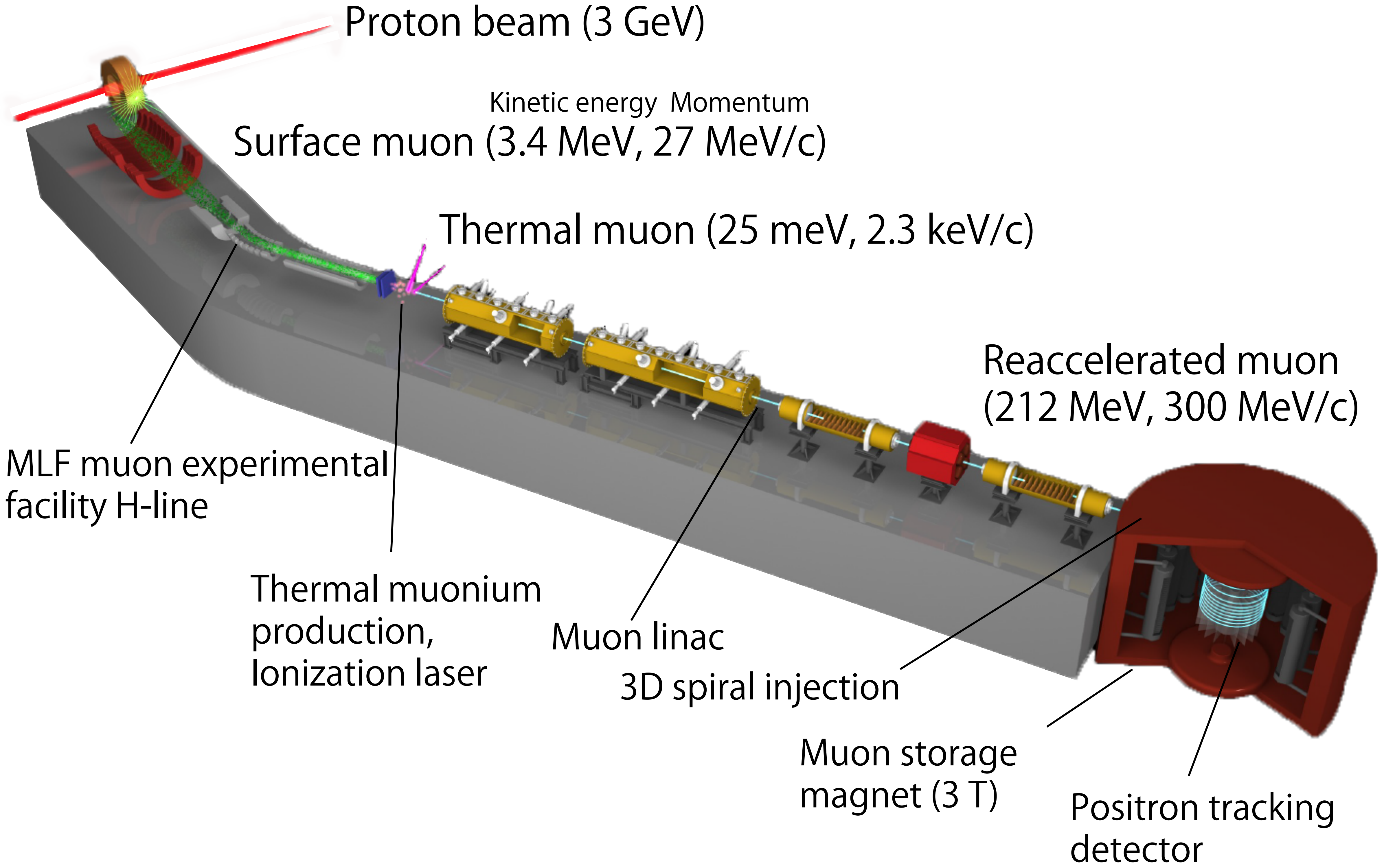
muon g-2: Fermilab running for the next few years; also J-PARC

$a_\mu(\mathrm{SM})=(11659182.3\pm0.1\pm3.4\pm2.6)\times10^{-10}$, $a_\mu(\mathrm{exp})=(11659209.1\pm5.4\pm3.3)\times10^{-10}$

$$\Delta a_\mu \equiv a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM}) = (26.8 \pm 7.6) \times 10^{-10}$$



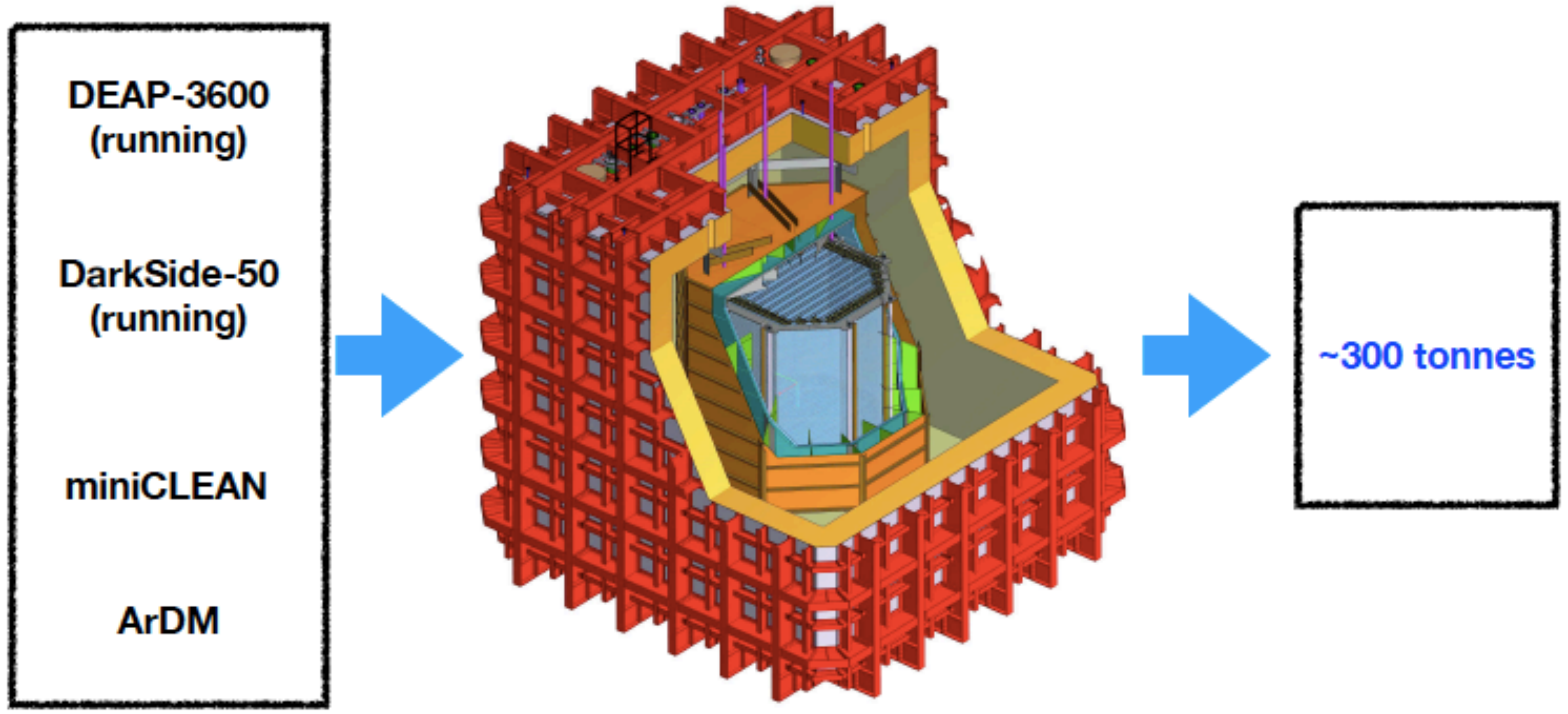
Fermilab: has already surpassed BNL data (1st results to come soon?)



J-PARC: independent systematics, moving from R&D to construction

direct detection dark matter experiments

Global Argon Dark Matter Collaboration



DEAP-3600 (running)

DarkSide-50 (running)

miniCLEAN

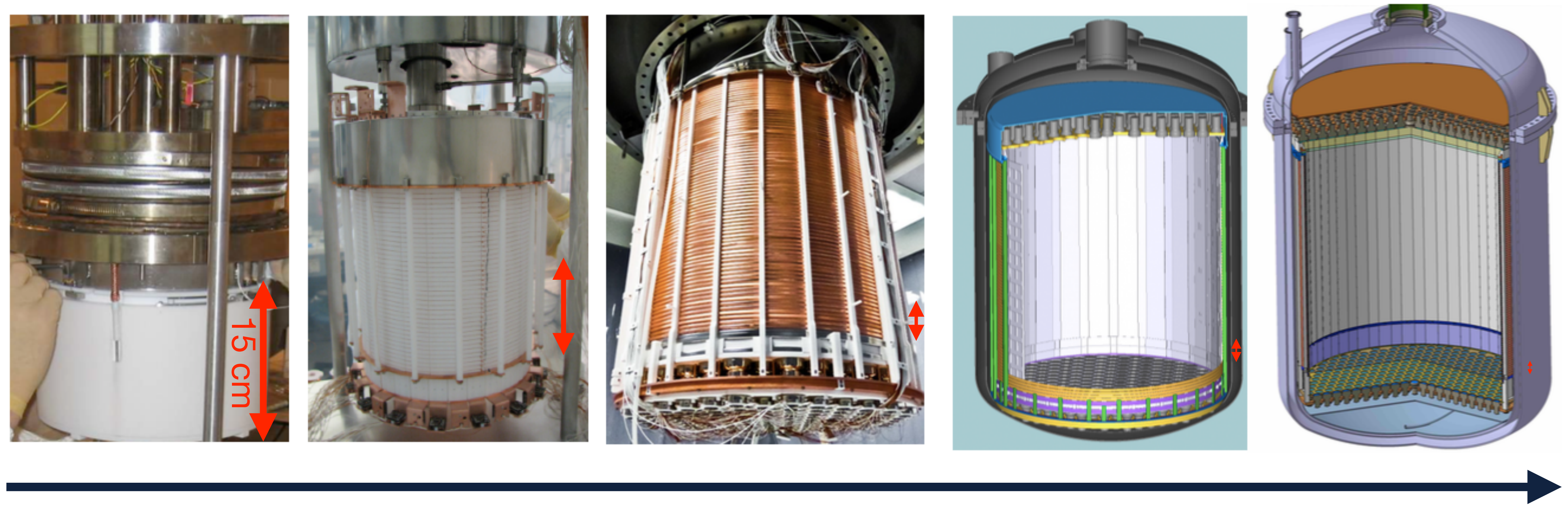
ArDM

~300 tonnes

DarkSide-20k
2022~

ARGO
2029~

Slide credit: Y. Wang



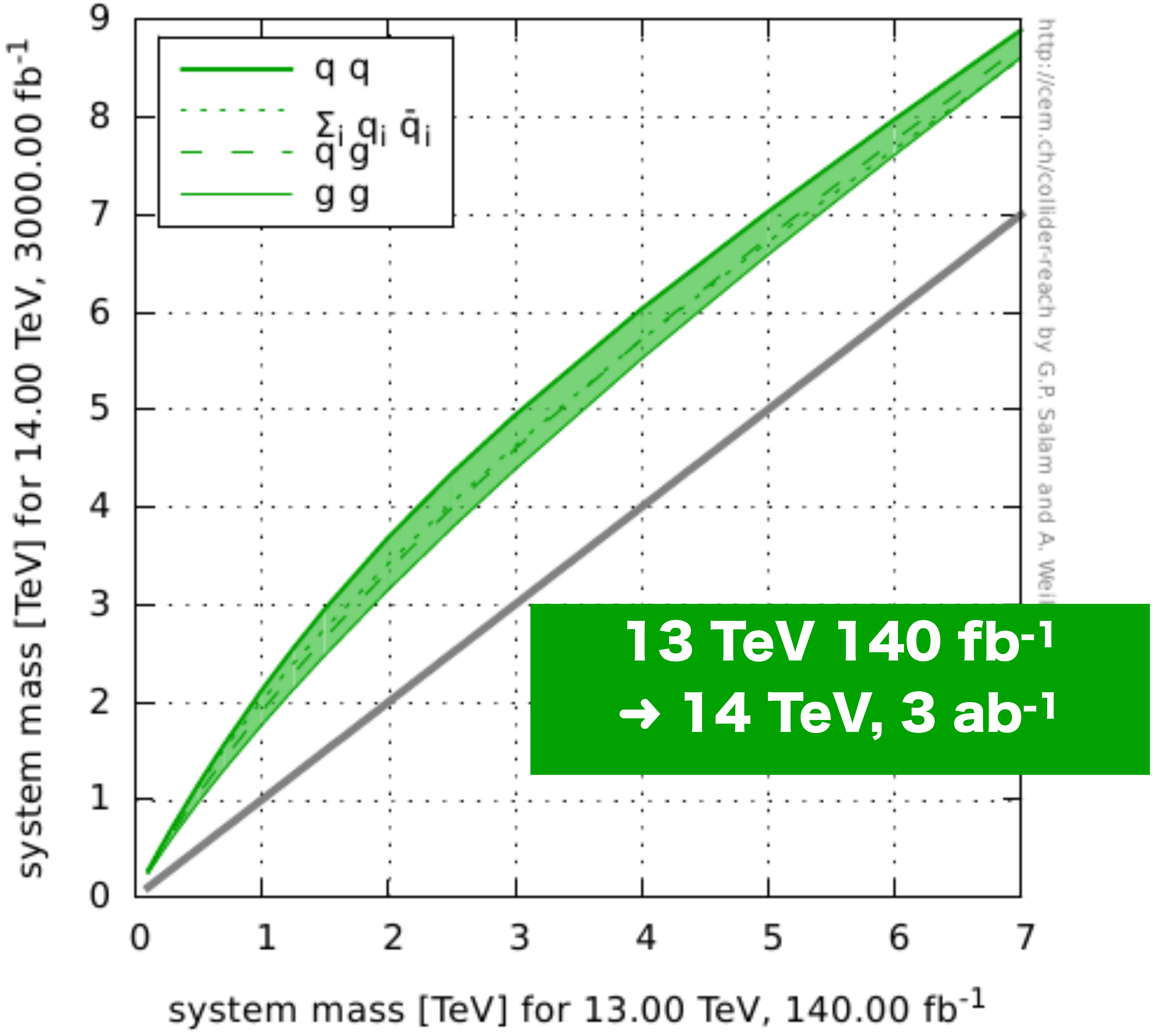
XENON10	**XENON100**	**XENON1T**	**XENONnT**	**DARWIN**
2005 – 2007	2008 – 2016	2012 – 2018	2019 – 2023	2025 –
~15 kg	~62 kg	~2 t	~5.9 t	40 t
15 cm	30 cm	1 m	1.5 m	2.6 m
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

many ongoing & medium and small experiments

- NA61
- NA62
- NA64
- Compass
- HPS
- SeaQuest
- KATRIN
- …

direct new-particle searches

LHC direct search prospects



13 TeV 140 fb^{-1}
→ 14 TeV, 3 ab^{-1}

- Roughly 1.5 – 2 TeV increase in mass reach
- Proportionally more significant for searches at lower end of mass scale

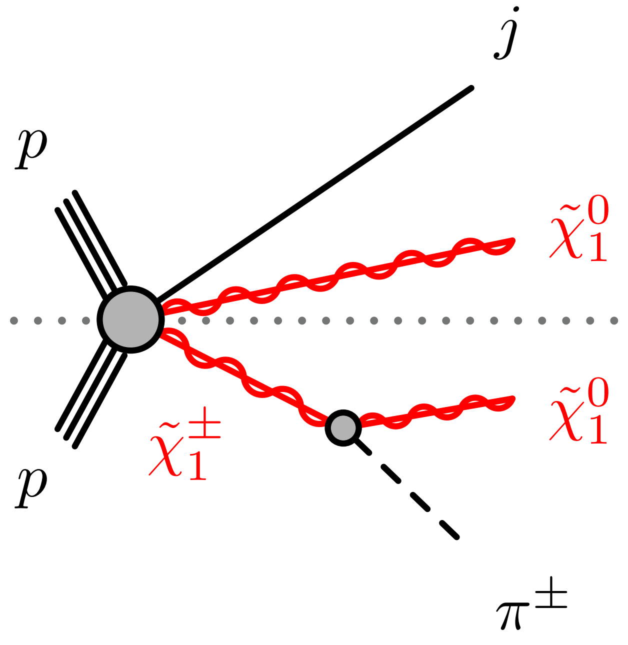
long-term pp(bar) view: phases of fast, then slow energy frontier increase are normal

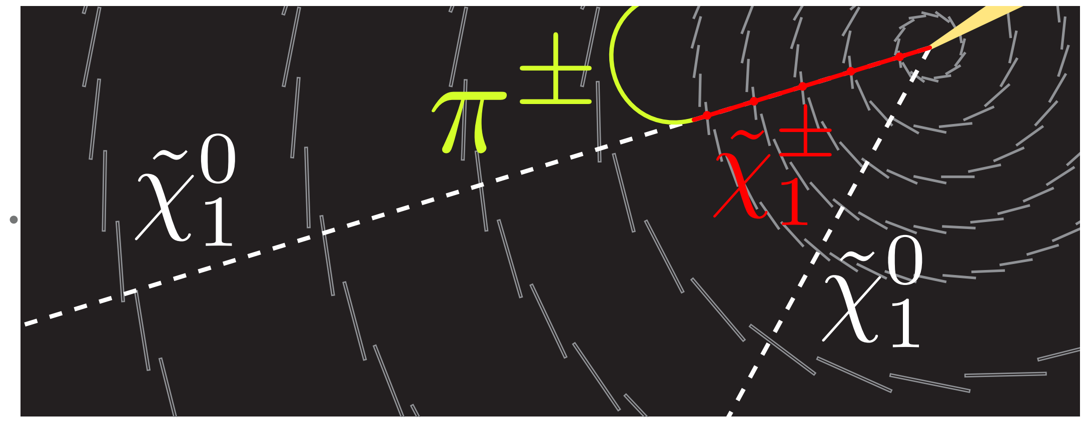
GPS + AW 2019 (with http://cern.ch/collider-reach)

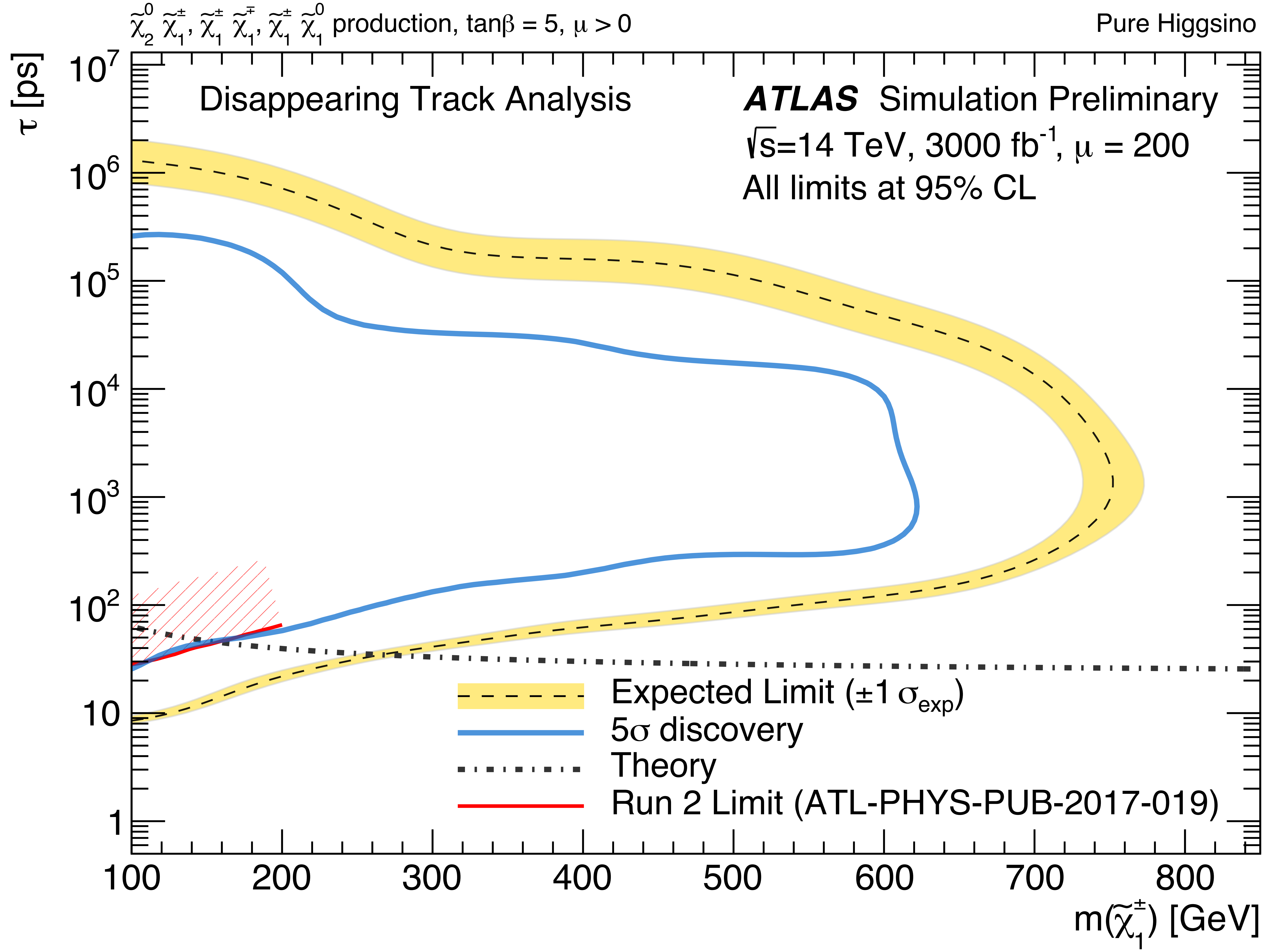
long-term pp(bar) view: phases of fast, then slow energy frontier increase are normal

average increase in reach roughly × 2 / decade

disappearing track analyses

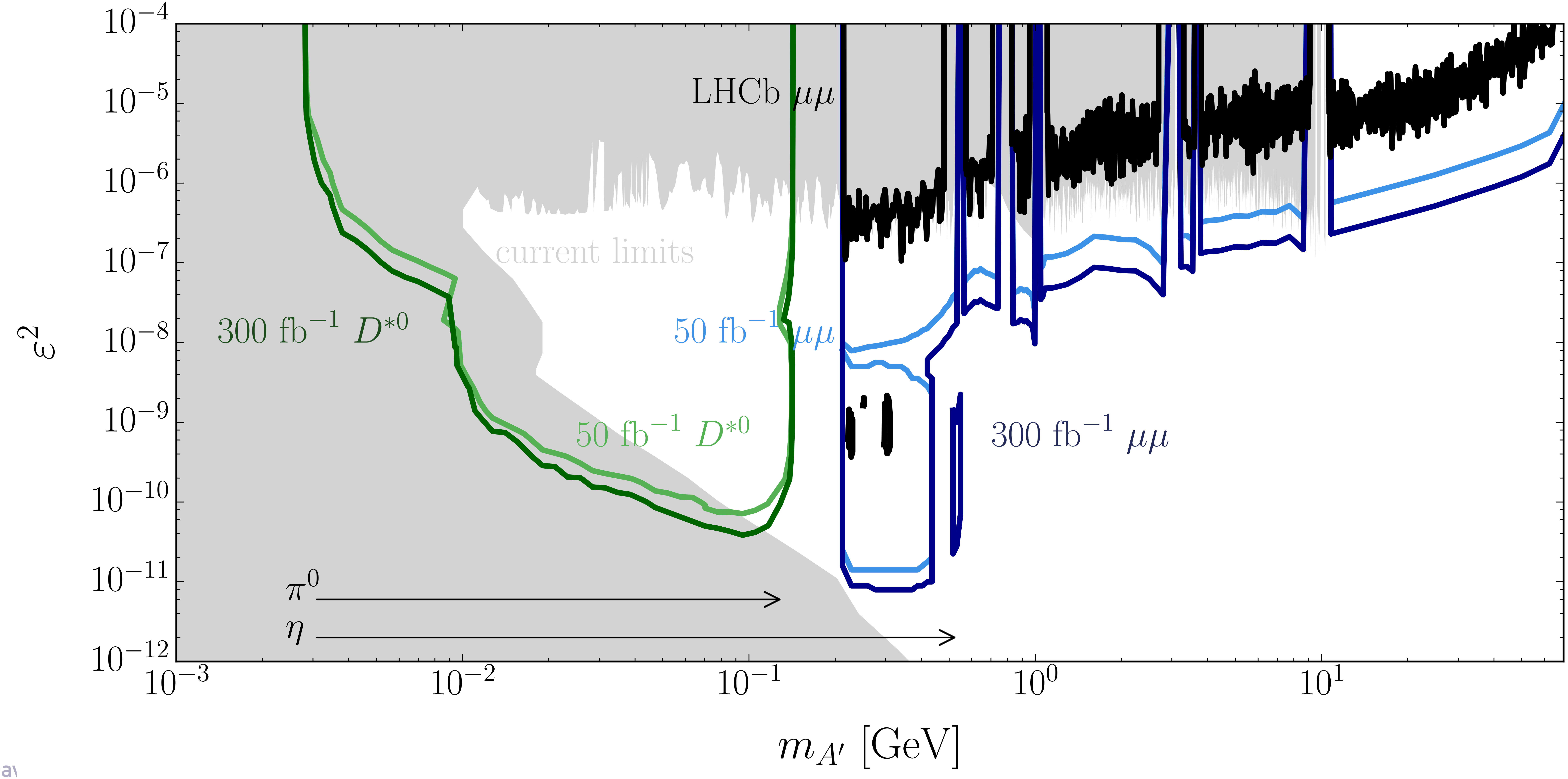




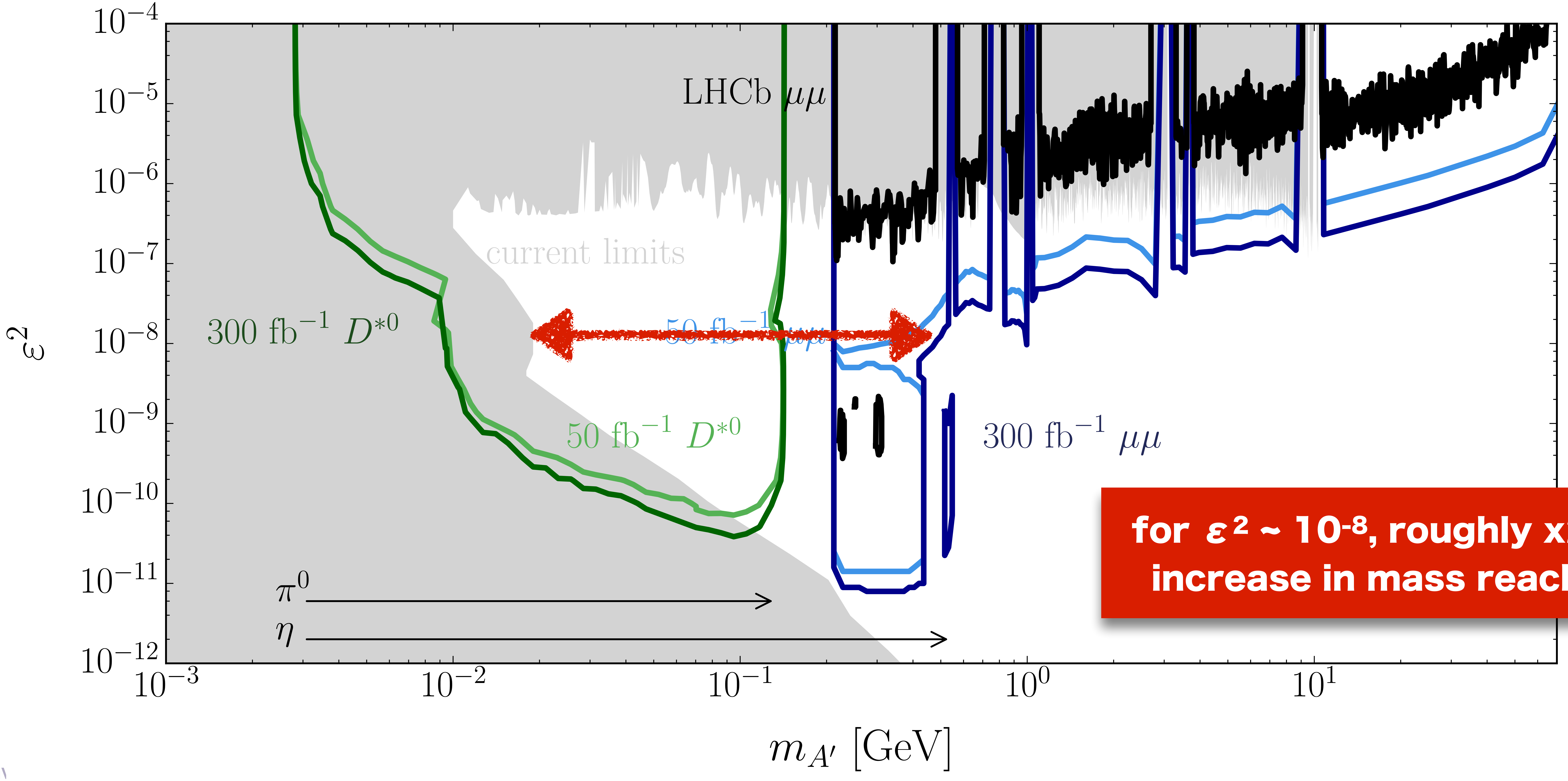


LHC lumi increase
& detector upgrades bring
unprecedented reach for
processes with small cross
sections (& sometimes weird
signatures)

extreme lower end: A′ searches at LHCb

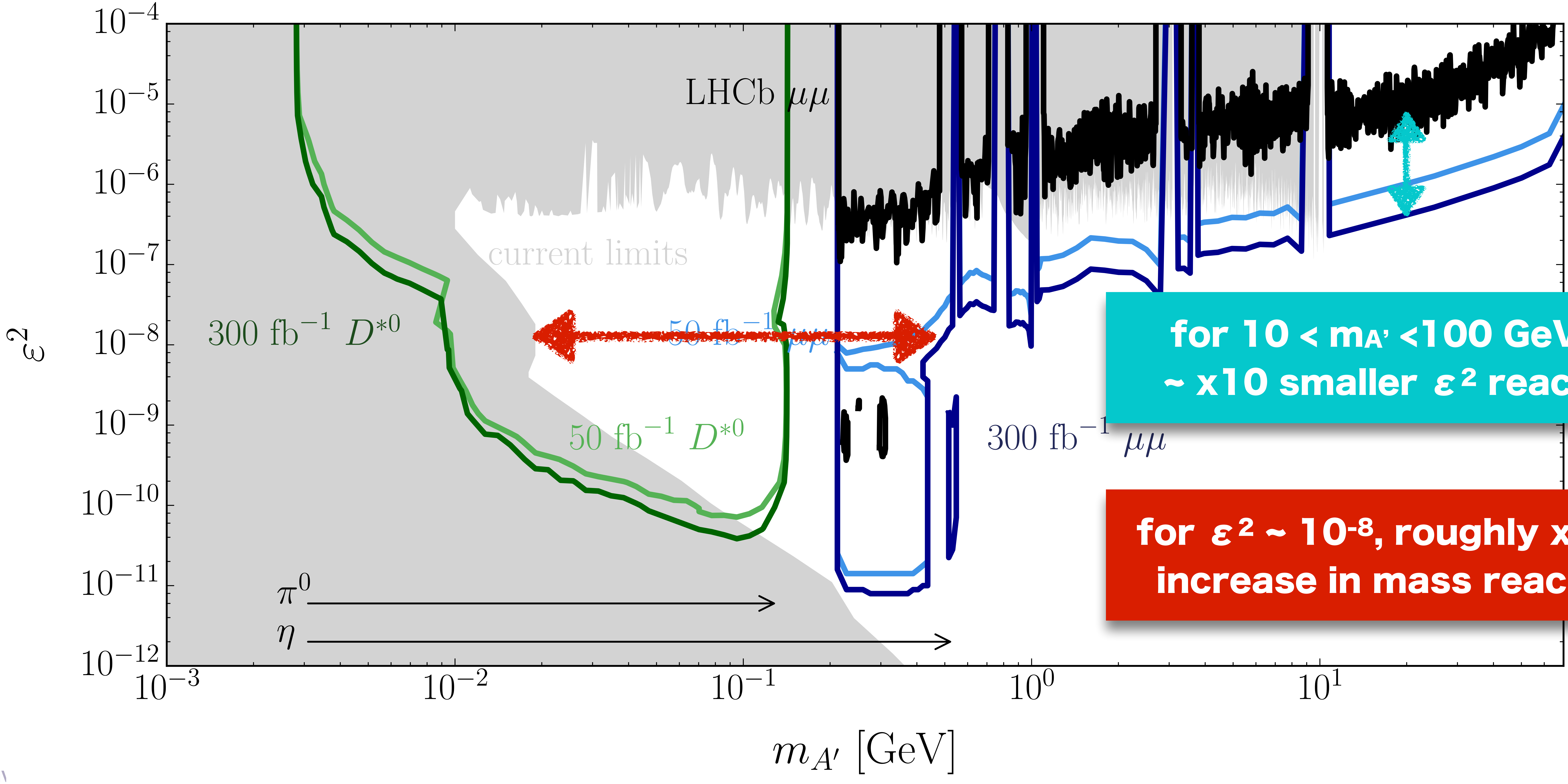


extreme lower end: A′ searches at LHCb



for ε^2 ~ 10^{-8}, roughly x20 increase in mass reach!

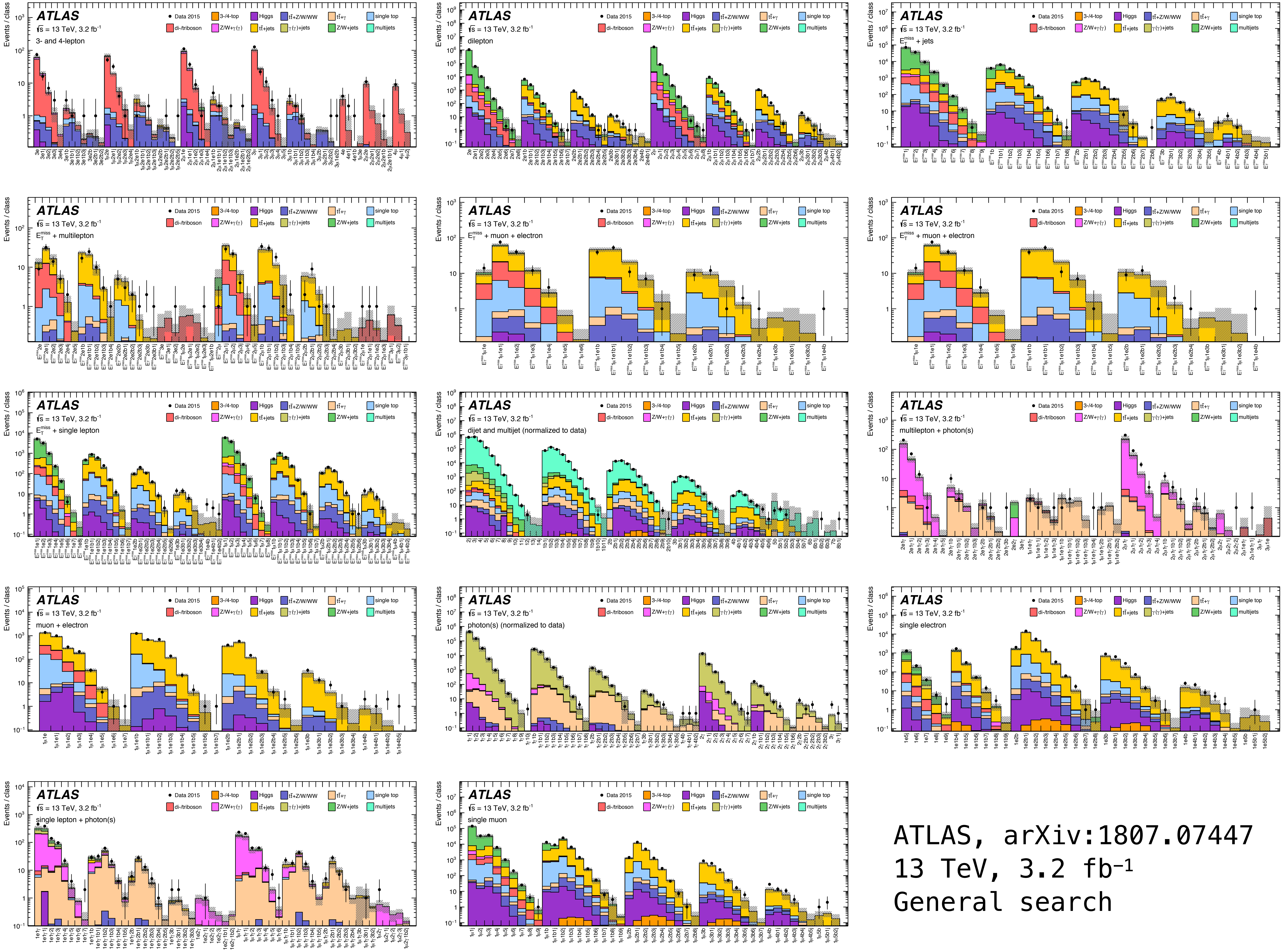
extreme lower end: A′ searches at LHCb



for 10 < $m_{A'}$ <100 GeV, ~ x10 smaller ε^2 reach

for $\varepsilon^2 \sim 10^{-8}$, roughly x20 increase in mass reach!

General searches (including an example with 704 event classes)



```
ATLAS, arXiv:1807.07447
13 TeV, 3.2 fb-1
General search
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As we move into regime where mass reach evolves more slowly, what's the best strategy?

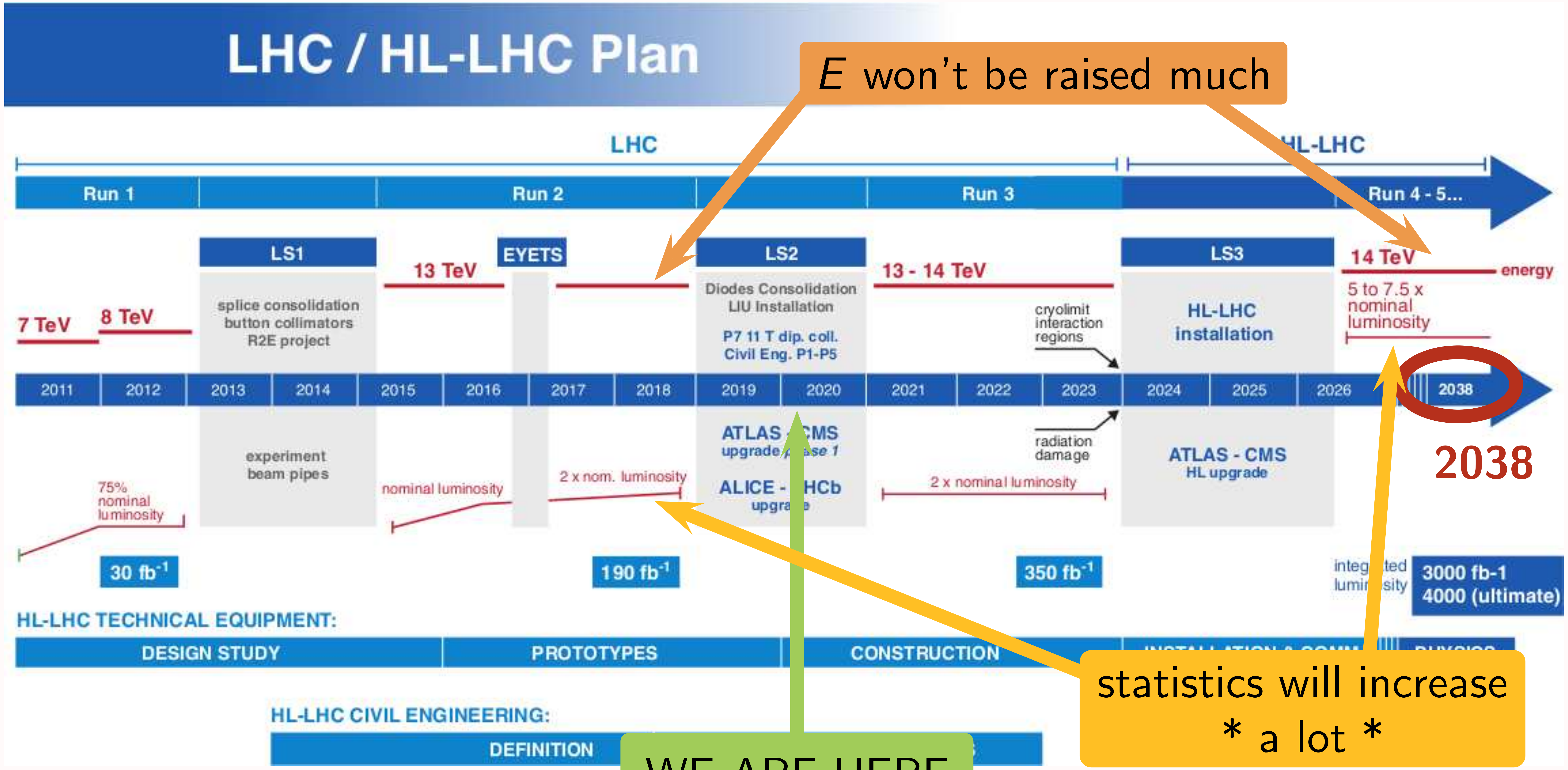
Can/should searches be automated?

Can they be incorporated into generic searches, freeing up time/ thought for novel searches?

indirect searches & Higgs

Big plans

Ilaria Brivio



E won't be raised much

WE ARE HERE

statistics will increase
* a lot *

there's much room for improvement in precision →

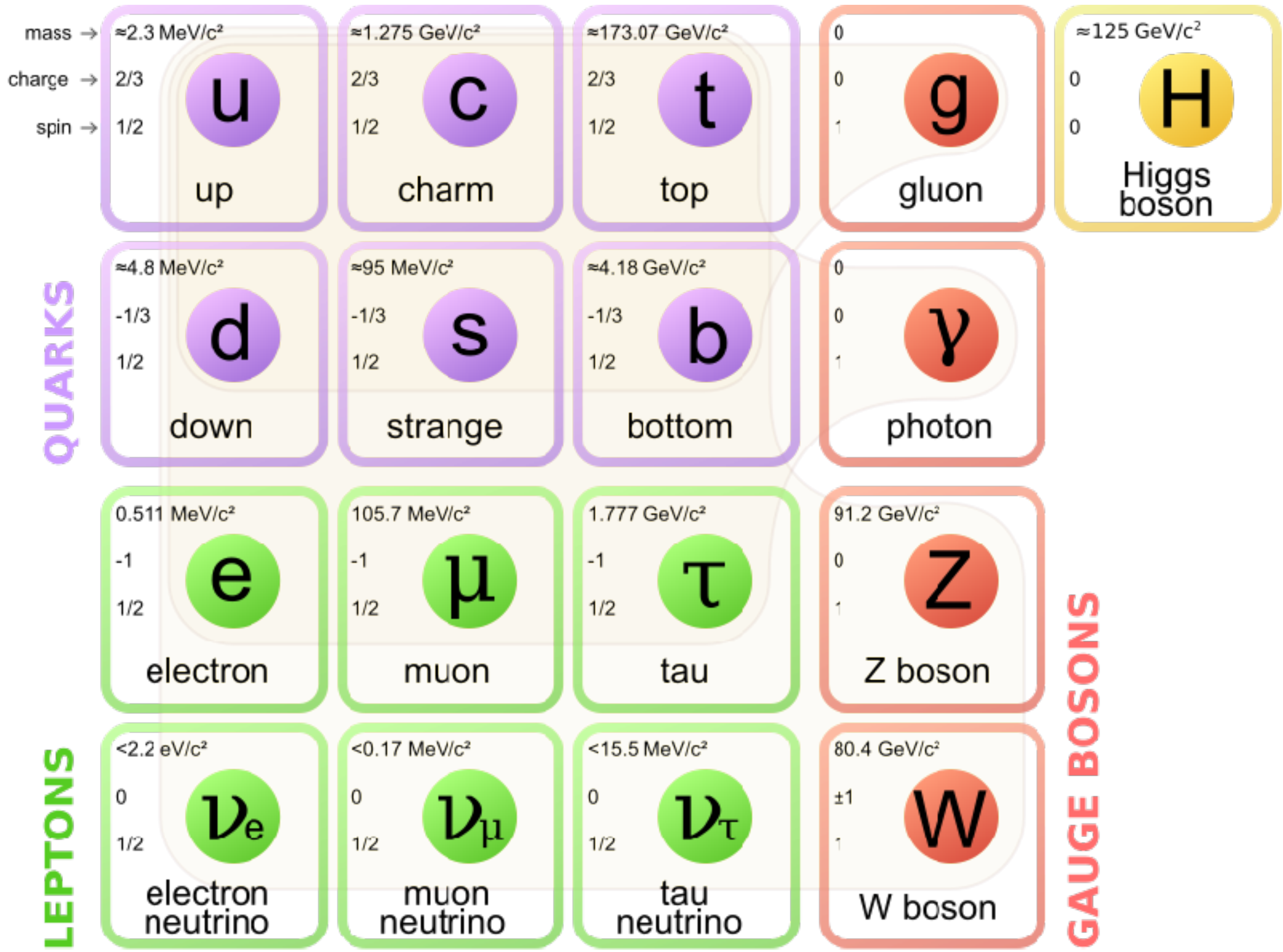
worth having
a systematic program
for **indirect searches**

What mass reach do we gain from indirect probes (EFT-style)?

- We have $\sim \times 20$ increase in luminosity from today to end of HL-LHC
- Statistical precision can go up by $\times\sqrt{20} \simeq 4.5$
- For dimension-6 operator × dimension-4 operator, probing a scale Λ for new physics, effects go as $1/\Lambda^2$
- Increase in Λ to which we're sensitive will be $\times\sqrt{4.5} \simeq 2.1$

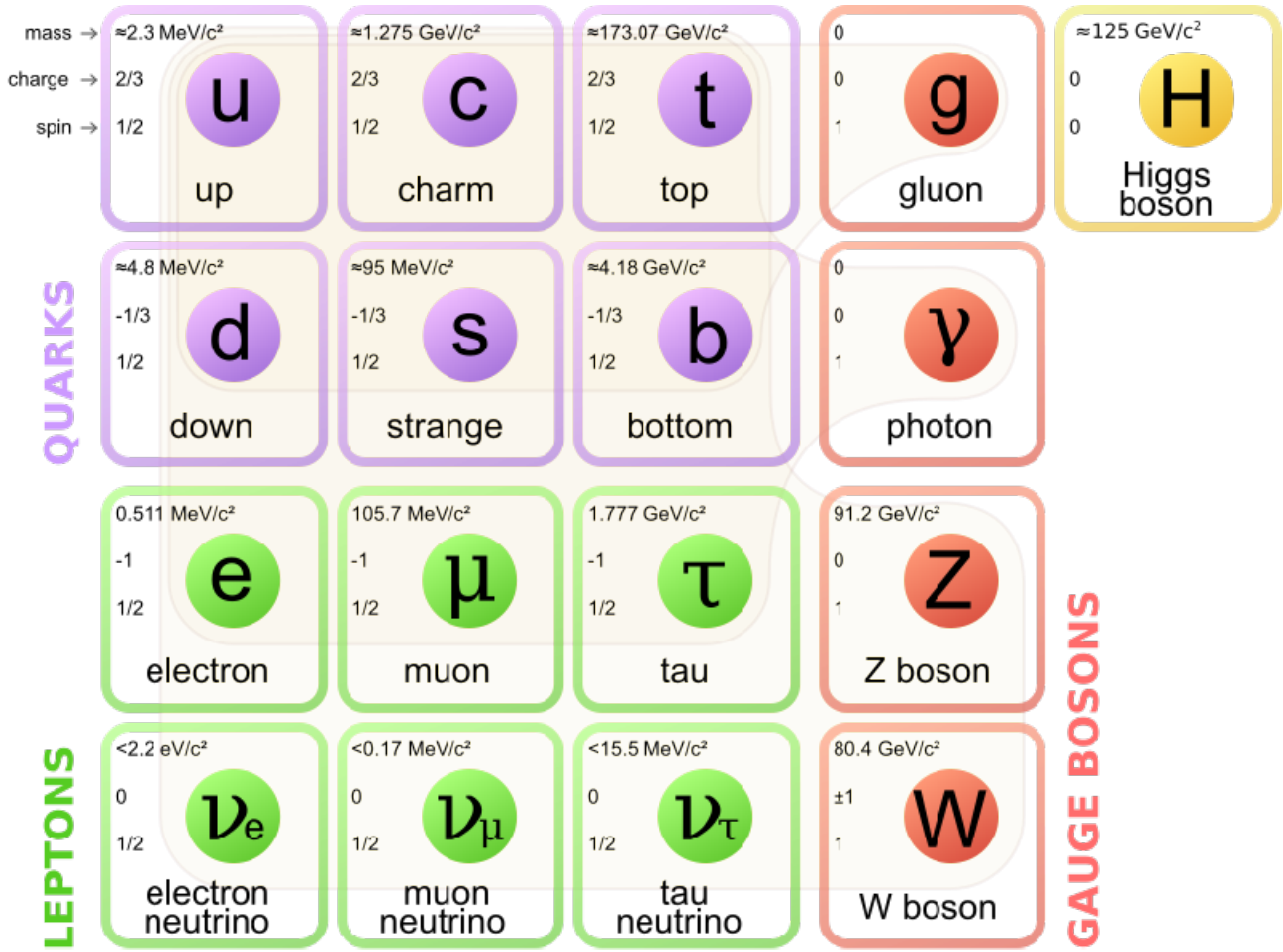
This is better improvement than direct searches at the high end of LHC mass reach, comparable for low end.

the Standard Model is **not** complete



particles

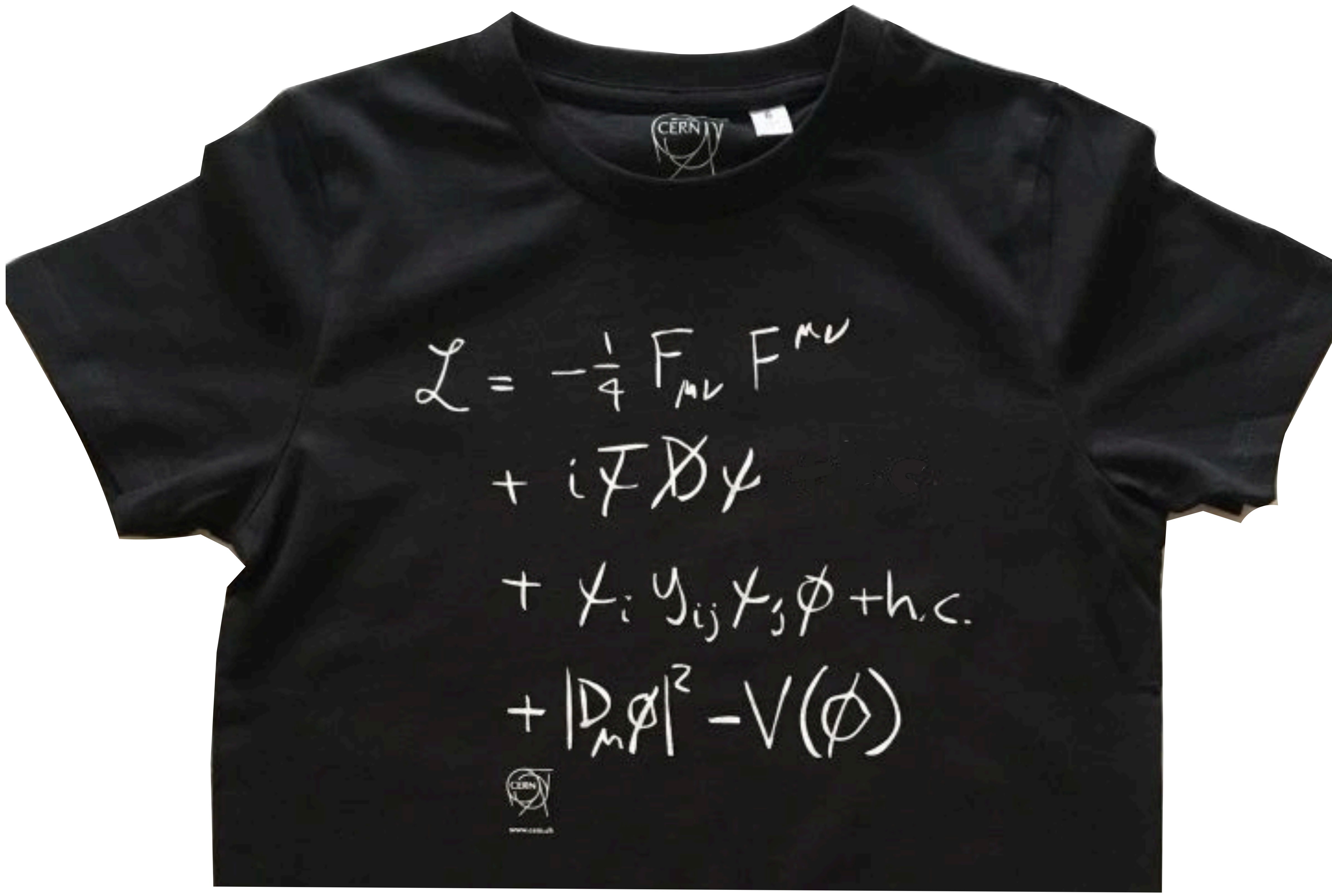
the Standard Model is not complete



mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈125 GeV/c^2 0 0 H Higgs boson
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	

GAUGE BOSONS

+



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

particles

interactions

particles

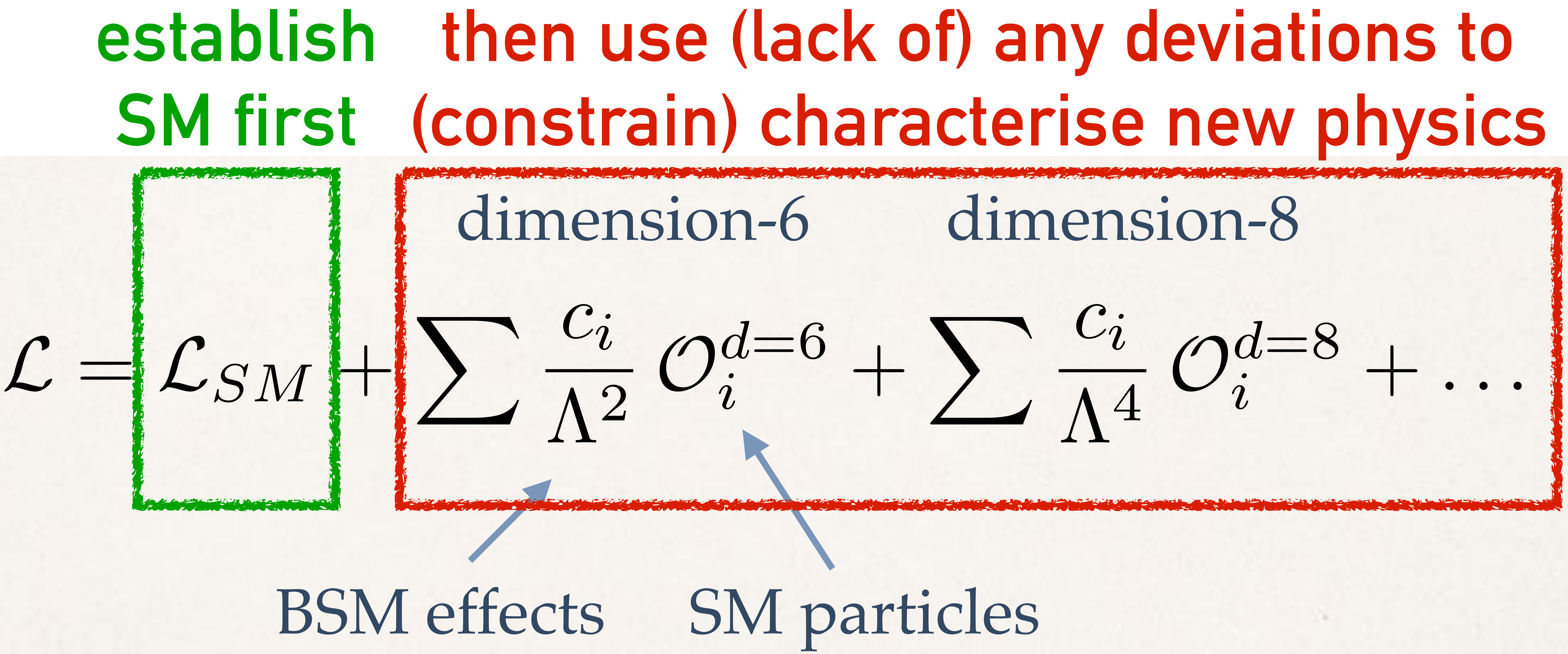
https://www.piqsels.com/en/public-domain-photo-fqrgz

particles + interactions

https://commons.wikimedia.org/wiki/File:LEGO_Expert_Builder_948_Go-Kart.jpg, CC-BY-SA-4.0

EFT (expressive formulation of constraints) or not?

- If you’ve observed a given channel, and it agrees roughly (±20%) with SM, then go to EFT
- if you’ve not observed it, e.g. charm Yukawa, Higgs self coupling, then use of EFT is more debatable



establish SM first

then use (lack of) any deviations to (constrain) characterise new physics

dimension-6

dimension-8

$$\mathcal{L} = \boxed{\mathcal{L}_{SM}} + \boxed{\sum \frac{c_i}{\Lambda^2}\, \mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\, \mathcal{O}_i^{d=8} + \ldots}$$

BSM effects

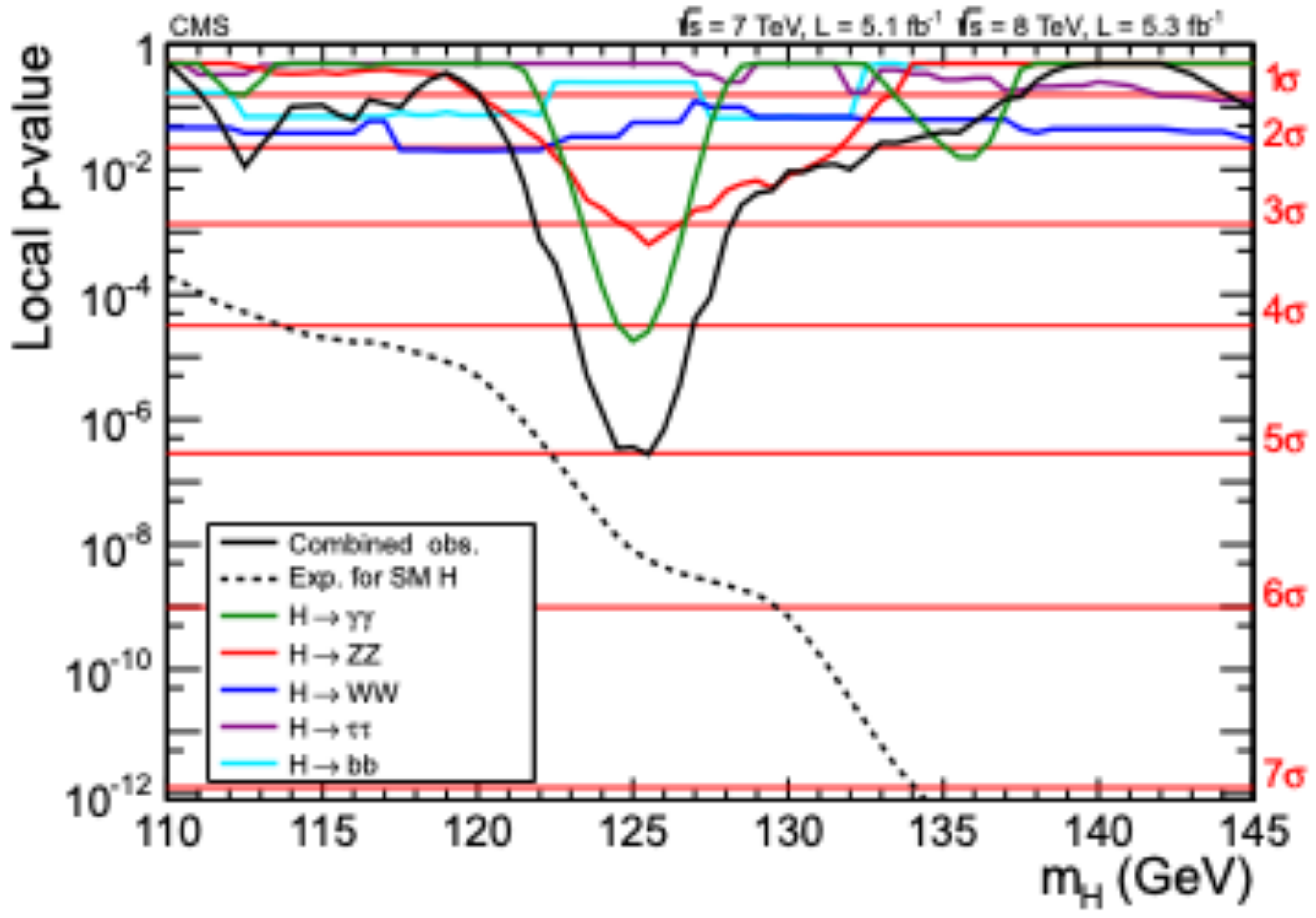
SM particles

LHC – FROM 5 SIGMA TO DIFFERENTIAL IN 360 WEEKS

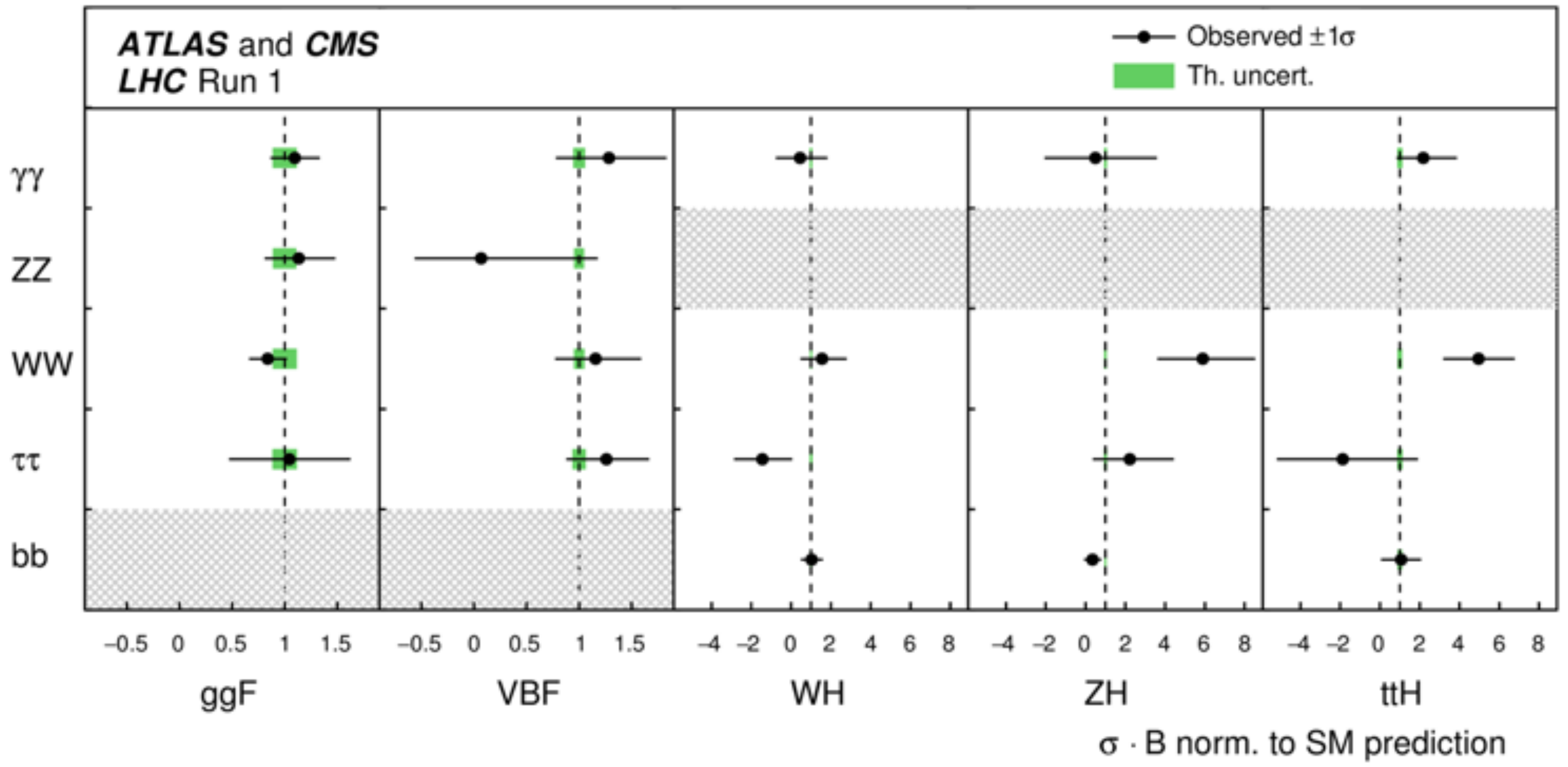
Some **Run 2** milestones:

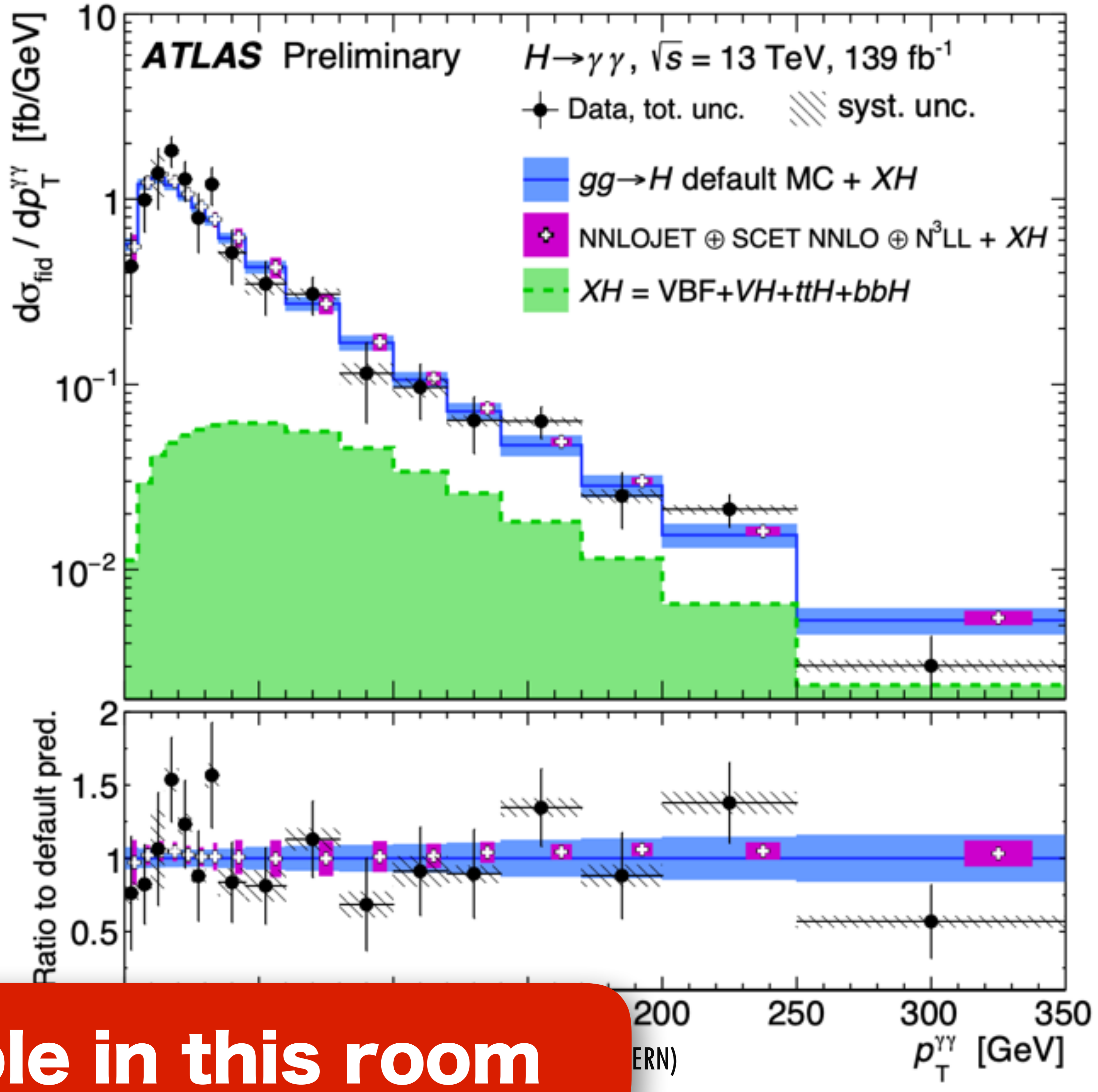
- Observation of H→ττ, H→bb, and ttH.
- Reaching SM-level limits on H→μμ.

July 2012



Run1 CMS-ATLAS combination

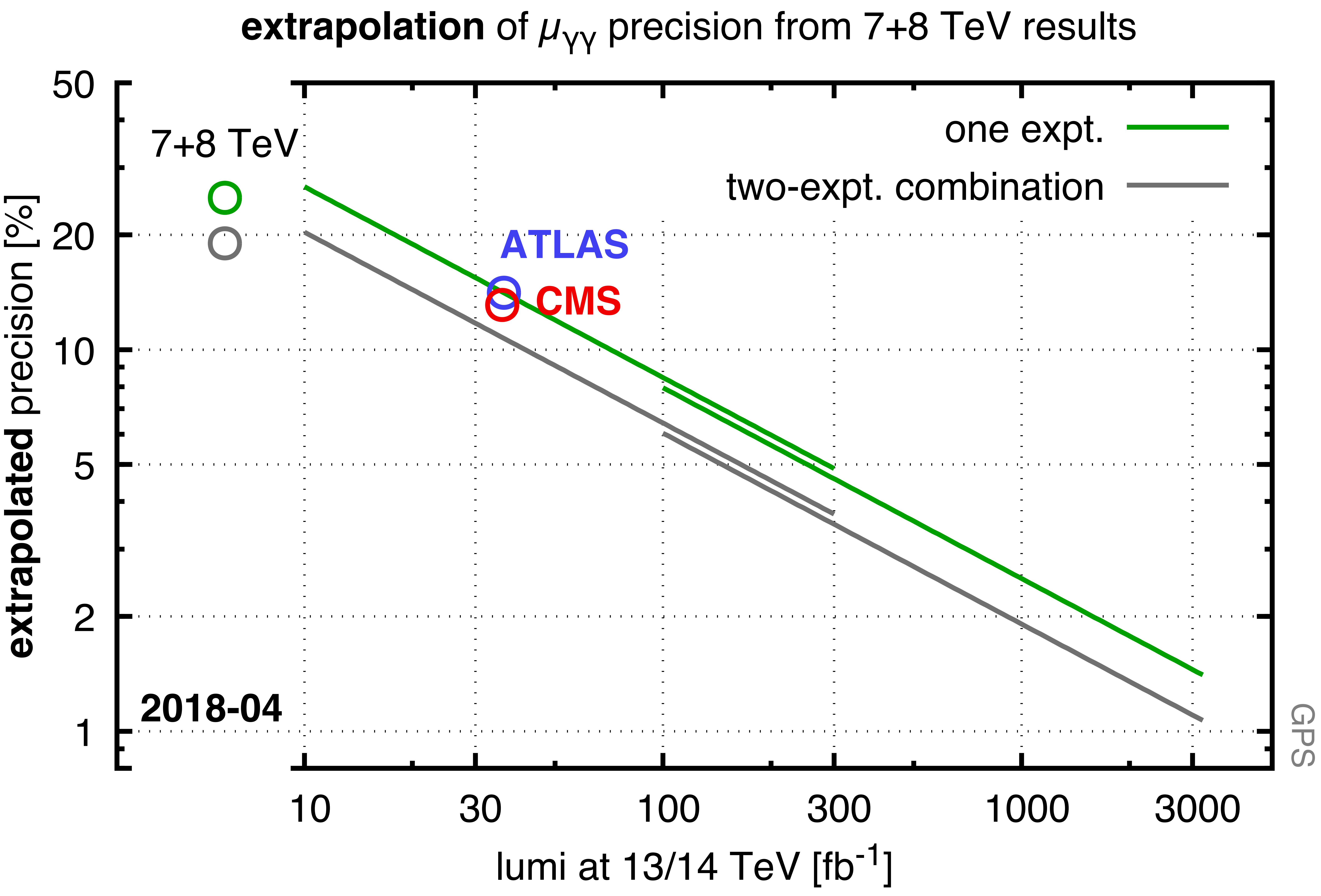




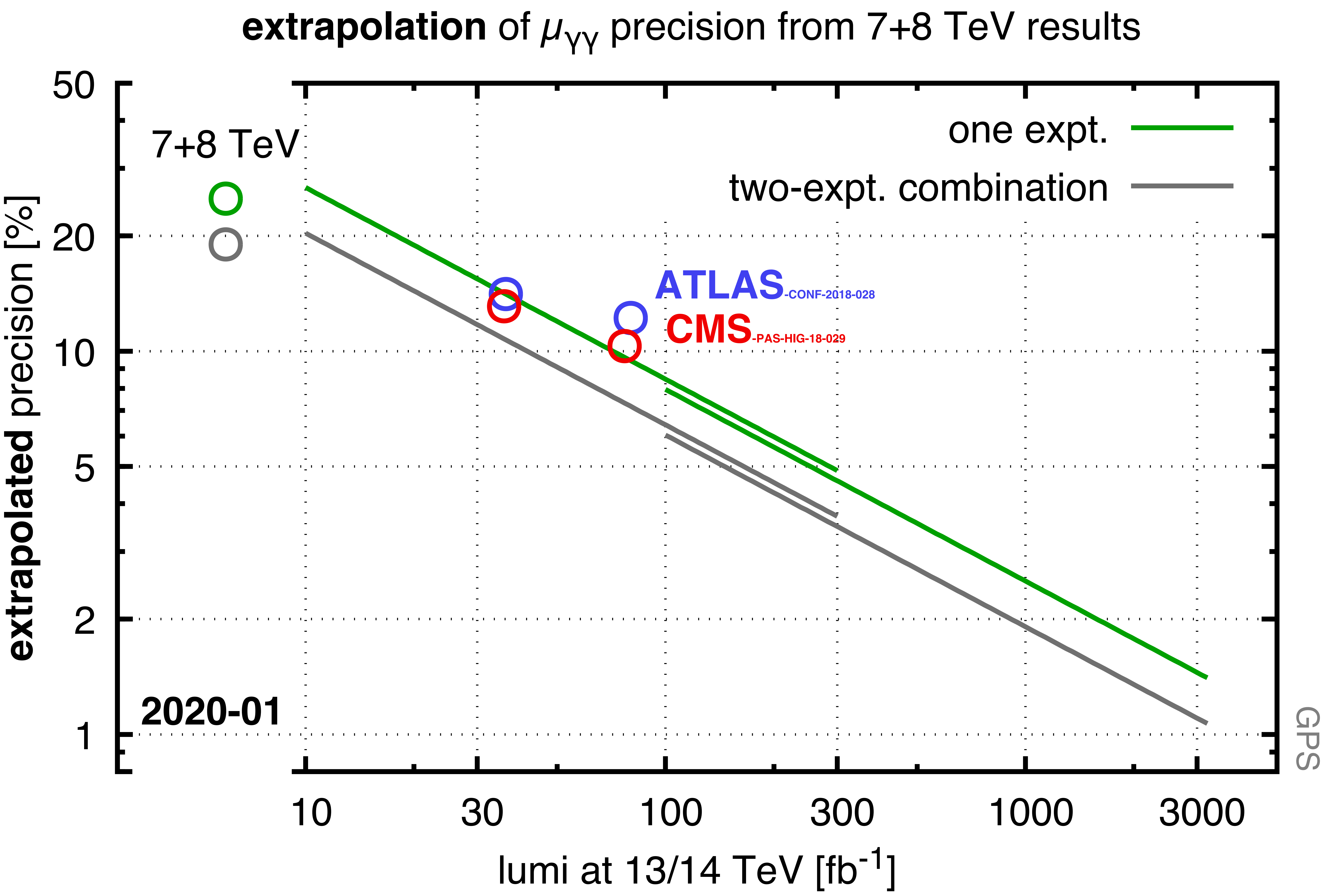
Andre David

+ theory calculations from many people in this room

how well does H→γγ uncertainty track increase in lumi?

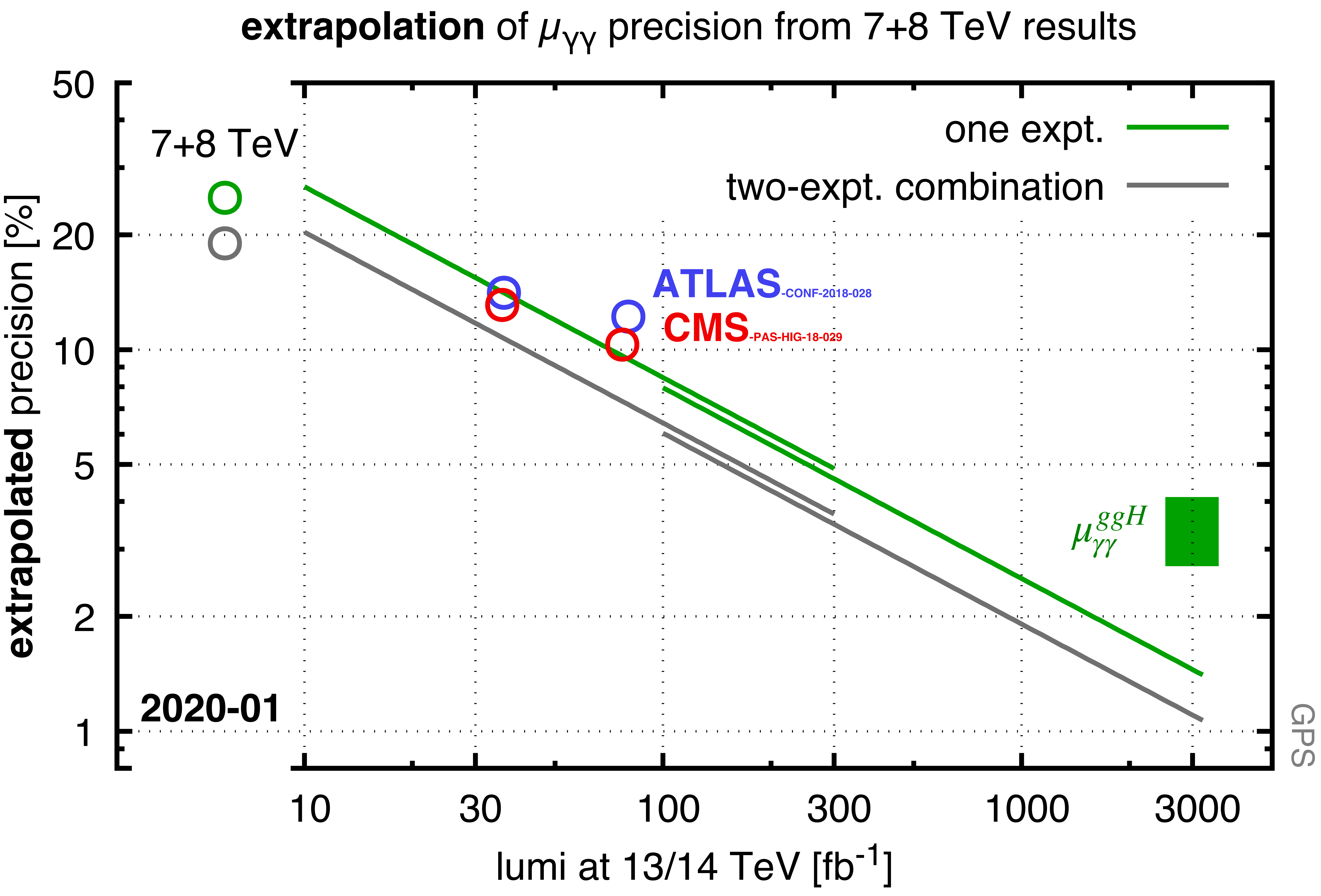


how well does H→γγ uncertainty track increase in lumi?



To what extent do we understand how systematics (will) evolve?

how well does H→γγ uncertainty track increase in lumi?



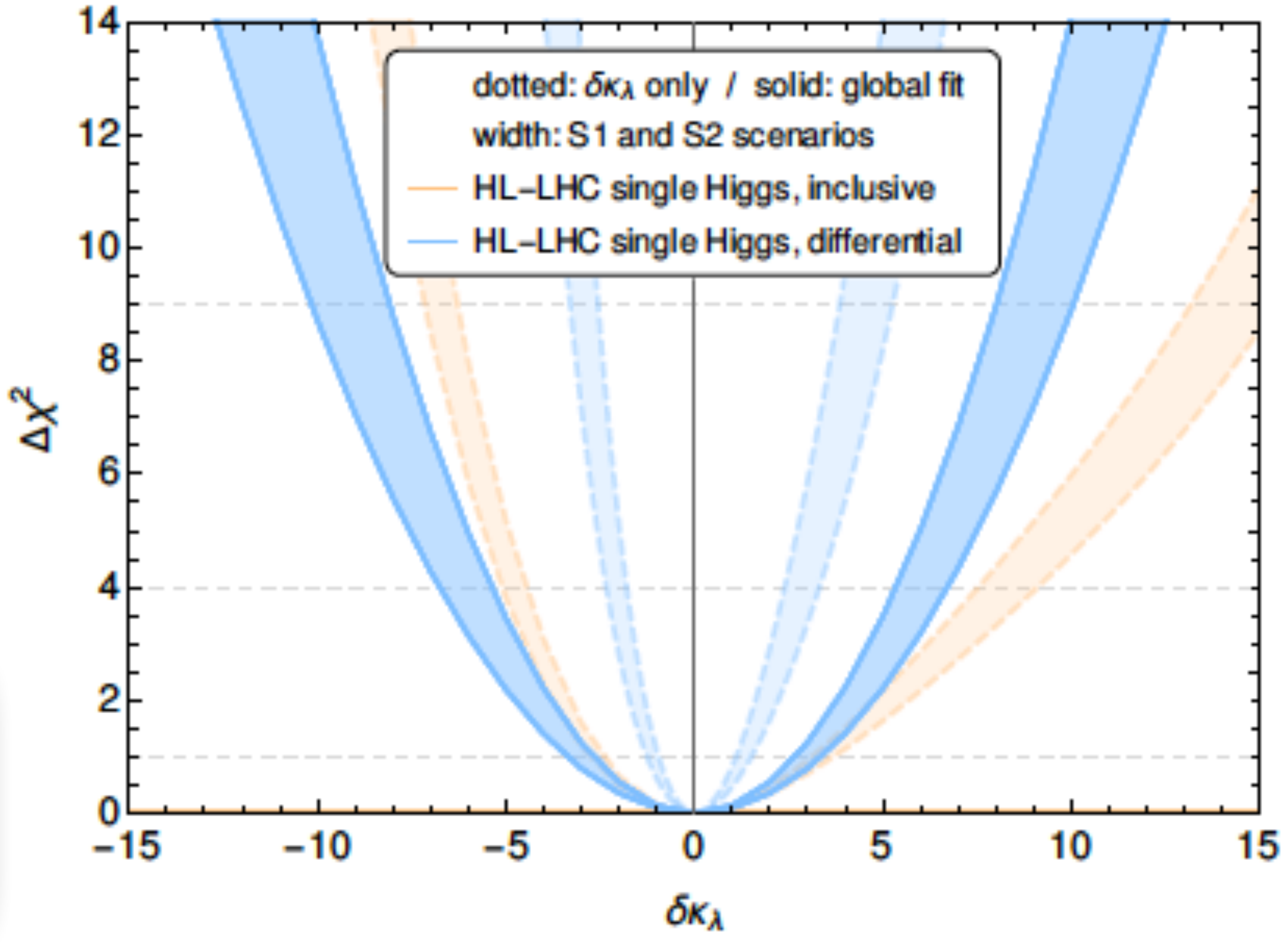
To what extent do we understand how systematics (will) evolve?

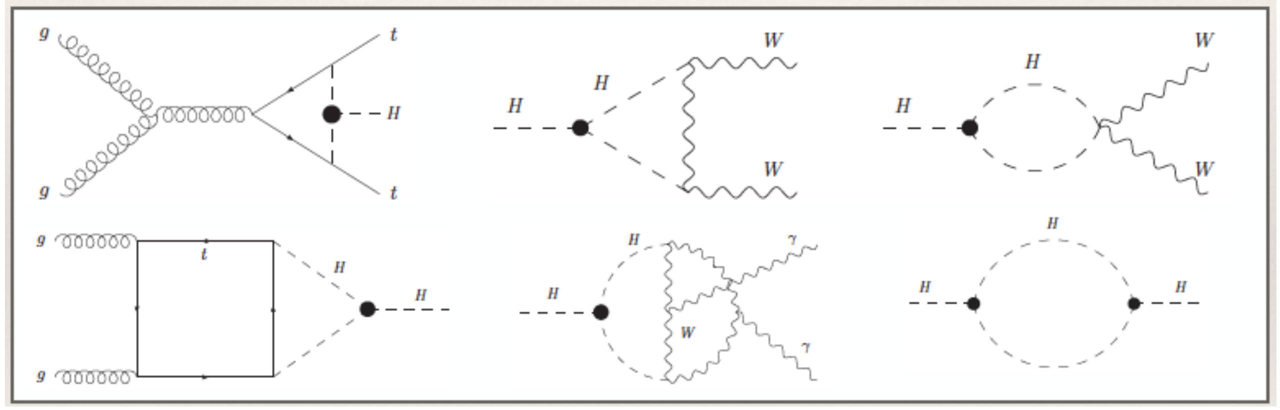
Top & Higgs

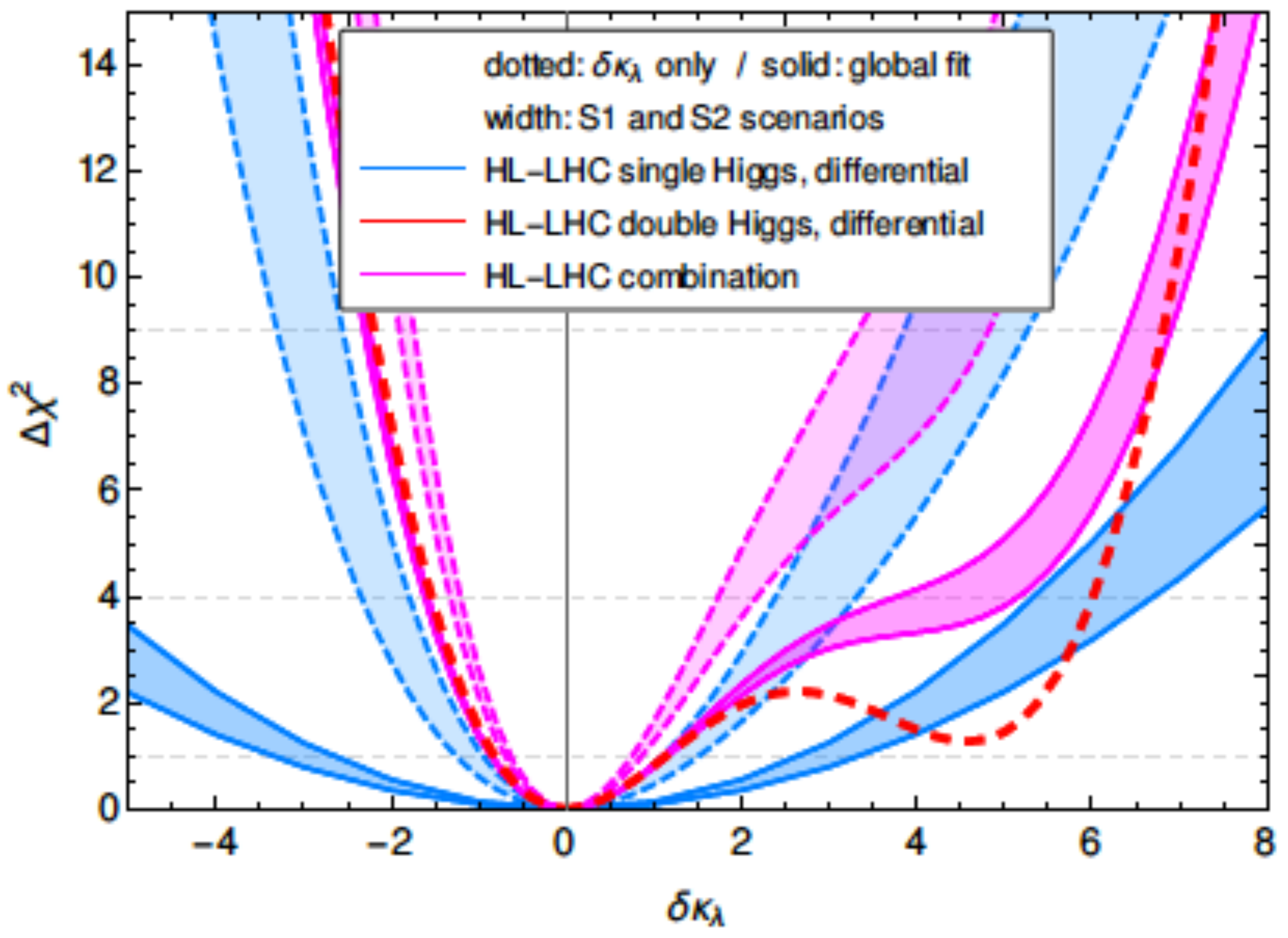
Top-Higgs interplay in HH

Future prospects for Higgs self-coupling:

Eleni Vryonidou

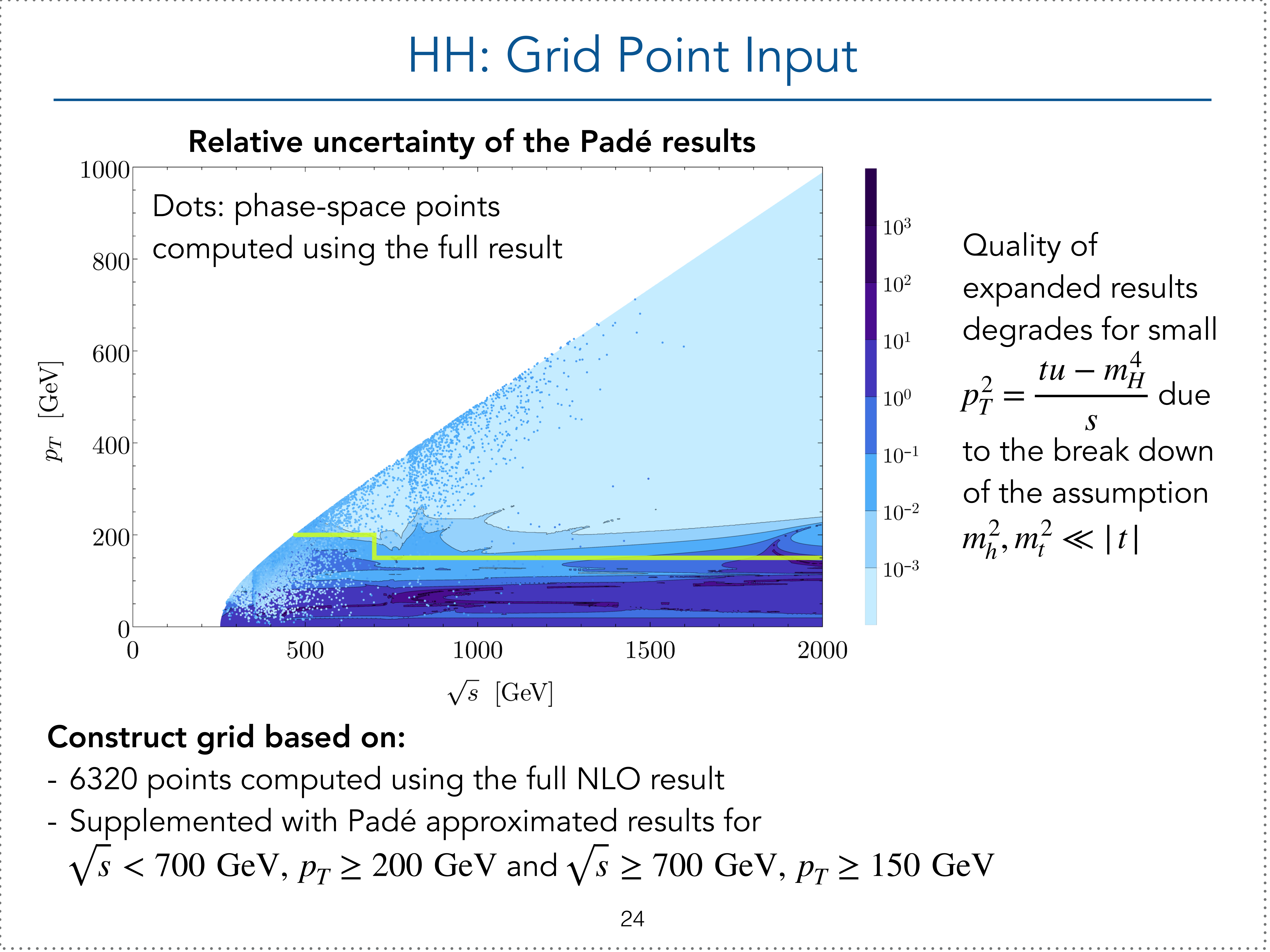






Di Vita et al. arXiv:1704.01953 and HH white paper

Degeneracy with Yukawa and contact ggH operators worsens HHH sensitivity



HH: Grid Point Input

Relative uncertainty of the Padé results

Dots: phase-space points computed using the full result

Quality of expanded results degrades for small $p_T^2 = \dfrac{tu - m_H^4}{s}$ due to the break down of the assumption $m_h^2, m_t^2 \ll |t|$

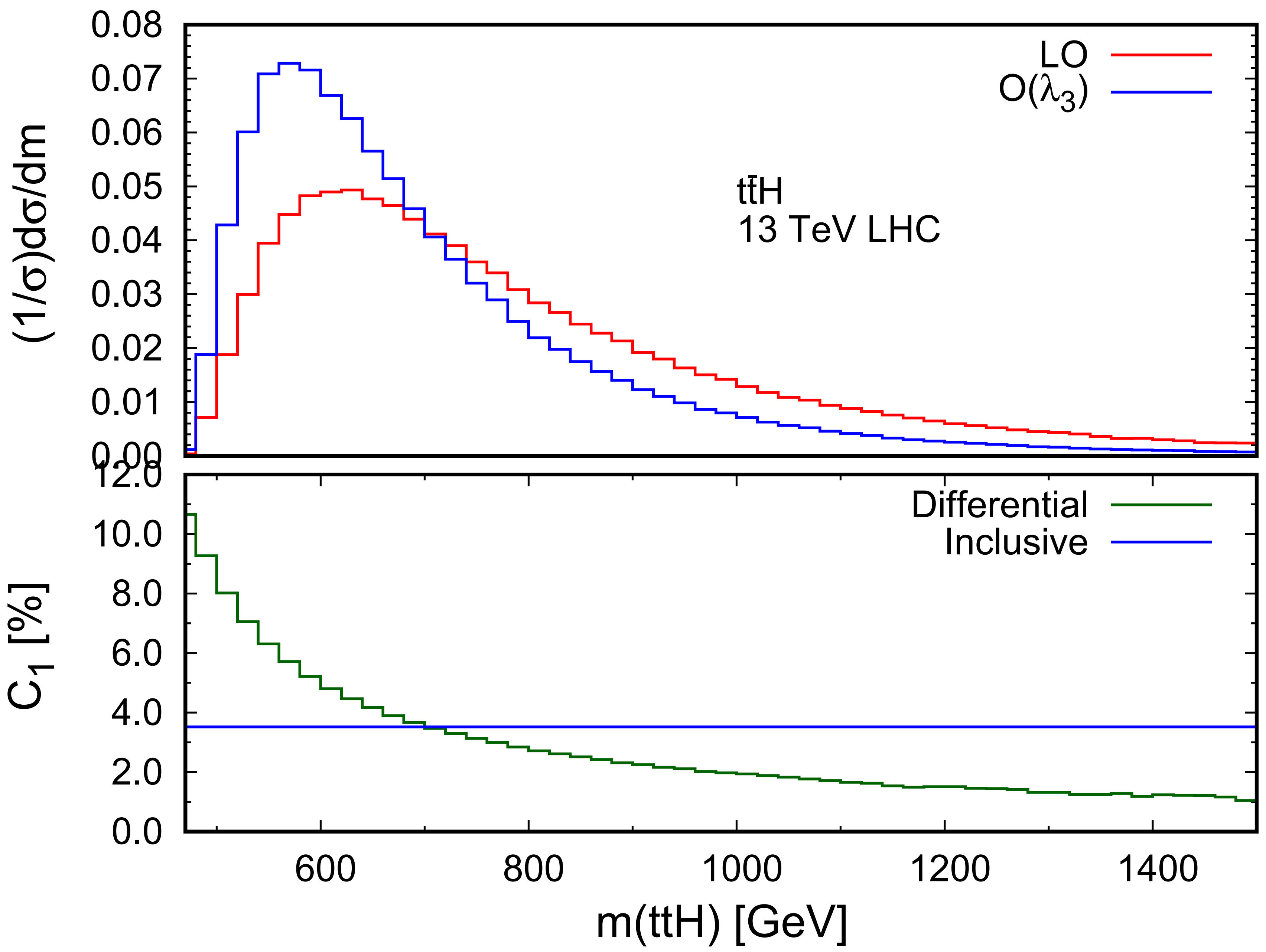
Construct grid based on:

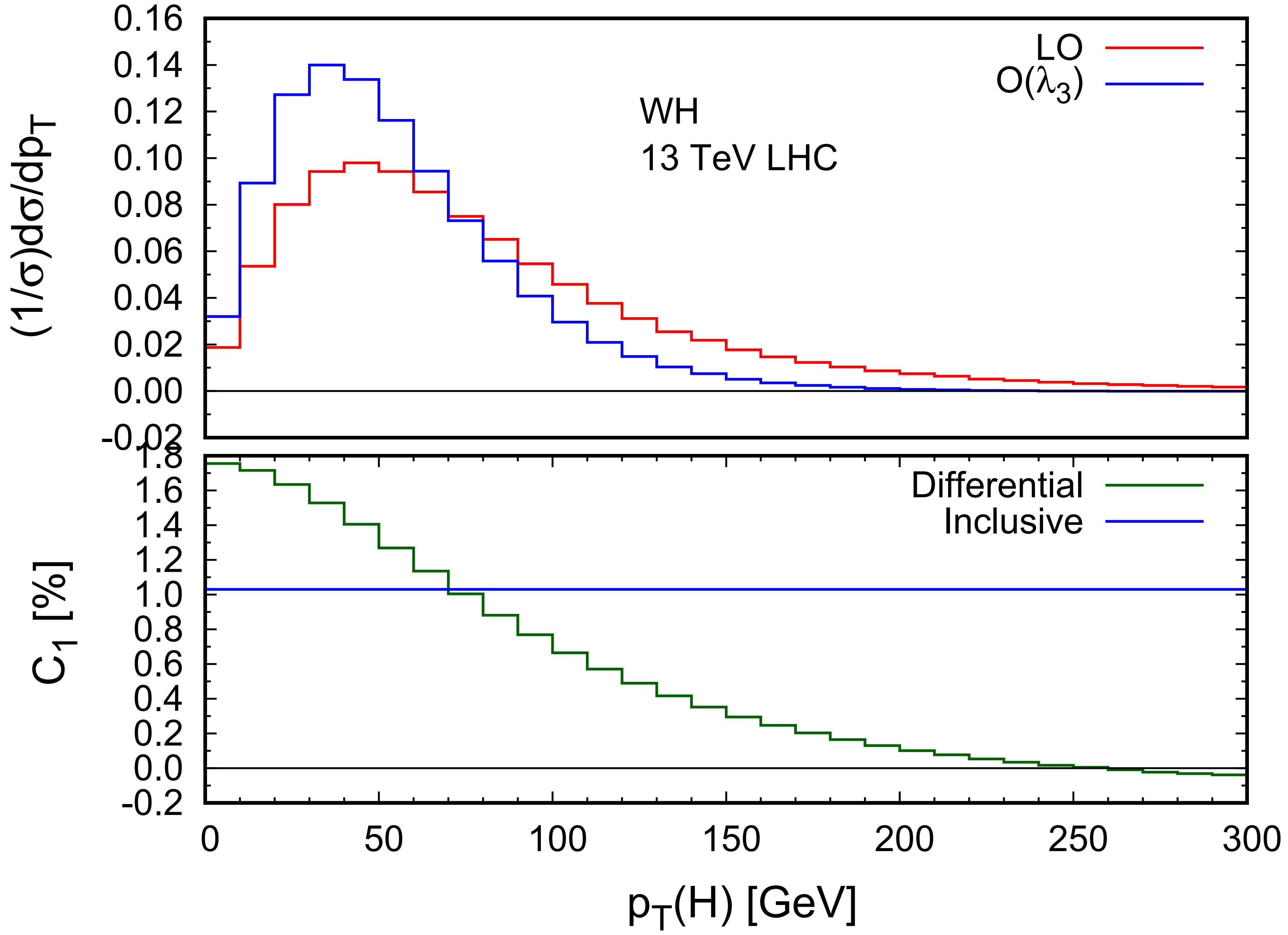
- 6320 points computed using the full NLO result
- Supplemented with Padé approximated results for $\sqrt{s} < 700$ GeV, $p_T \geq 200$ GeV and $\sqrt{s} \geq 700$ GeV, $p_T \geq 150$ GeV

Steven Jones

the challenges and progress in putting together top-mass effects for di-Higgs

C1: kinematic dependence



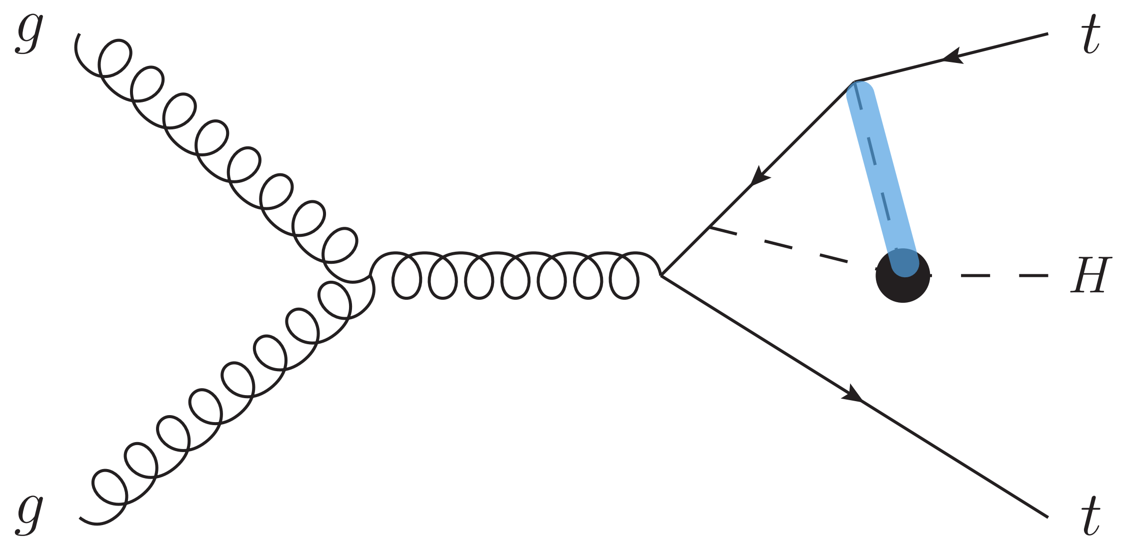


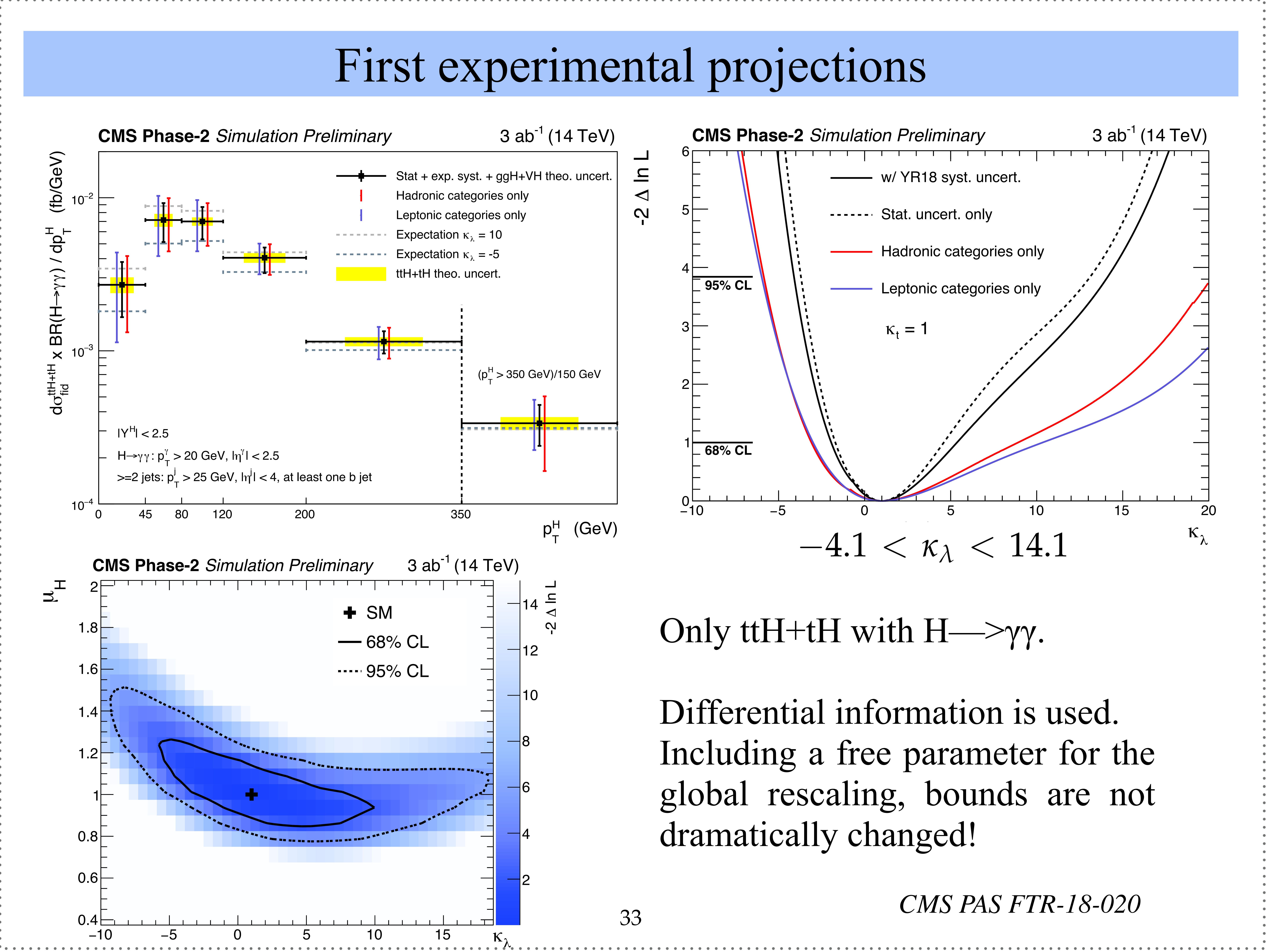
Davide Pagani

complementary to direct searches for HH

Maltoni, DP, Shivaji, Zhao ’17

Contributions to ttH and HV processes can be seen as induced by a Yukawa potential, giving a Sommerfeld enhancement at the threshold.





First experimental projections

$$-4.1 < \kappa_\lambda < 14.1$$

Only ttH+tH with H—>γγ.

Differential information is used. Including a free parameter for the global rescaling, bounds are not dramatically changed!

CMS PAS FTR-18-020

33

Davide Pagani

complementary to direct searches for HH

only the start of studying its potential

MC programs for 4FS ttbb at NLO+PS

- Several tools on the market
  - Sherpa + OpenLoops [1309.5912]
  - PowHel + Pythia/Herwig [1709.06915]
  - .00426]

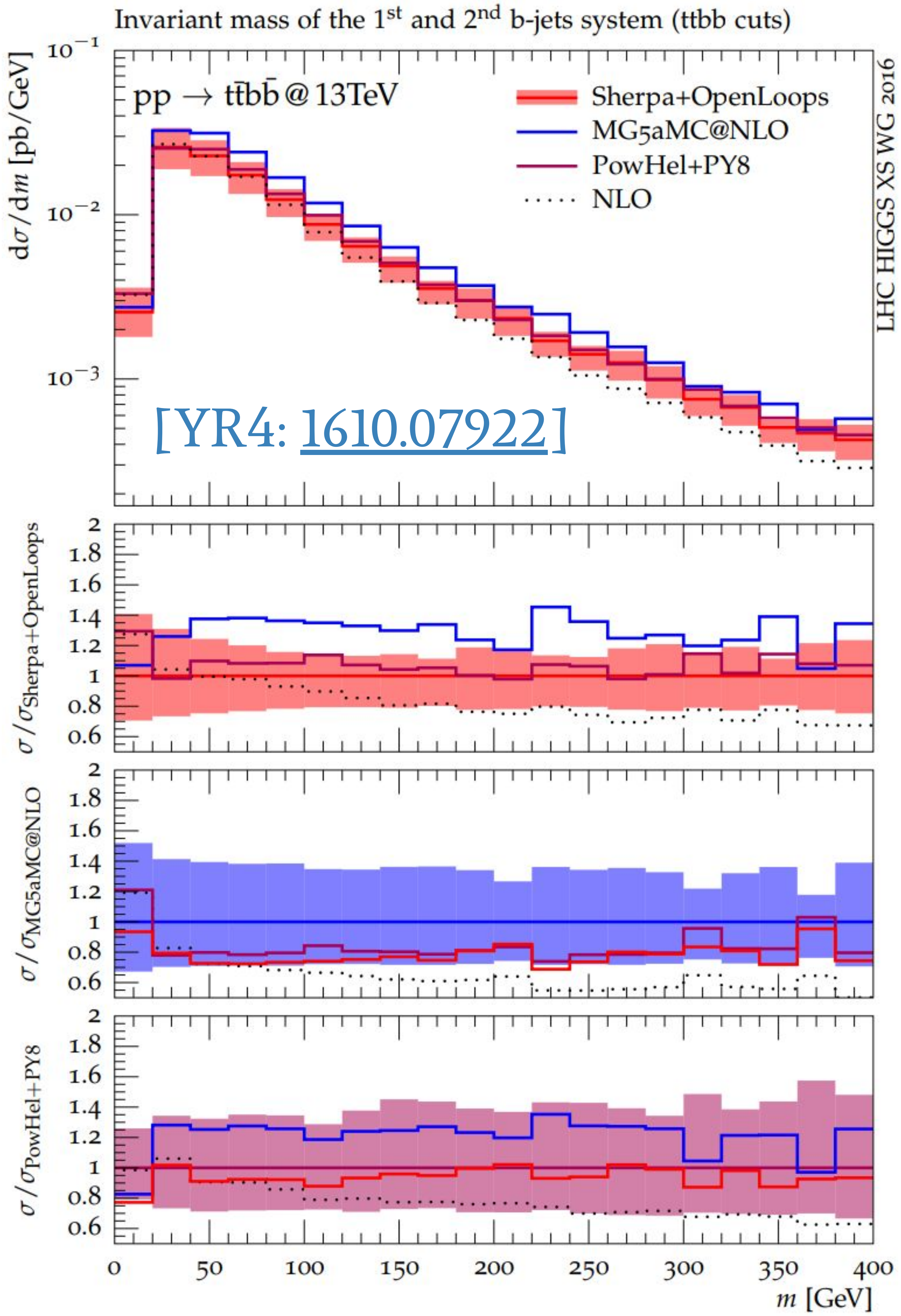
ching algorithm?

e or accept as **uncertainties** (and kill ttH(bb)?)?

Arguably one of the most complex processes for NLO+PS matching

→ Strong challenge to understand unc's as prototype for other processes!

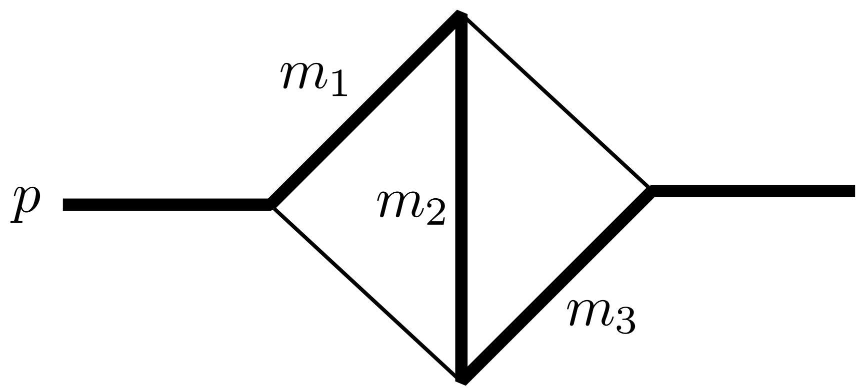
Frank Siegert



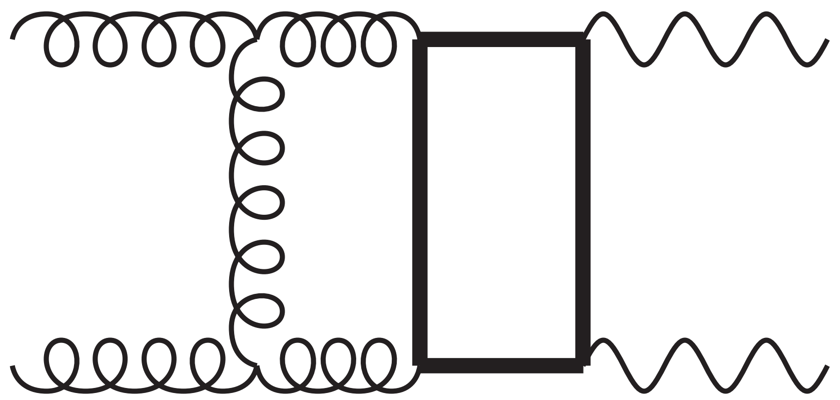
[YR4: 1610.07922]

TOWARDS HIGGS AND TOPS @ NNLO

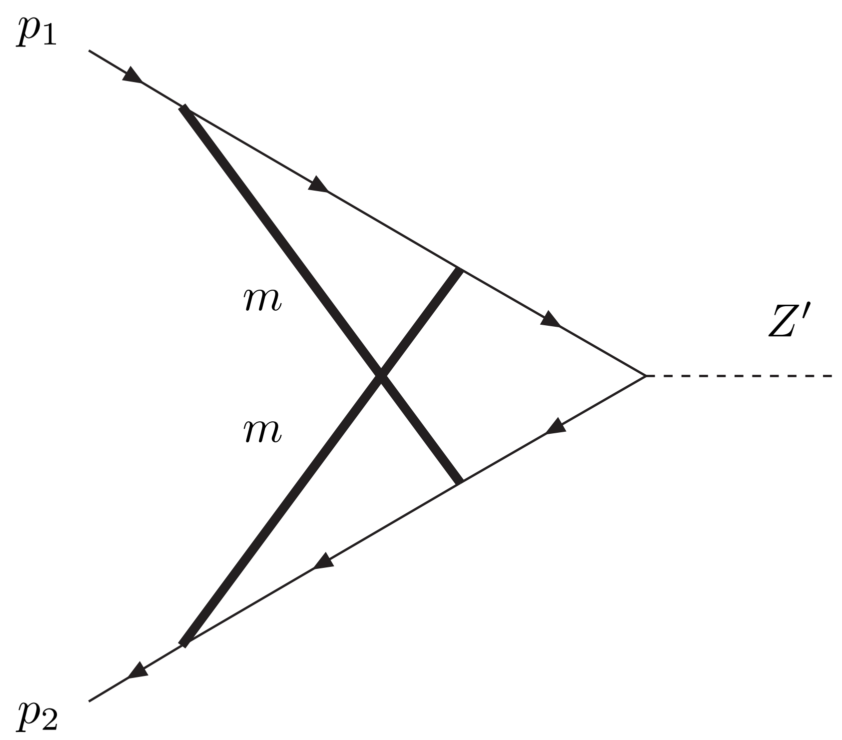
Lorenzo Tancredi



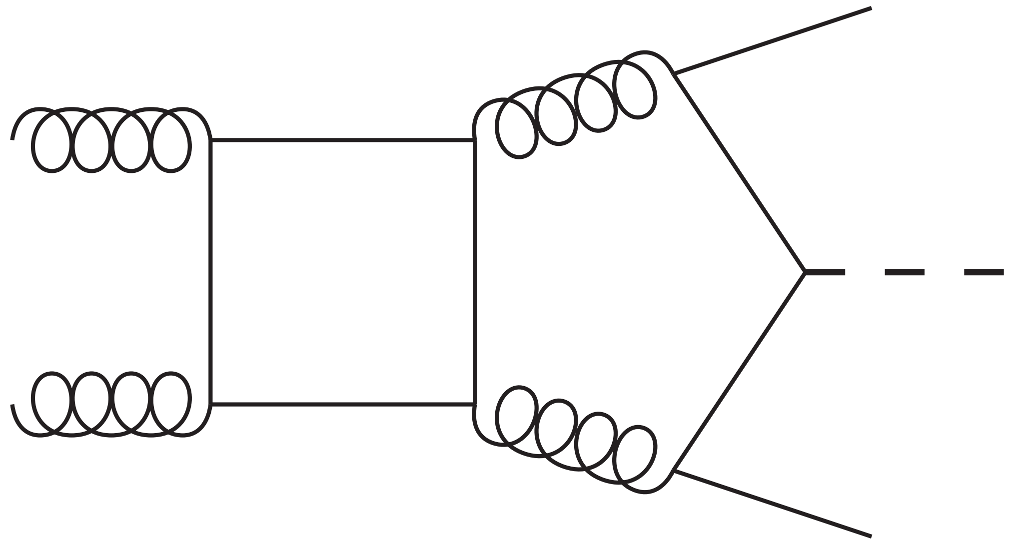
Kite integral (self-energies…)



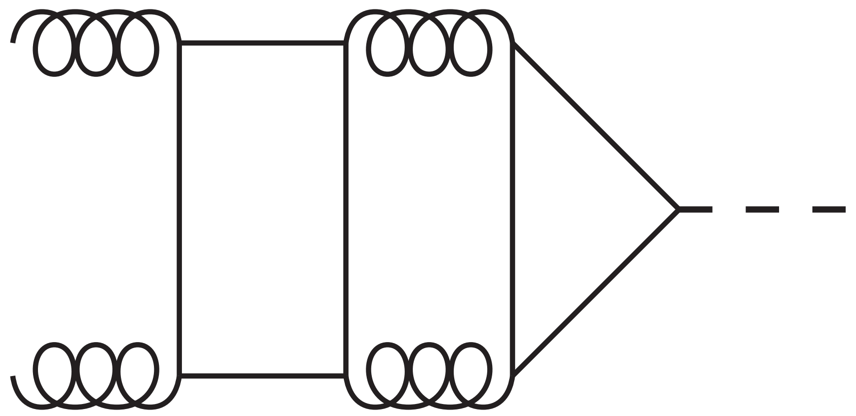
QCD with top quarks



EW form factor



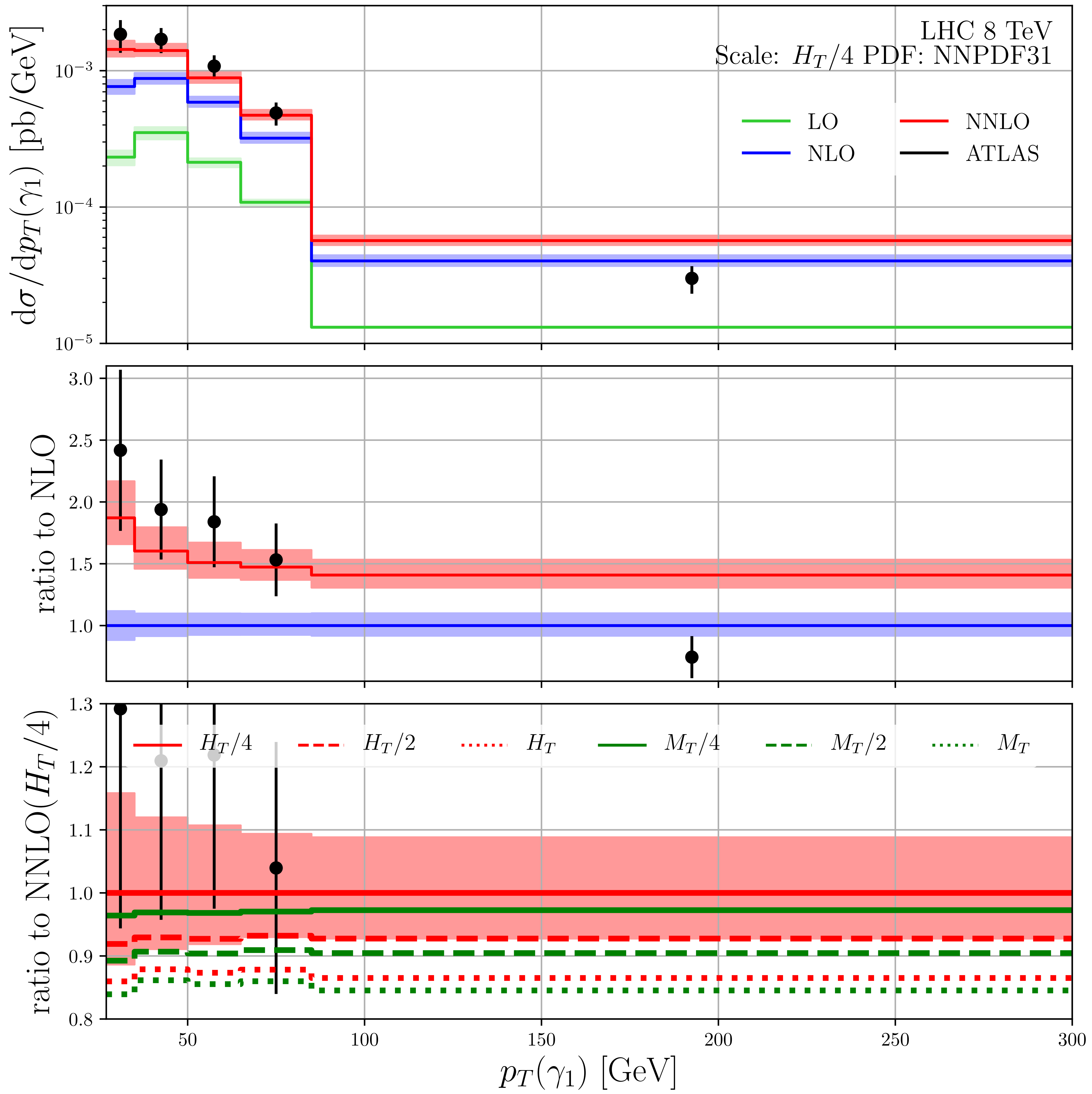
ttb + X processes



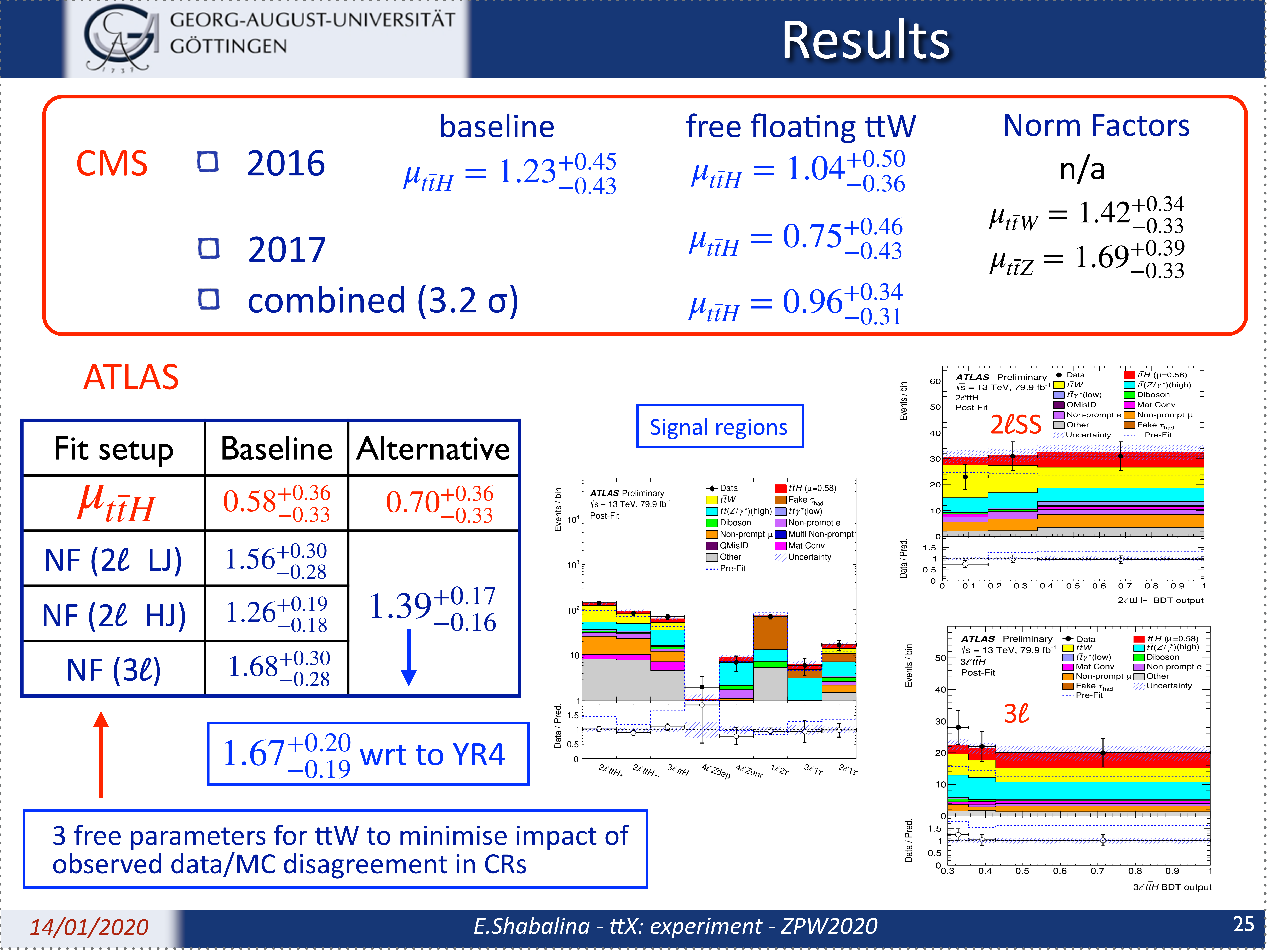
H form factor at 3 loops

Iterated integrals of elliptic type are crucial for **high precision calculations** in the **Higgs and top sectors** !

First 2 → 3 NNLO calculation: for pp → γγγ + X



- Chawdhry, Czakon, Mitov & Poncelet, arXiv:1911.00479
- simpler than ttH (in particular, no external mass scales)
- significant advance



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Results

		baseline	free floating ttW	Norm Factors
CMS	☐ 2016	$\mu_{t\bar{t}H} = 1.23^{+0.45}_{-0.43}$	$\mu_{t\bar{t}H} = 1.04^{+0.50}_{-0.36}$	n/a
	☐ 2017		$\mu_{t\bar{t}H} = 0.75^{+0.46}_{-0.43}$	$\mu_{t\bar{t}W} = 1.42^{+0.34}_{-0.33}$ $\mu_{t\bar{t}Z} = 1.69^{+0.39}_{-0.33}$
	☐ combined (3.2 σ)		$\mu_{t\bar{t}H} = 0.96^{+0.34}_{-0.31}$	

ATLAS

Fit setup	Baseline	Alternative
$\mu_{t\bar{t}H}$	$0.58^{+0.36}_{-0.33}$	$0.70^{+0.36}_{-0.33}$
NF (2ℓ LJ)	$1.56^{+0.30}_{-0.28}$	$1.39^{+0.17}_{-0.16}$ ↓
NF (2ℓ HJ)	$1.26^{+0.19}_{-0.18}$	
NF (3ℓ)	$1.68^{+0.30}_{-0.28}$	

$1.67^{+0.20}_{-0.19}$ wrt to YR4

Signal regions

3 free parameters for ttW to minimise impact of observed data/MC disagreement in CRs

Elisaveta Shabalina

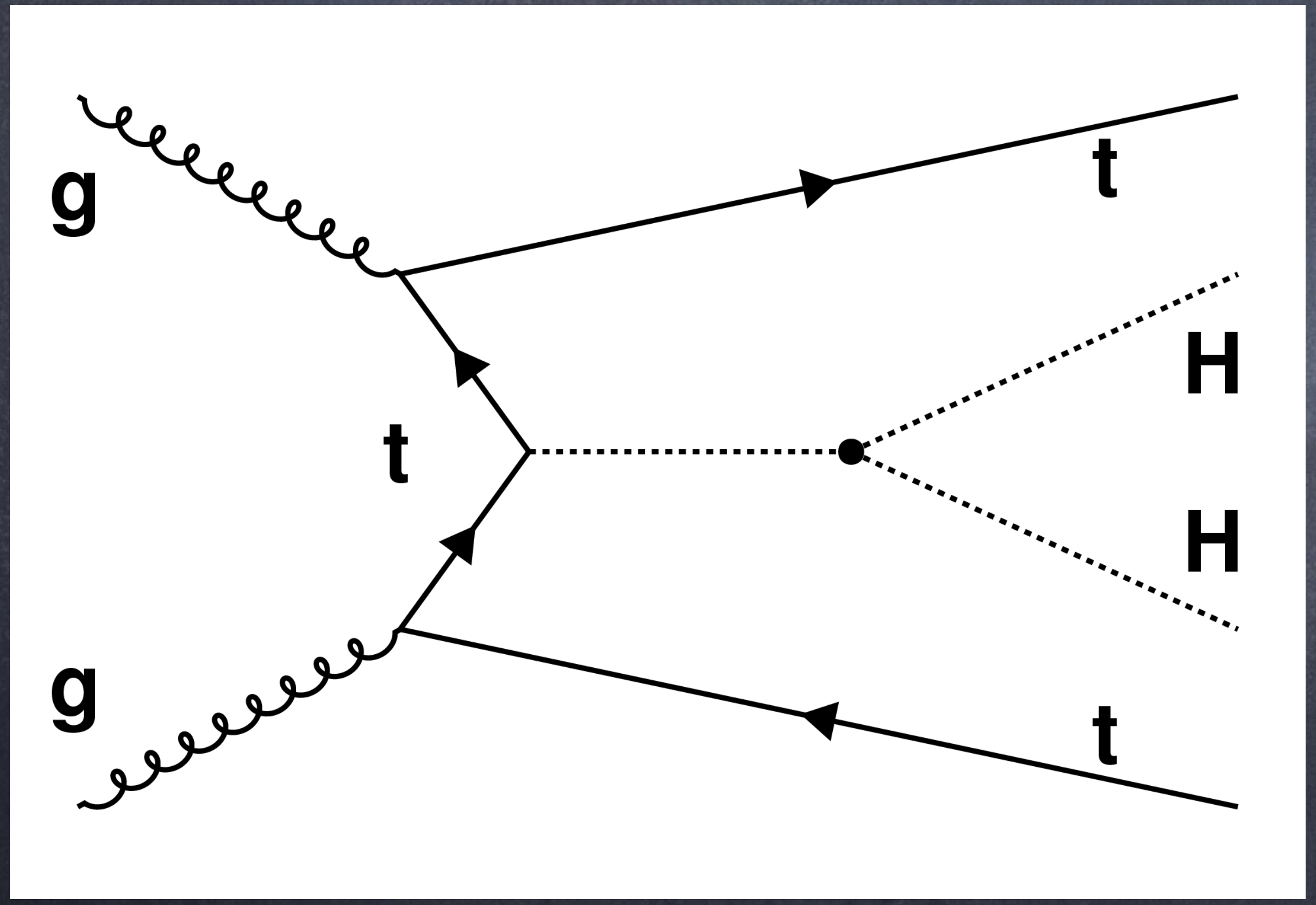
Understanding top & Higgs is not just about signal but also backgrounds

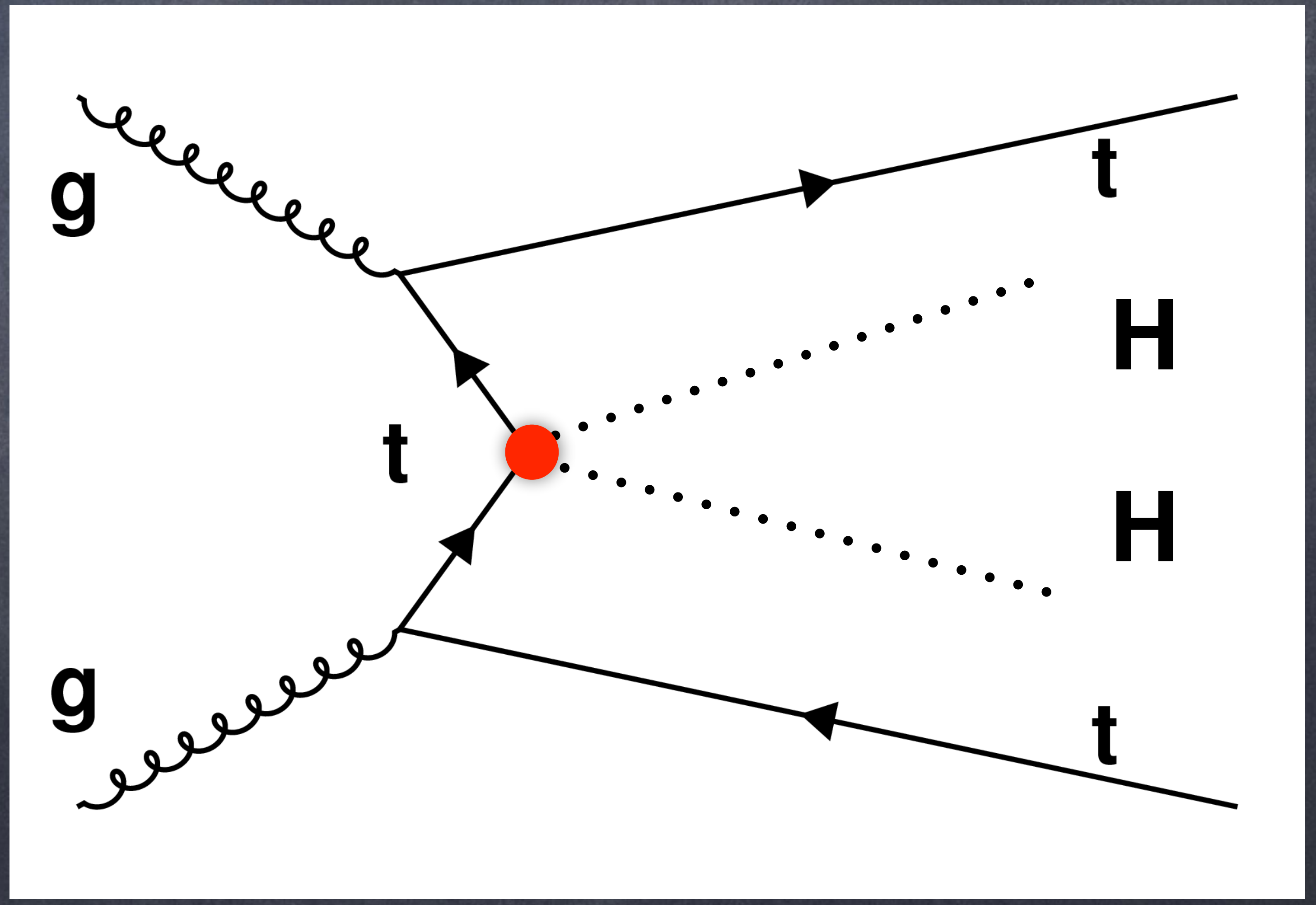
E.g. here importance of ttW

Next project:

ttHH production

Process directly sensitive to the ttHH coupling (non-linearity effect)





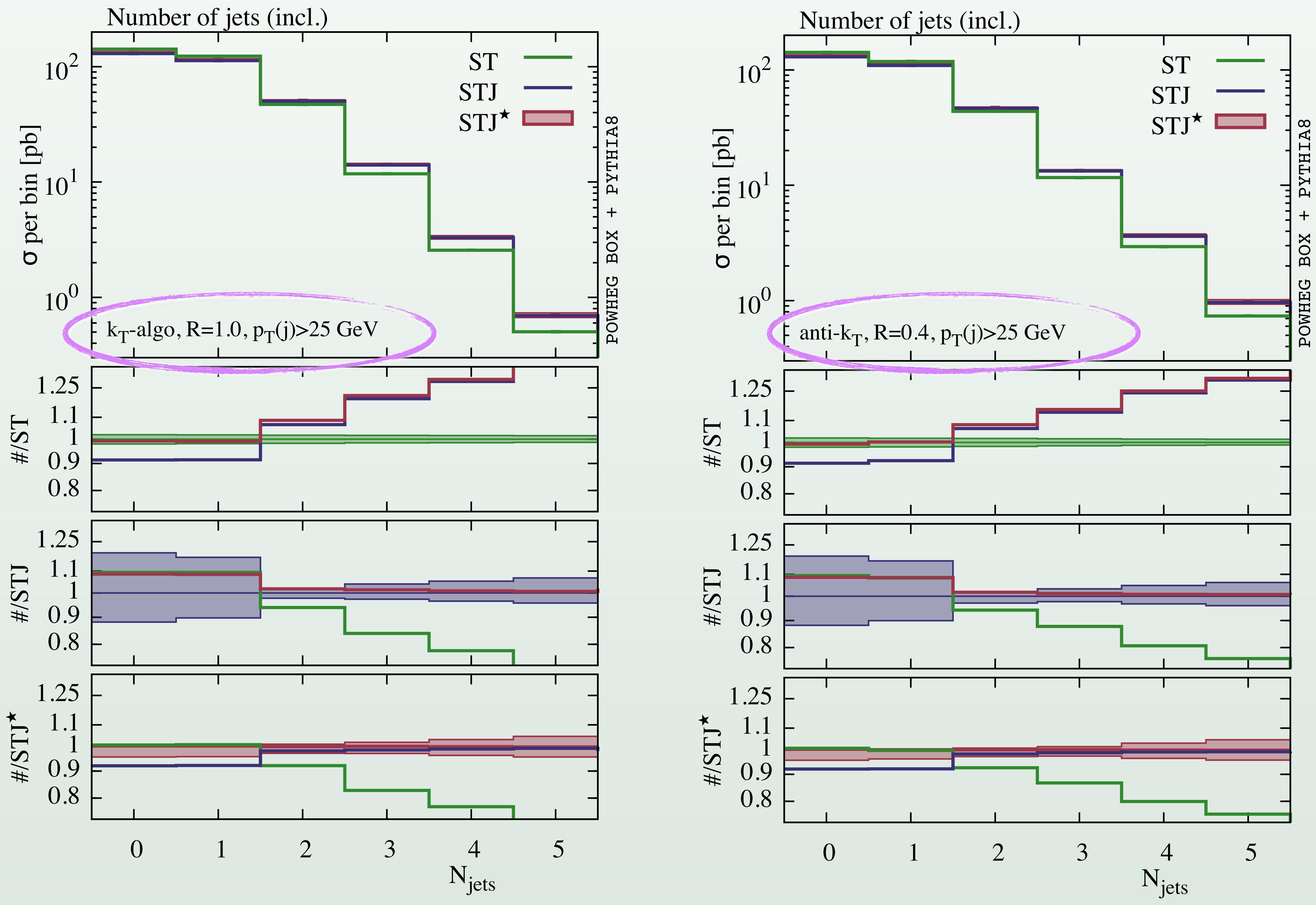
Giacomo Cacciapaglia

rich future for thinking about top & Higgs from BSM point of view

differential top production

Rikkert Frederix

Single top Inclusive jet rates

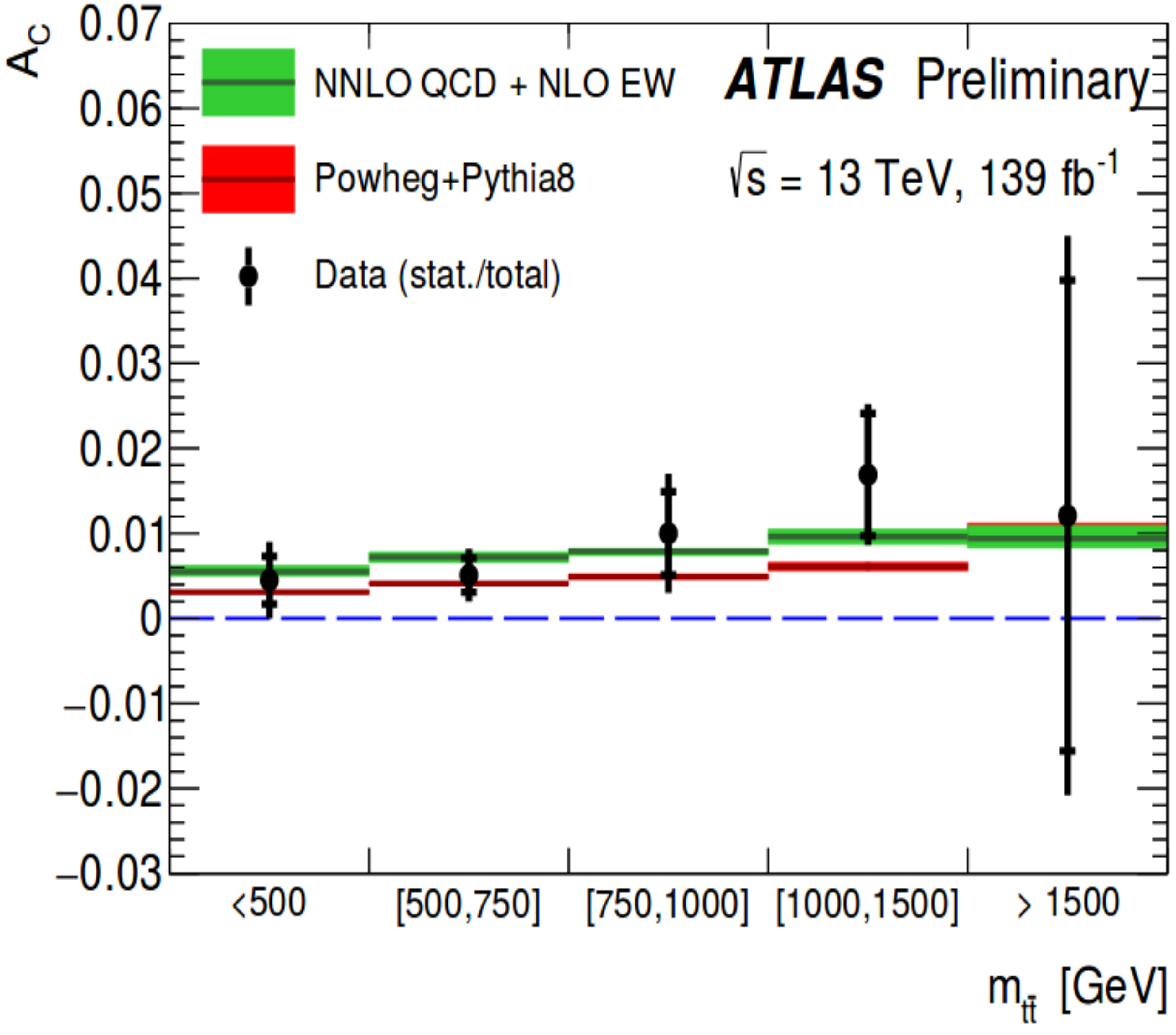


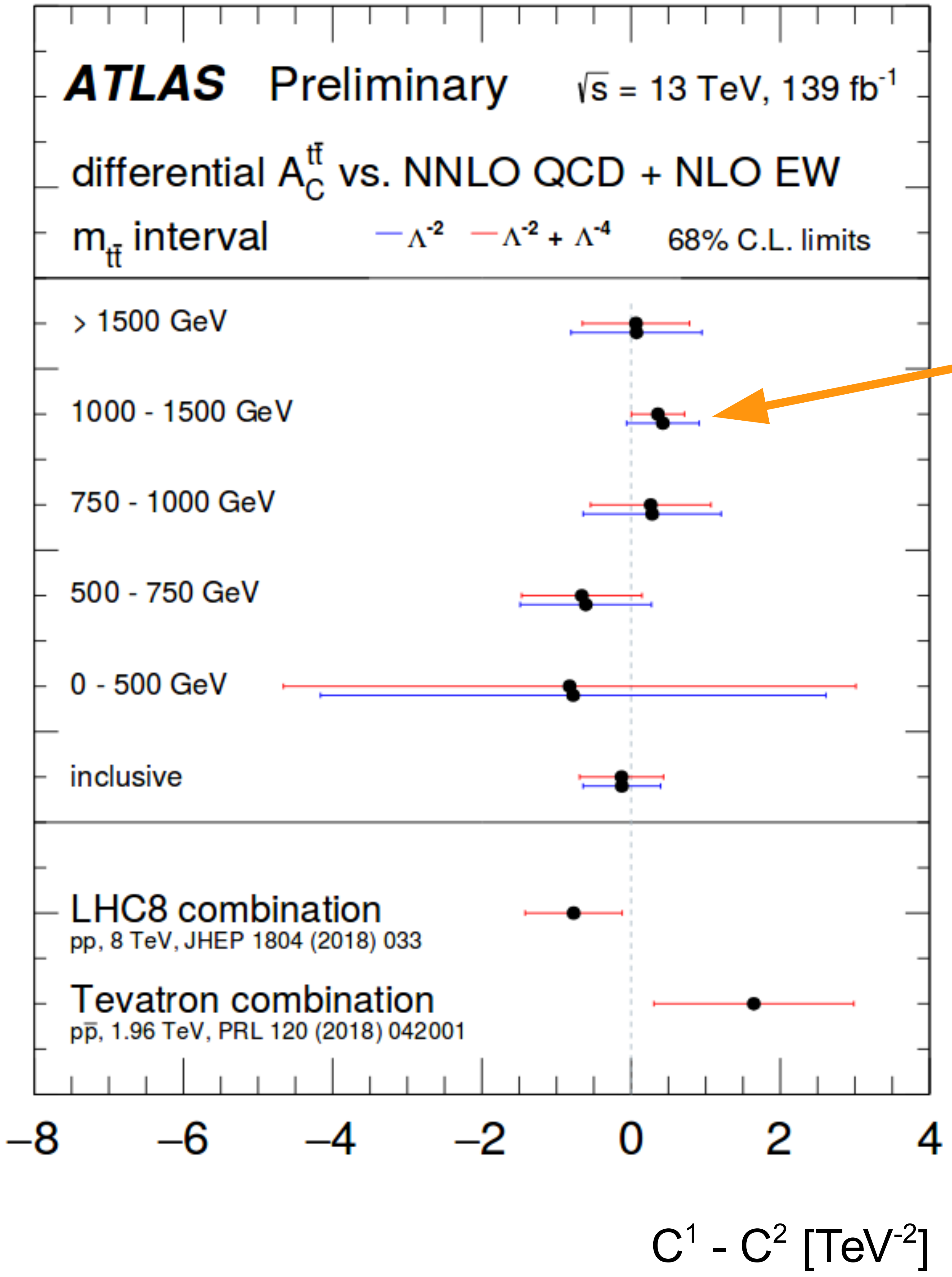
- For $N_{jets} \geq 0,1$ bins **ST** is NLO accurate; for $N_{jets} \geq 2$ bin the **STJ** is NLO accurate
- **STJ*** is NLO accurate in the first three bins
- Excellent agreement among results where expected
- Due to POWHEG methodology the uncertainty bands for the higher-multiplicity bins artificially small

tH is key to controlling sign of y_t

Understanding single top is key first step to controlling tH

Differential distributions and EFT constraints





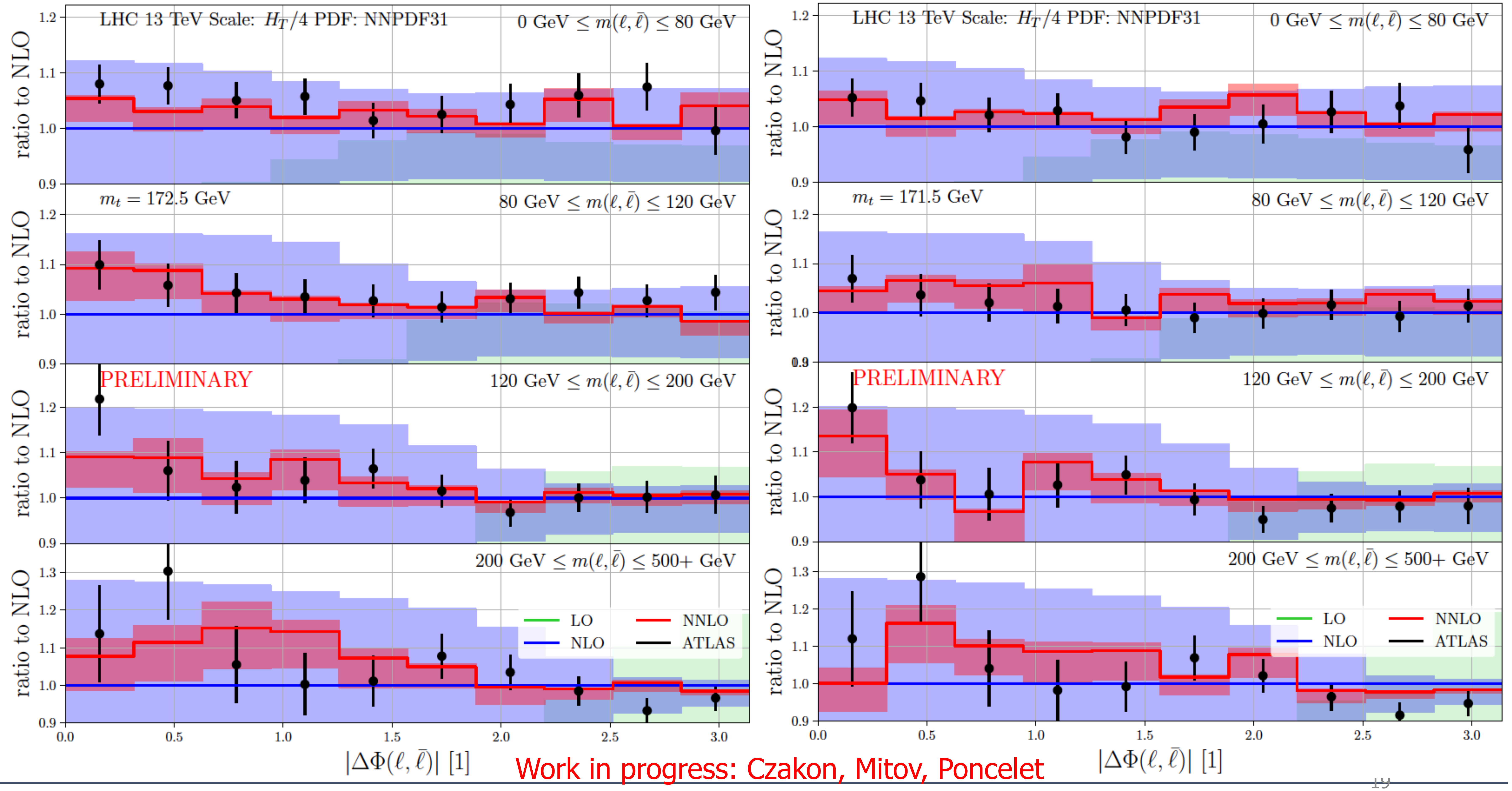
best trade off between $m_{t\bar{t}}$ EFT enhancement and A_c precision

Alexander Grohsjean

NNLO QCD vs ATLAS data: 2-dim

Alex Mitov

- ✓ **Δφ** vs. m(tt) (others are computed, too, not shown)
  - ✓ Great reduction of scale error at NNLO (vs NLO). Mostly small K-factors
  - ✓ Both m_t=171.5GeV and m_t=172.5GeV seem to work
  - ✓ Improved MC error required to draw quantitative conclusion (m_t sensitivity is apparent)



Work in progress: Czakon, Mitov, Poncelet

precise comparisons with leptonic data

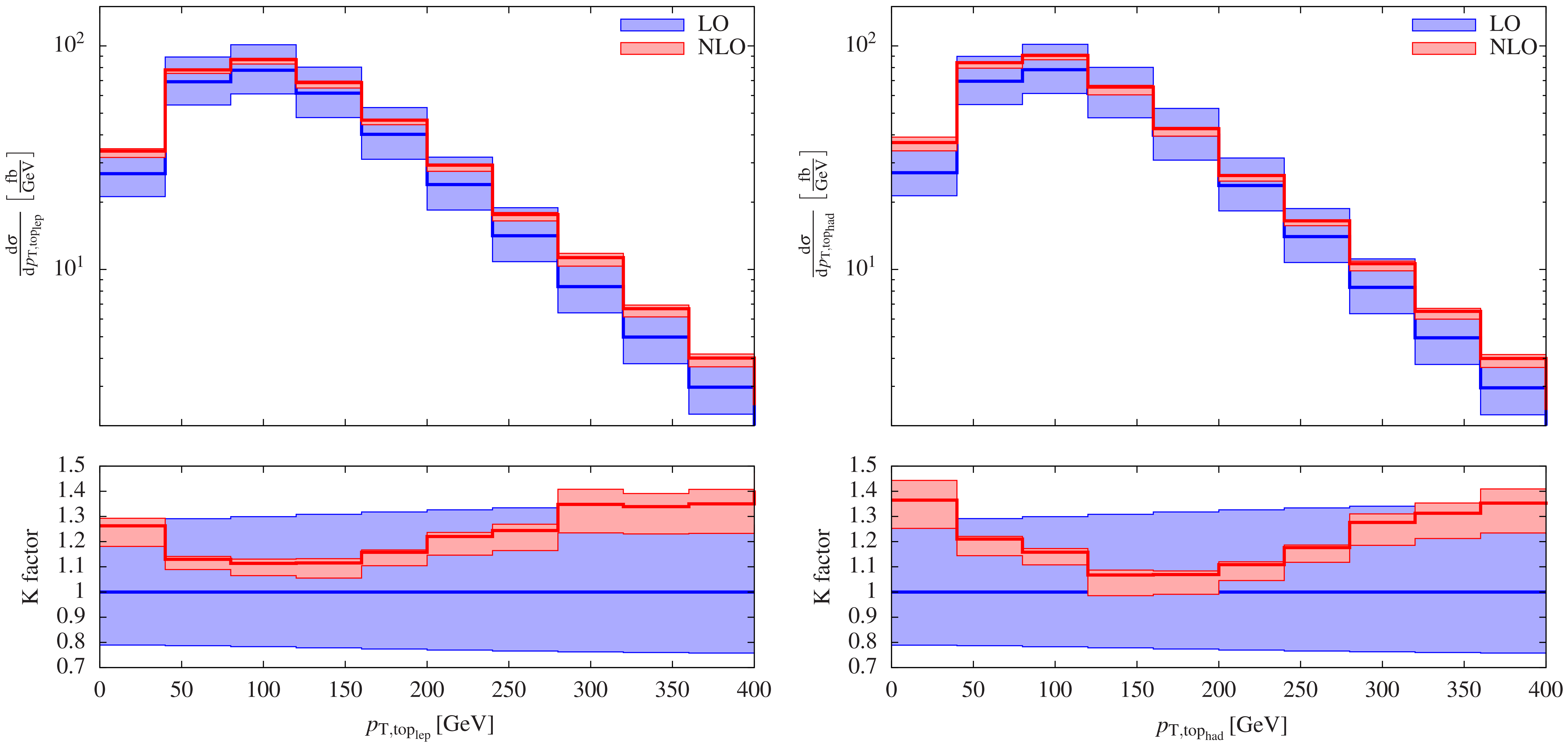
data is with 36 fb^{-1}

so $\sim \times 2$

improvement to come with current data

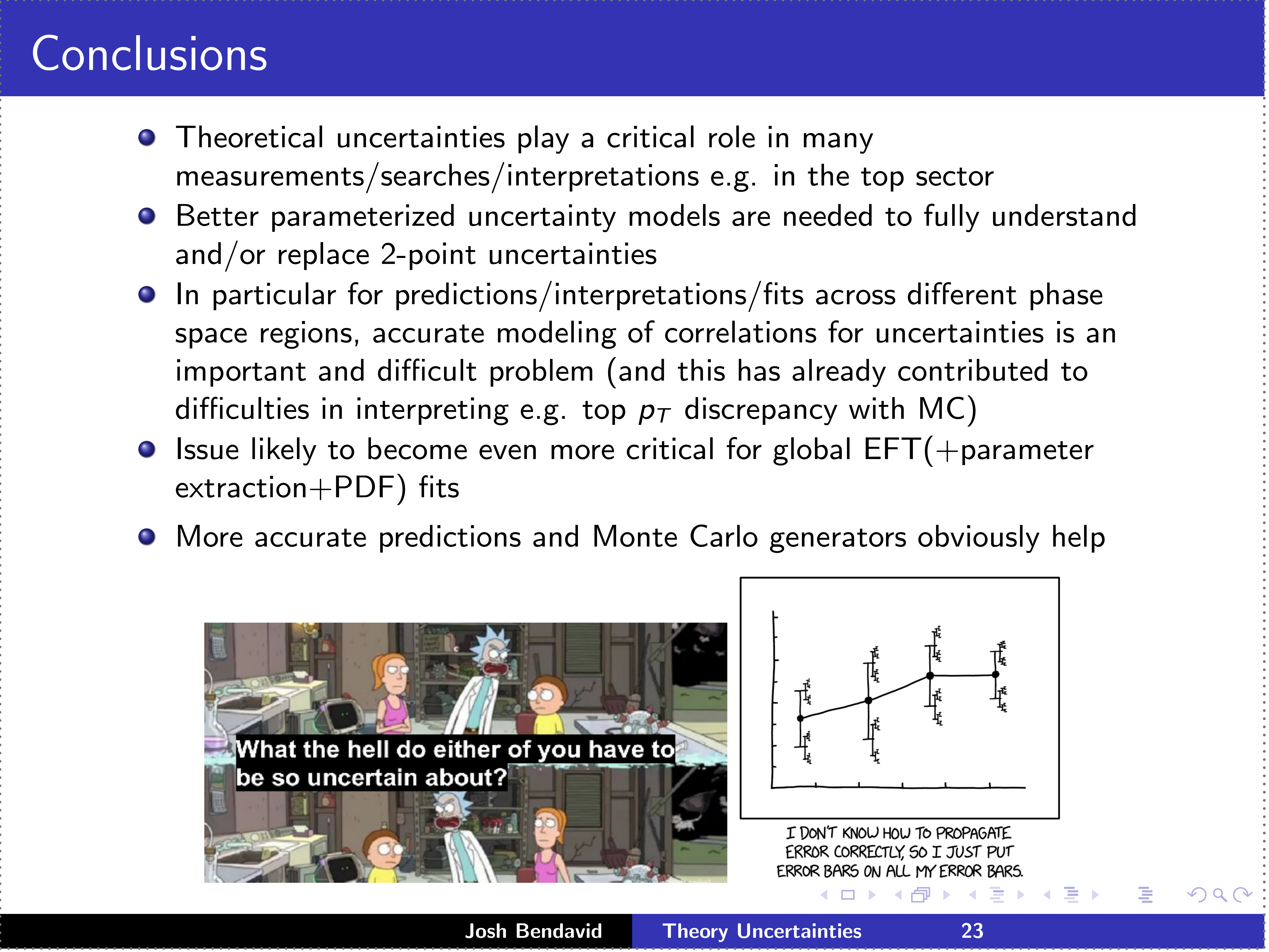
3) NLO QCD to off-shell pp → $\mu^-\bar{\nu}_\mu b\bar{b}jj$

Mathieu Pellen



[Denner, MP; 1711.10359]

→ Different NLO behaviour between the hadronic and leptonic top quark



Conclusions

- Theoretical uncertainties play a critical role in many measurements/searches/interpretations e.g. in the top sector
- Better parameterized uncertainty models are needed to fully understand and/or replace 2-point uncertainties
- In particular for predictions/interpretations/fits across different phase space regions, accurate modeling of correlations for uncertainties is an important and difficult problem (and this has already contributed to difficulties in interpreting e.g. top p_T discrepancy with MC)
- Issue likely to become even more critical for global EFT(+parameter extraction+PDF) fits
- More accurate predictions and Monte Carlo generators obviously help

I DON'T KNOW HOW TO PROPAGATE ERROR CORRECTLY, SO I JUST PUT ERROR BARS ON ALL MY ERROR BARS.

Josh Bendavid

one problem in understanding correlations of uncertainties is that our main method for estimating uncertainties (scale variation) is a convention, rather than motivated by some deeper physics understanding

top mass

A plot we've all seen many times

Degrassi et al. 2012

Véronique Boisvert

~~“MC” mass~~

kinematic reconstruction of individual top quarks

CMS l+jets: 172.25 ±0.63 (0.37%)

ATLAS SMT: 174.48 ±0.78 (0.45%)

ATLAS Comb.: 172.69 ±0.48 (0.28%)

CMS Comb.: 172.44 ±0.48 (0.28%)

Tevatron Comb.: 174.30 ±0.65 (0.37%)

World Comb.: 173.34 ±0.76 (0.44%)

~~Pole mass~~

kinematic reconstruction of $t\bar{t}$ (+jets) system

ATLAS tt+1 jet: 171.1 +1.2 - 1.0 (0.7%)

CMS 3D diff: 170.9 ±0.8 (0.47%)

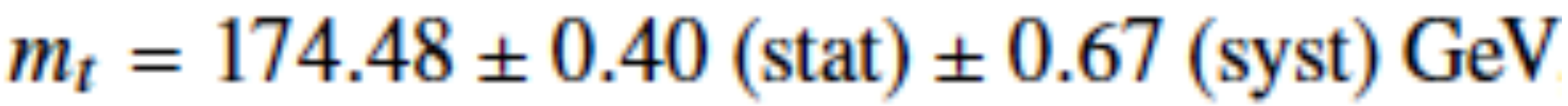
Véronique Boisvert

CMS: 3d cross-section fit

170.9 ±0.8 (0.47%)

3.2-σ difference — problematic or not?

ATLAS $\ell + (b \to)\mu$



$$m_t = 174.48 \pm 0.40\ (\mathrm{stat}) \pm 0.67\ (\mathrm{syst})\ \mathrm{GeV}$$

174.48 ±0.78 (0.45%)

~~"MC" mass~~

CMS l+jets: 172.25 ±0.63 (0.37%)

ATLAS SMT: 174.48 ±0.78 (0.45%)

ATLAS Comb.: 172.69 ±0.48 (0.28%)

CMS Comb.: 172.44 ±0.48 (0.28%)

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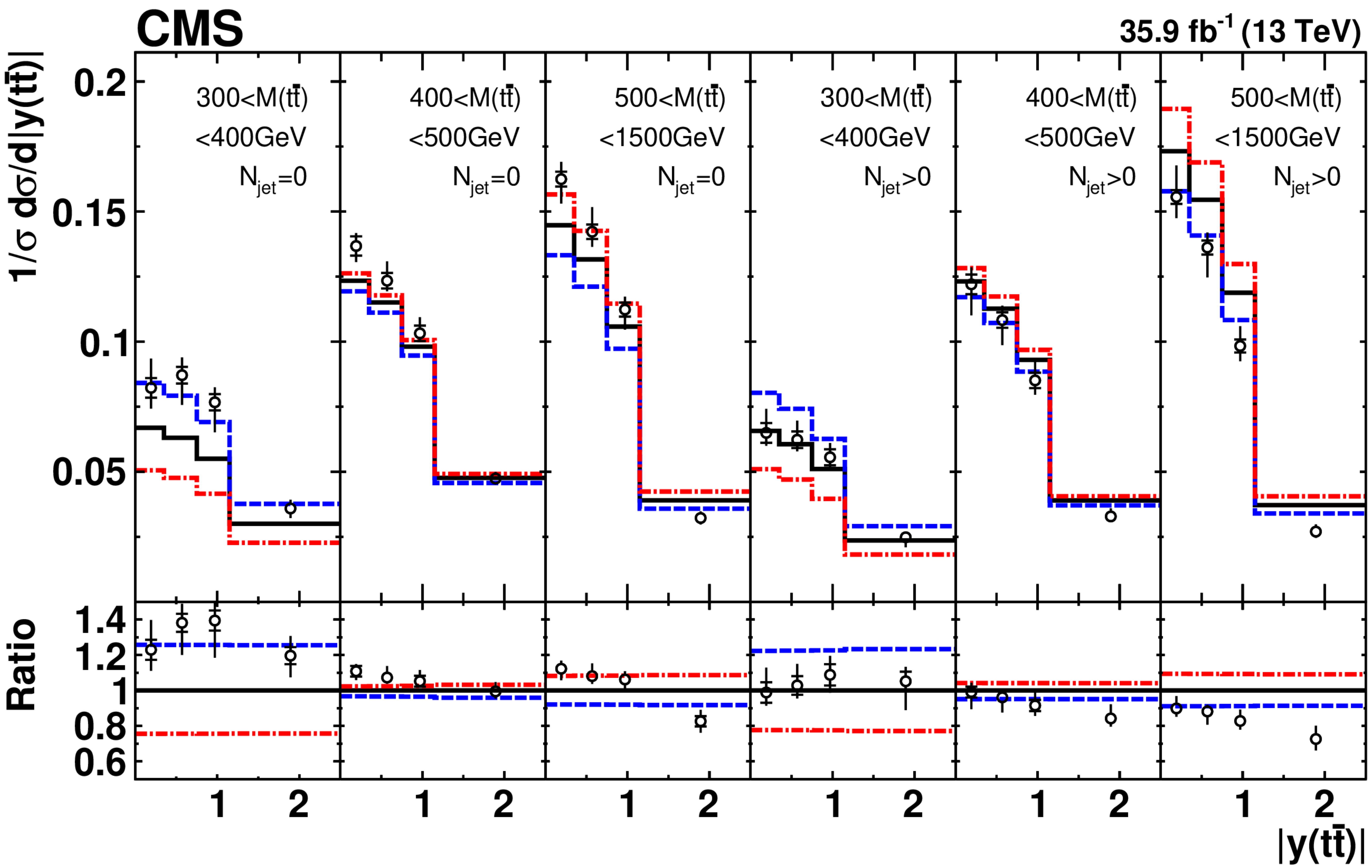
World Comb.: 173.34 ±0.76 (0.44%)

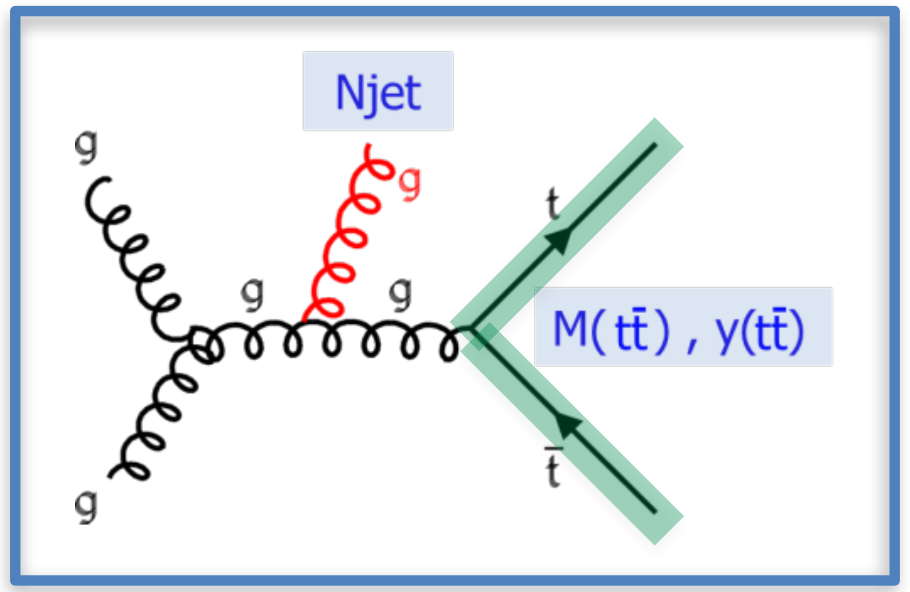
~~Pole mass~~

ATLAS tt+1 jet: 171.1 +1.2 - 1.0 (0.7%)

CMS 3D diff: 170.9 ±0.8 (0.47%)

Results: $[N_{jet}^{0,1+}, M(t\bar{t}), y(t\bar{t})]$ vs NLO with diff. m_t^{pole}





→ m_t^{pole} sensitivity mainly from first m(tt̄) bin

- *m_t^{pole} extraction technique follows: D0 results* [FERMILAB-CONF-16-383-PPD]

Olaf Behnke

should we fit everything?

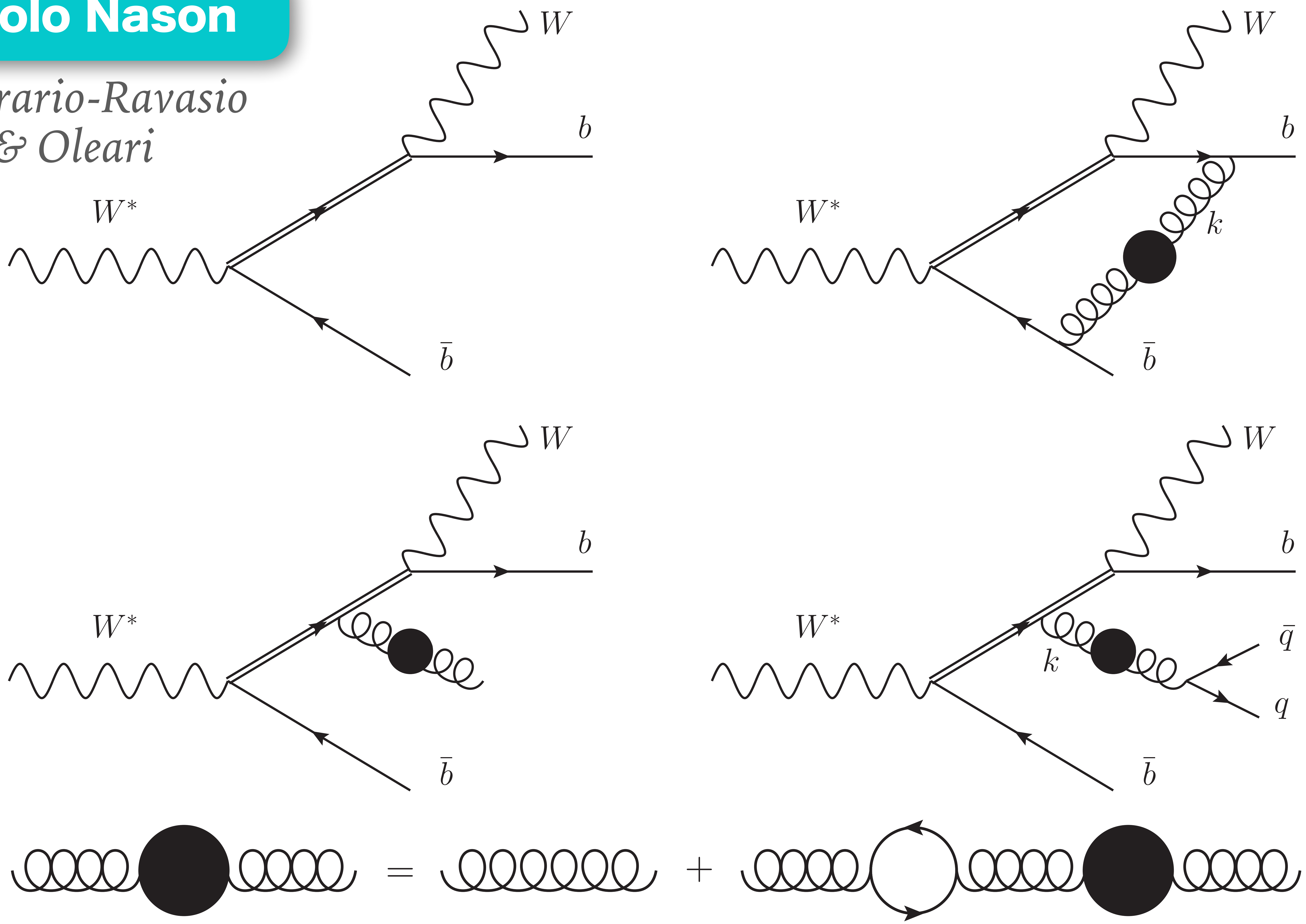
only if we understand everything

e.g. origins of dependence on m_{top} & α_s in each bin and degree of theory control over each bin

Diagrams up to leading N_f one gluon correction

Paolo Nason

+Ferrario-Ravasio & Oleari



revolution in treatment of non-perturbative effects

ultimate impact likely well beyond top physics

Prospects

Paolo Nason

- With some work, the renormalon approach can help to search for top mass observables that are free from linear renormalons.
- One may discuss calibration of jets on a theoretically sound ground.
- The fact that top CM leptonic distributions are free from linear renormalon may be exploited further.

Kawabata,Shimizu,Sumino,Yokoya,2013,2014 have proposed a method to measure physical parameters in the decay of a massive object involving a light lepton using only the lepton spectrum, and have proposed to apply it for the measurement of the top mass.

NB: jets are sensitive also to underlying event / MPI, for which we don't have comparable theory

Leptonic observables may be the only theoretically clean route?

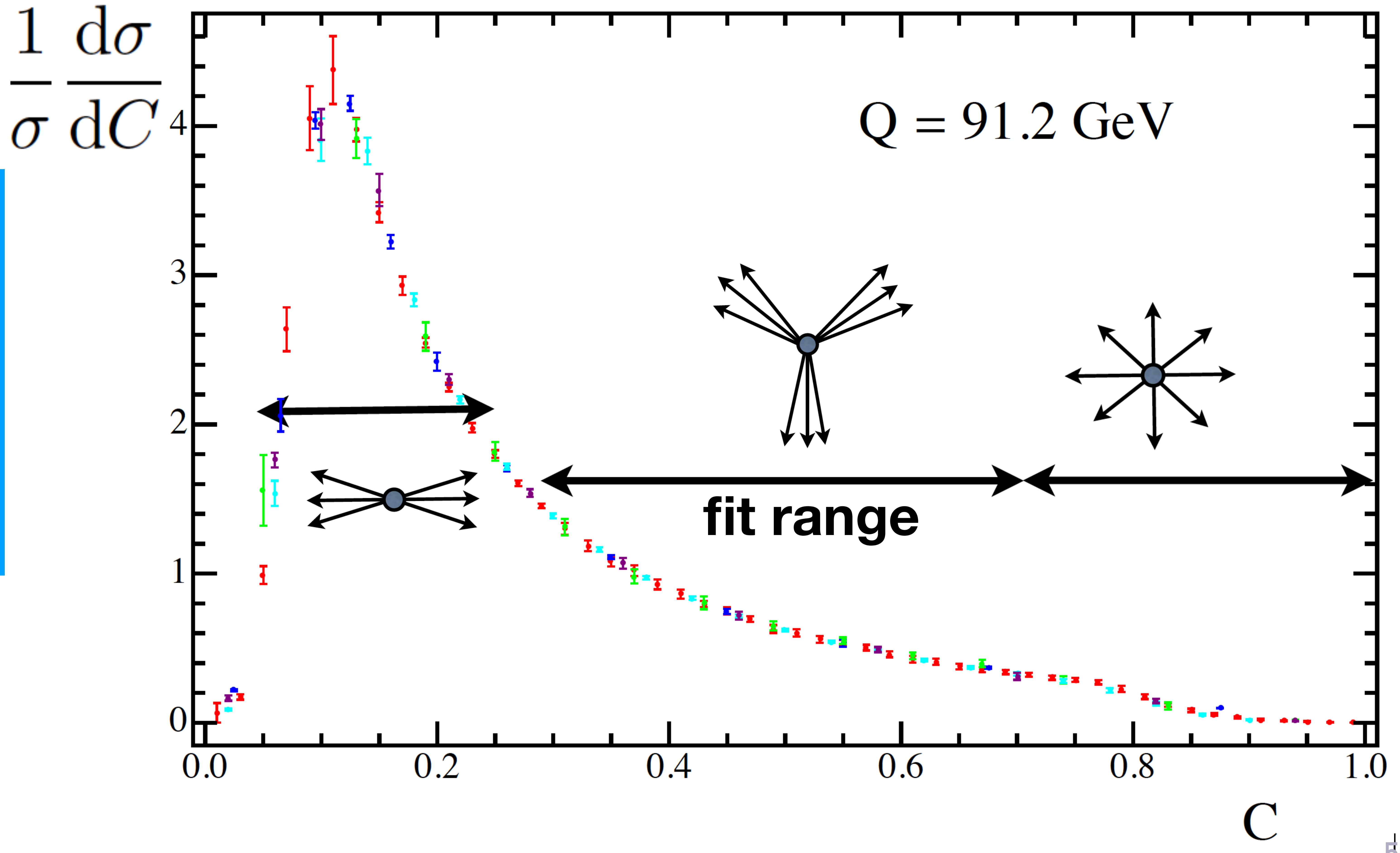
[modulo cuts to select $t\bar{t}$ events]

AN EXAMPLE: C PARAMETER

$$C = 3 - \frac{3}{2}\sum_{i,j}\frac{(p_i \cdot p_j)^2}{(p_i \cdot Q)(p_j \cdot Q)}$$

- Analytic power correction coefficient calculated in the 2-jet limit
- Fit of the coupling performed in the 3-jet regime (contribution from gluon jet substantial)

[Plot by V. Mateu]



Fit performed with state of the art PT (N^{3}LL+NNLO) returns a low value for the coupling, with small error

$$\alpha_s(M_Z^2) = 0.1123 \pm 0.0015$$

[Hoang, Kolodrubetz, Mateu, Stewart '15]

[slide from Pier Monni]

AN EXAMPLE: C PARAMETER

$$d\sigma^{\mathrm{hadron}}_{\mathrm{MC}}(\mathcal{O}) \simeq d\sigma^{\mathrm{parton}}_{\mathrm{MC}}\left(\mathcal{O} - \frac{\alpha_0}{Q}\Delta(\mathcal{O})\right)$$

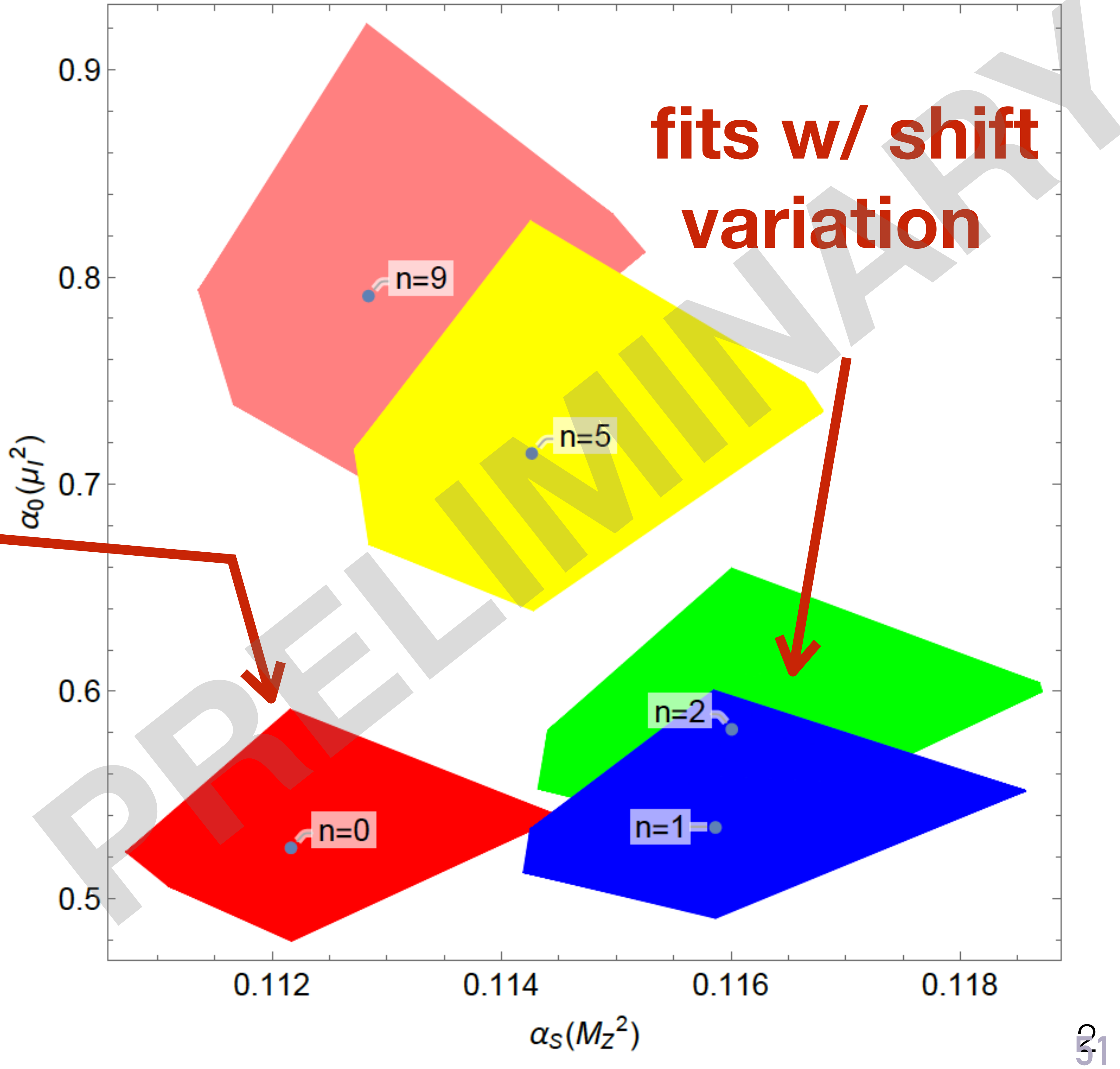
- Analytic power correction coefficient calculated in the 2-jet limit
- Fit of the coupling performed in the 3-jet regime (contribution from gluon jet substantial)
  - [**NEW**] direct calculation of leading power correction in the 3-jet symmetric limit reveals that $\Delta(\mathcal{O})$ is not constant & hadronisation is overestimated in the fit region

$$\Delta^{\mathrm{symm.}}_{3-\mathrm{jet}}(\mathcal{O}) \lesssim \frac{\Delta_{2-\mathrm{jet}}(\mathcal{O})}{2}$$

Variation of non-perturbative shift impacts αs fits by 3%-4% (becomes compatible with WA)

Luisoni, Monni & GPS (in prep.)

Impact on αs fits



Standard fit (constant shift)

fits w/ shift variation

[slide from Pier Monni]

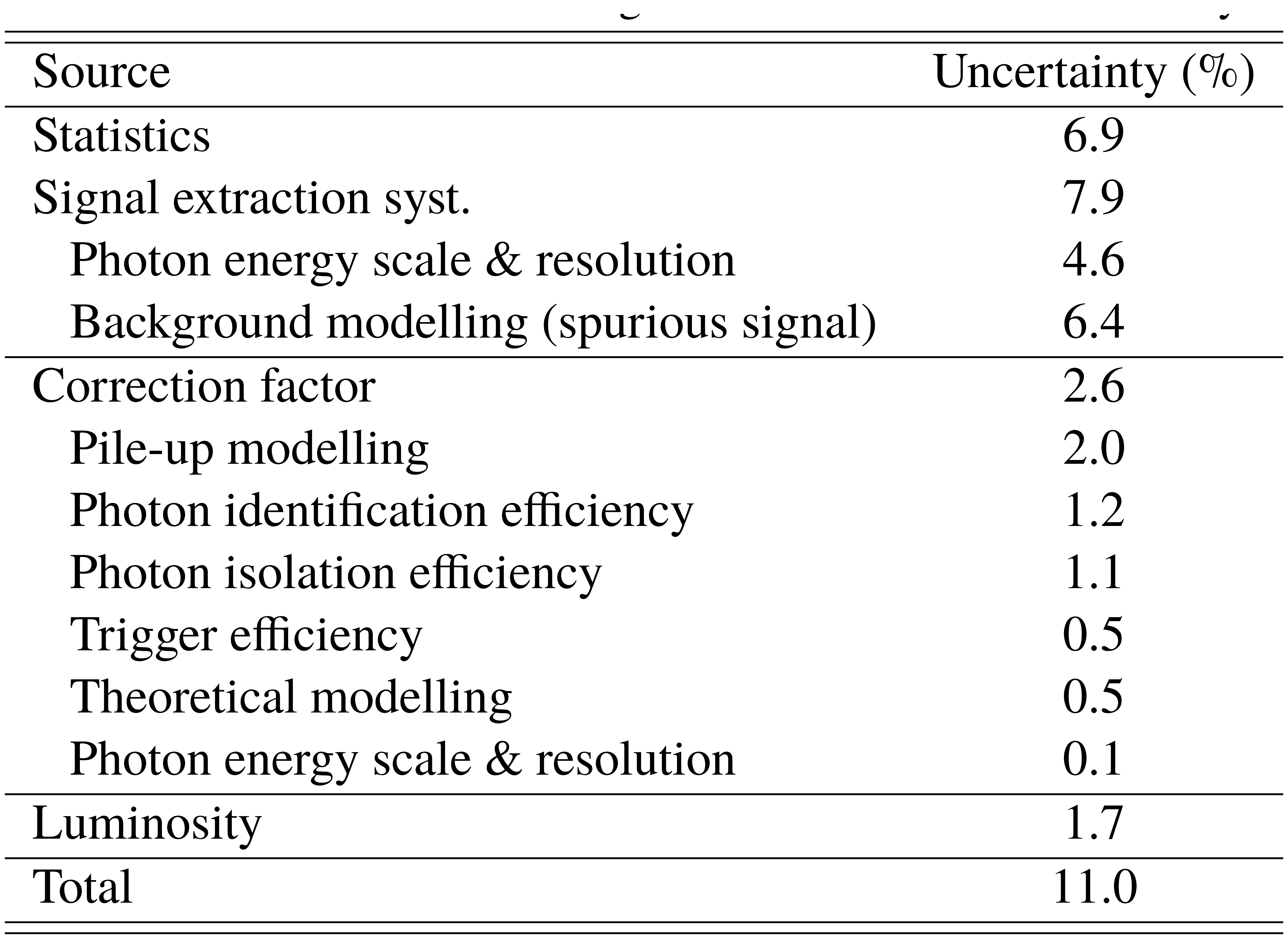
Conclusions

conclusions

- LHC has been doing precision for vector-boson production for some years
- what's new is that this is extending to Higgs, top, etc., with much progress still to be expected over next 15–20 years
- all crucial to establishing the Higgs sector of the SM (not just H boson)
- Some routes to progress are "obvious" (in sense of what needs to be achieved)
  - higher-precision data
  - higher-precision perturbative QCD & EW calculations
- But we will also need to learn to do things in new ways
  - how we select observables to measure (according to what we're aiming for, e.g. top mass, EFT fits, etc.)
  - understanding non-perturbative physics, potentially at same level of precision as perturbative calculations (few %)

BACKUP

ATLAS Higgs γγ systematics (fiducial cross section)



Source	Uncertainty (%)
Statistics	6.9
Signal extraction syst.	7.9
Photon energy scale & resolution	4.6
Background modelling (spurious signal)	6.4
Correction factor	2.6
Pile-up modelling	2.0
Photon identification efficiency	1.2
Photon isolation efficiency	1.1
Trigger efficiency	0.5
Theoretical modelling	0.5
Photon energy scale & resolution	0.1
Luminosity	1.7
Total	11.0

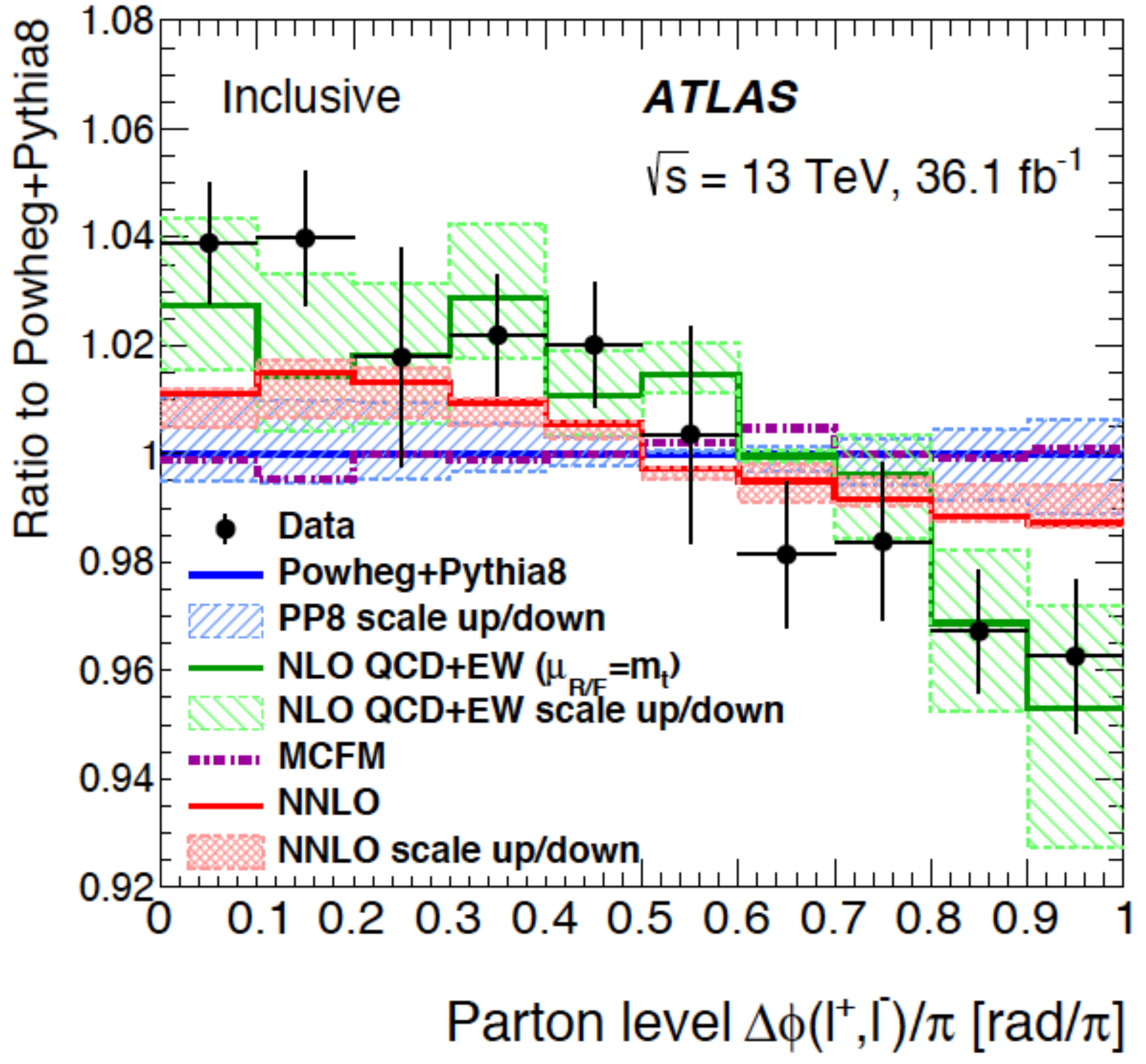
ATLAS-CONF-2019-029

compare CMS systematics?

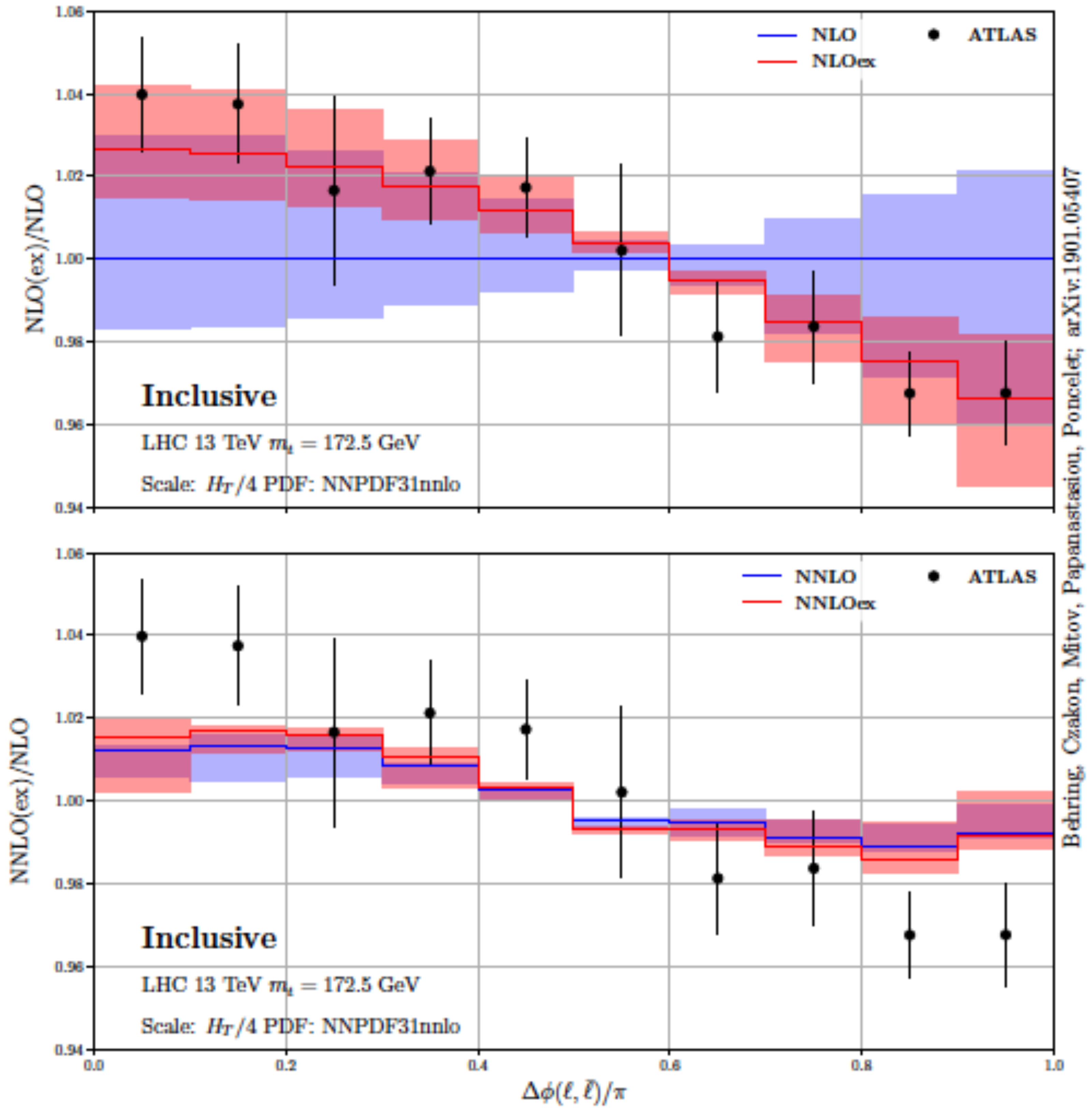
ttbar spin correlations

- ✓ QCD works! One can do the same expansion for the NNLO calculation

Behring, Czakon, Mitov, Papanastasiou, Poncelet arXiv:1901.05407



ATLAS: arXiv:1903.07570



- ✓ At NLO the expanded definition has big impact. It makes NLO agree with data.
- ✓ However at NNLO the difference is tiny. This implies, ultimately, there is no th/data agreement
- ✓ My understanding is the ATLAS plot will be updated given its important implications