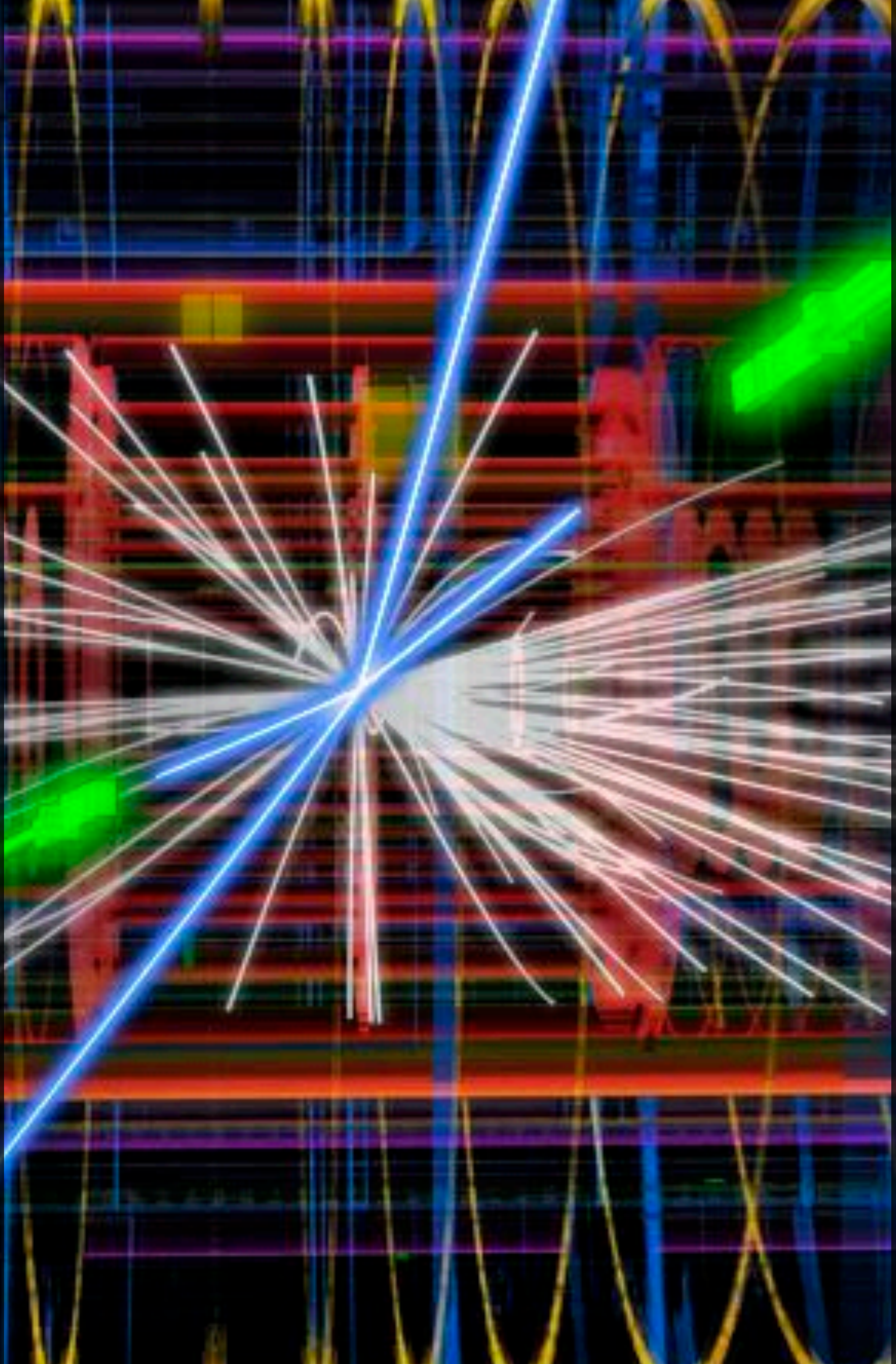
Amplitudes & beyond at the LHC

Gavin Salam*
Rudolf Peierls Centre for Theoretical Physics
& All Souls College, Oxford



Amplitudes 2020
Zoom@Brown
May 2020

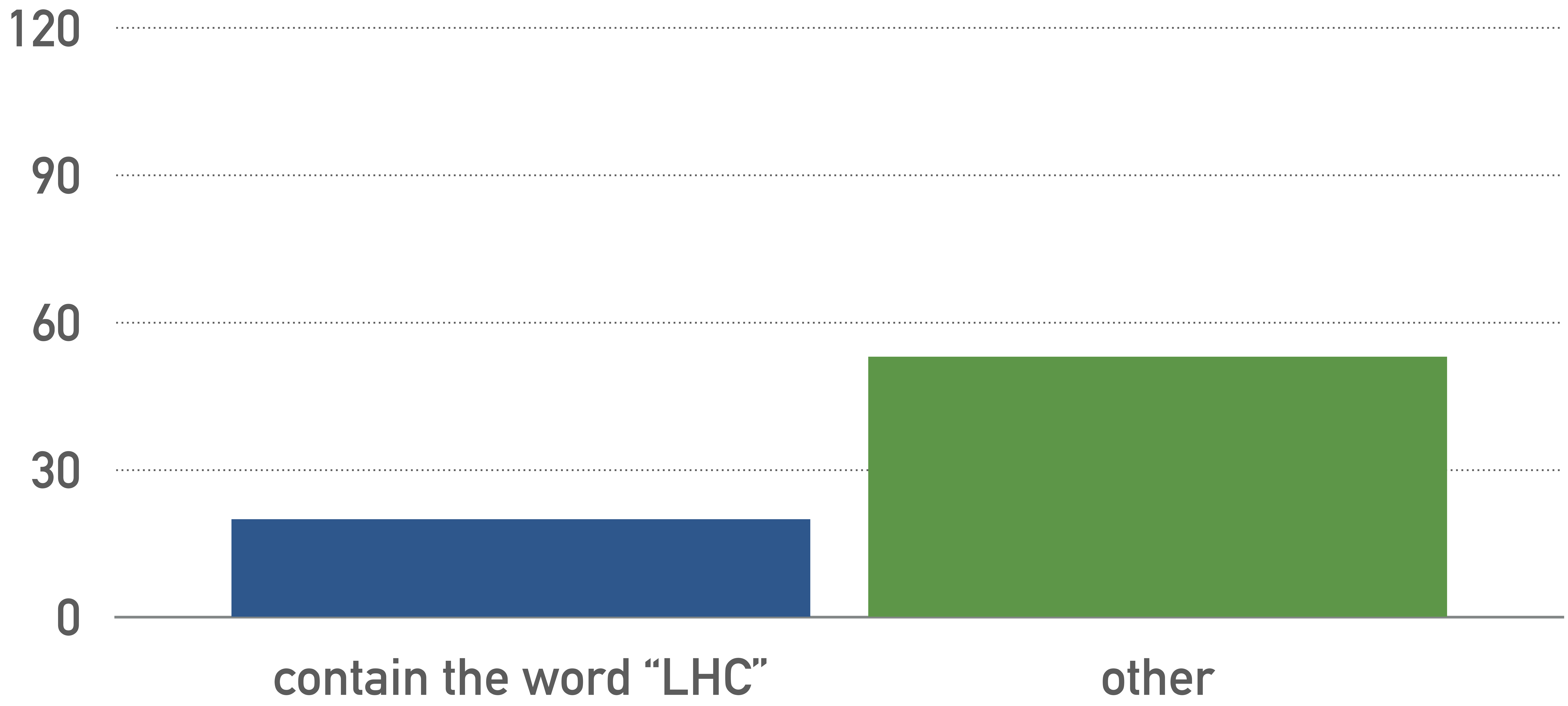
THE ROYAL SOCIETY

UNIVERSITY OF OXFORD

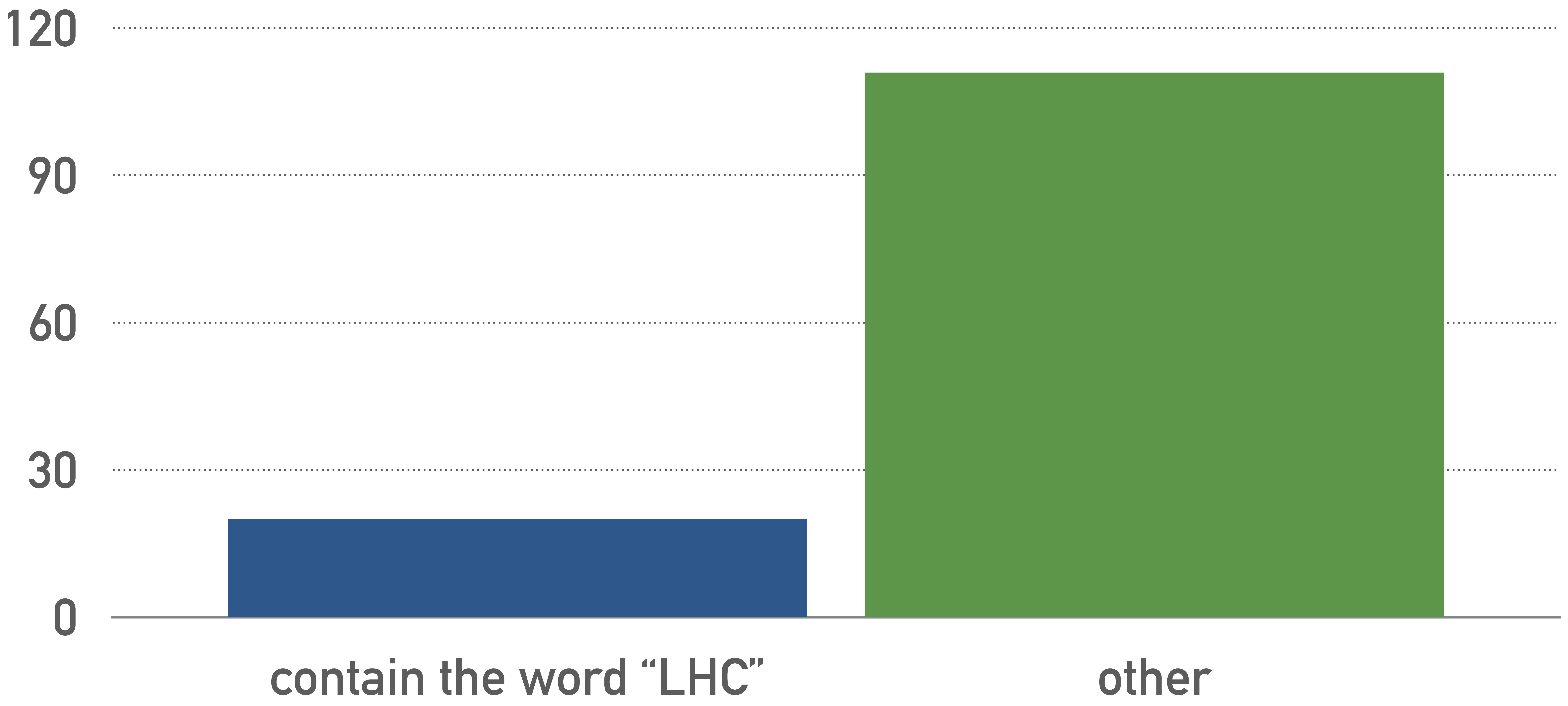
European Research Council
Established by the European Commission

** on leave from CERN and CNRS*

papers c. 2009 by Amplitudes 2009 speakers (3 from each)

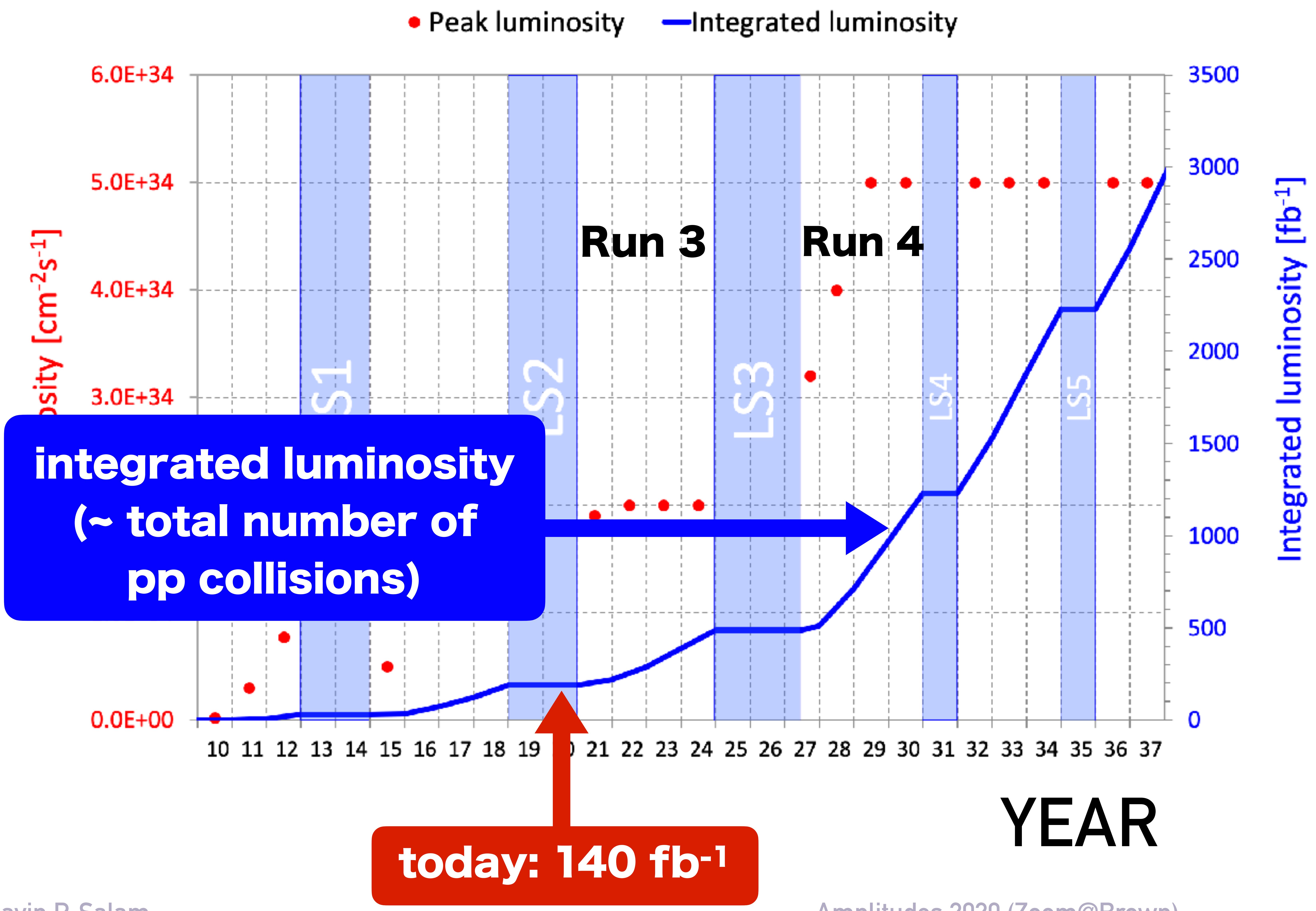


papers c. 2020 by Amplitudes 2020 speakers (3 from each)



experimental particle physics in the 2020 & 30s

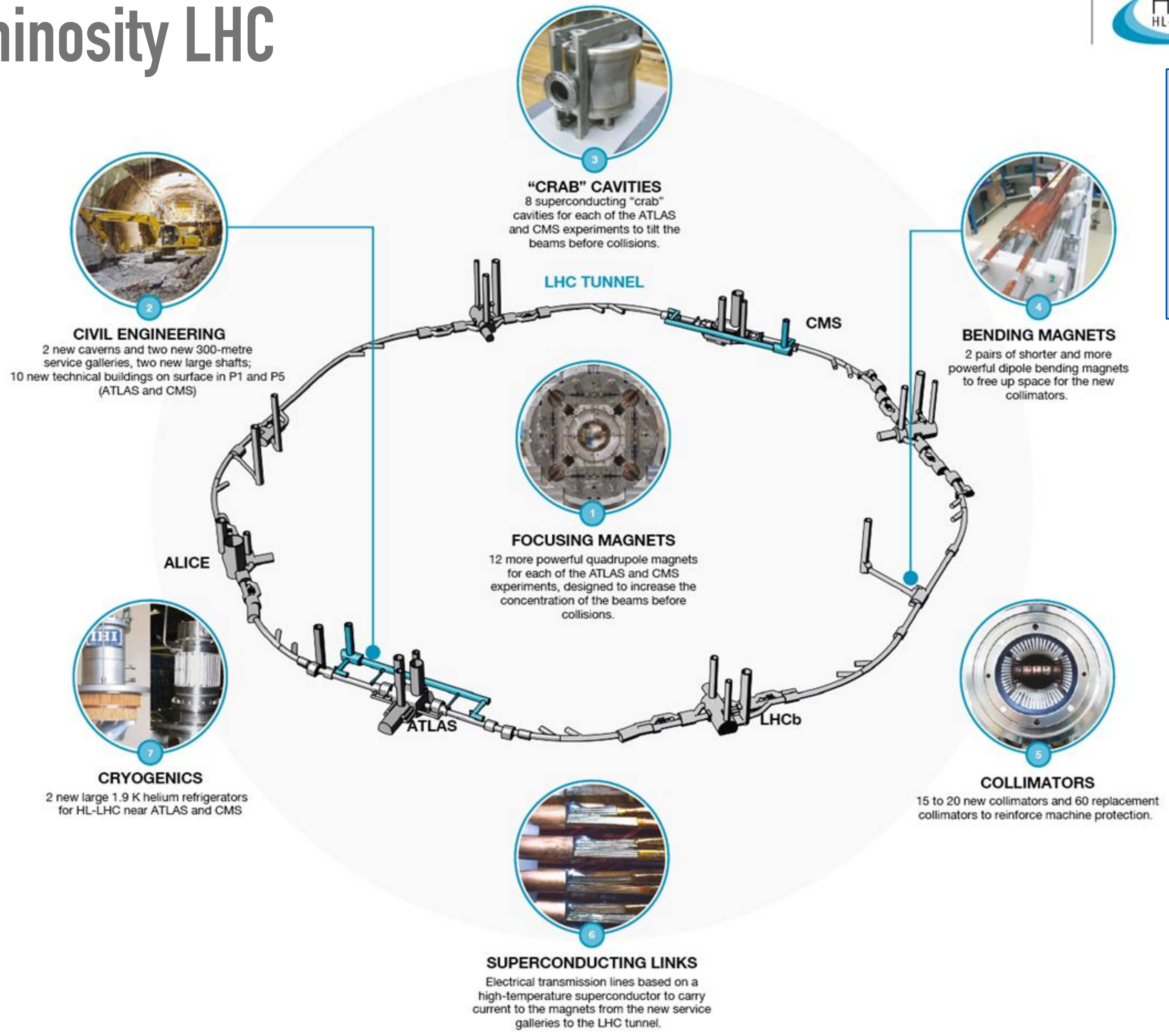
LHC luminosity v. time



year	lumi (fb^{-1})	
2020	140	
2025	450	(× 3)
2030	1200	(× 8)
2037	3000	(× 20)

95% of collisions still to be delivered

High-luminosity LHC

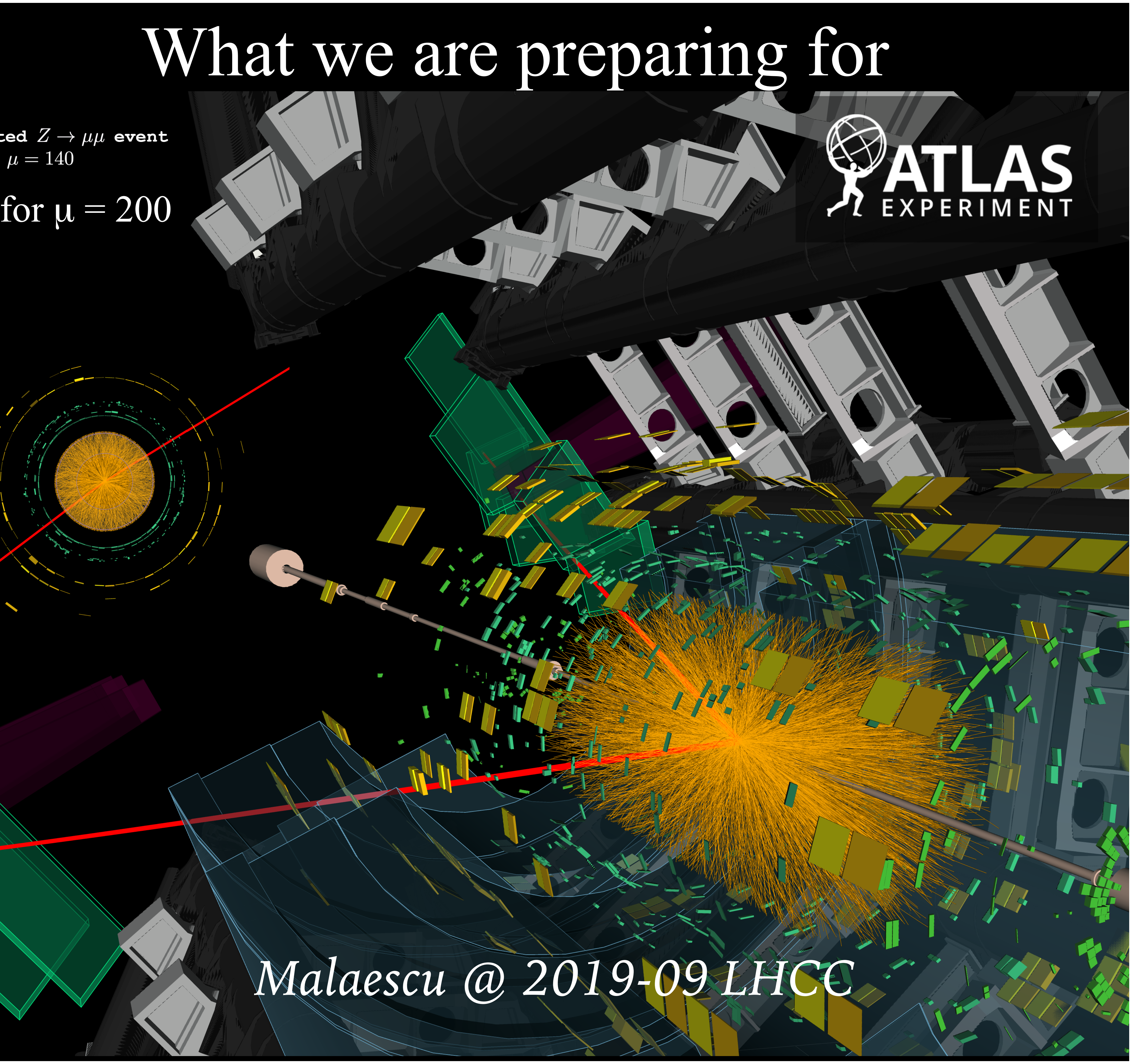


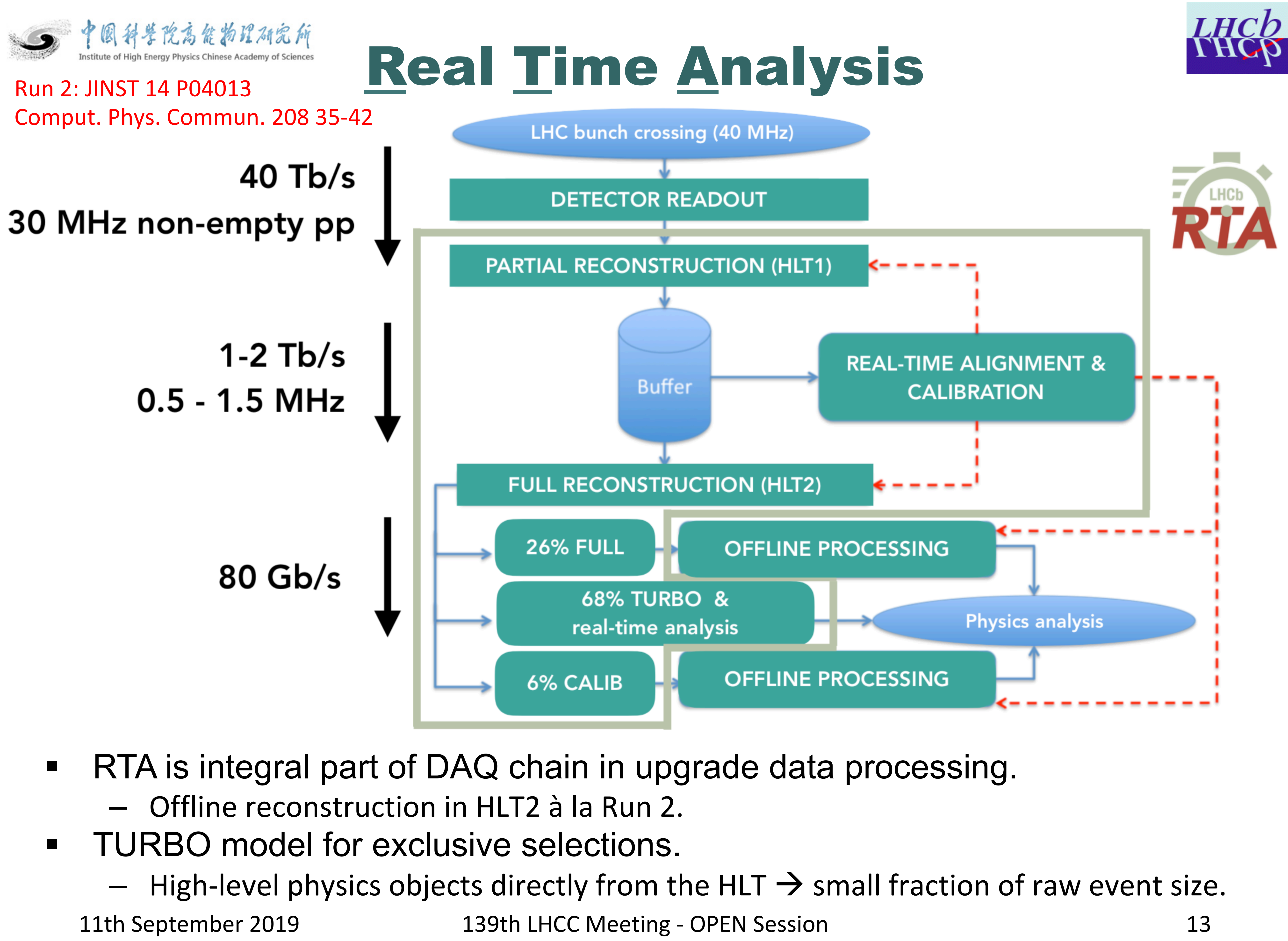
Rebuilding ~1.2km of LHC (the most complicated bit!)

But also touches very many other systems around the machine

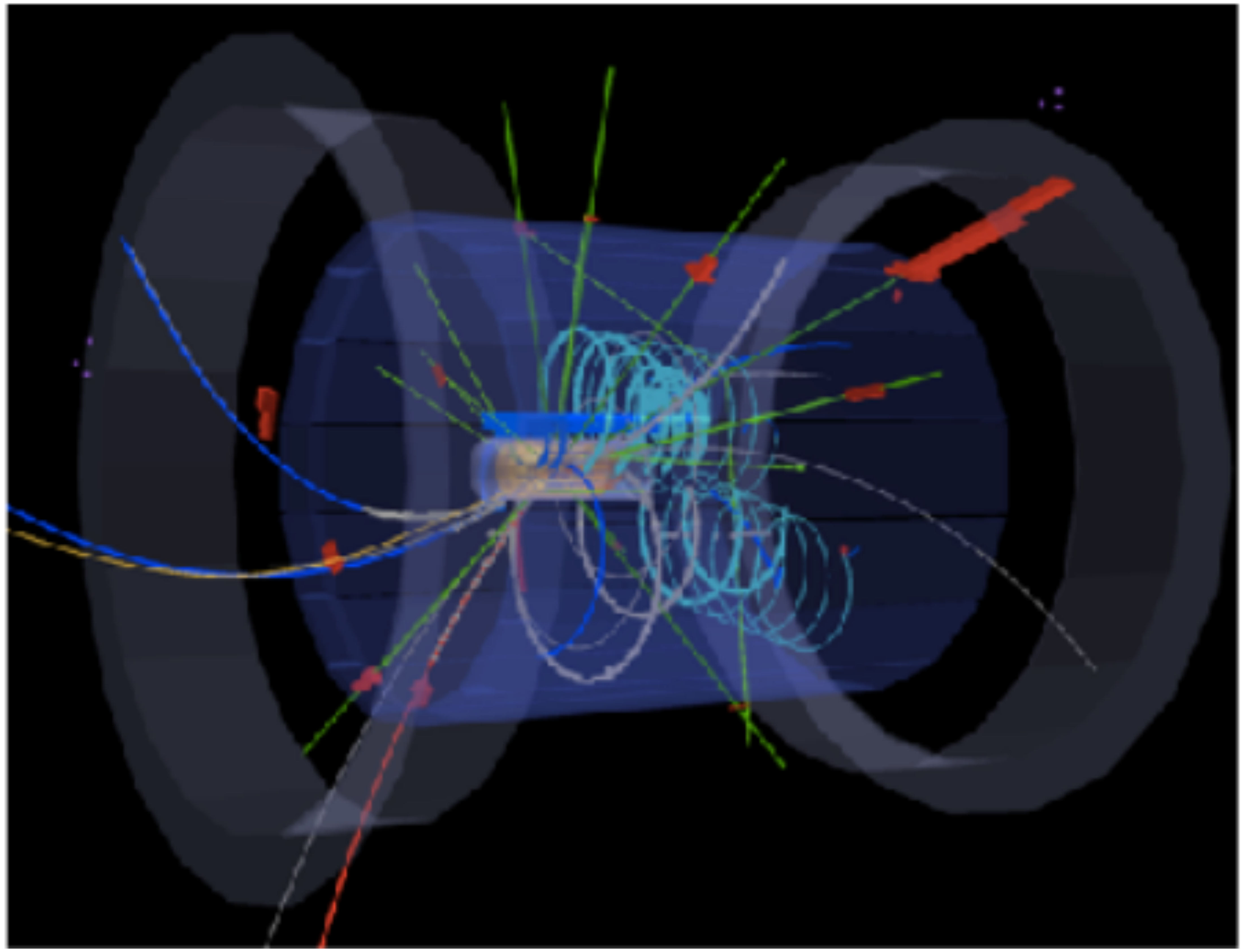
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Other NbTi magnets in the IR
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

huge experimental advances



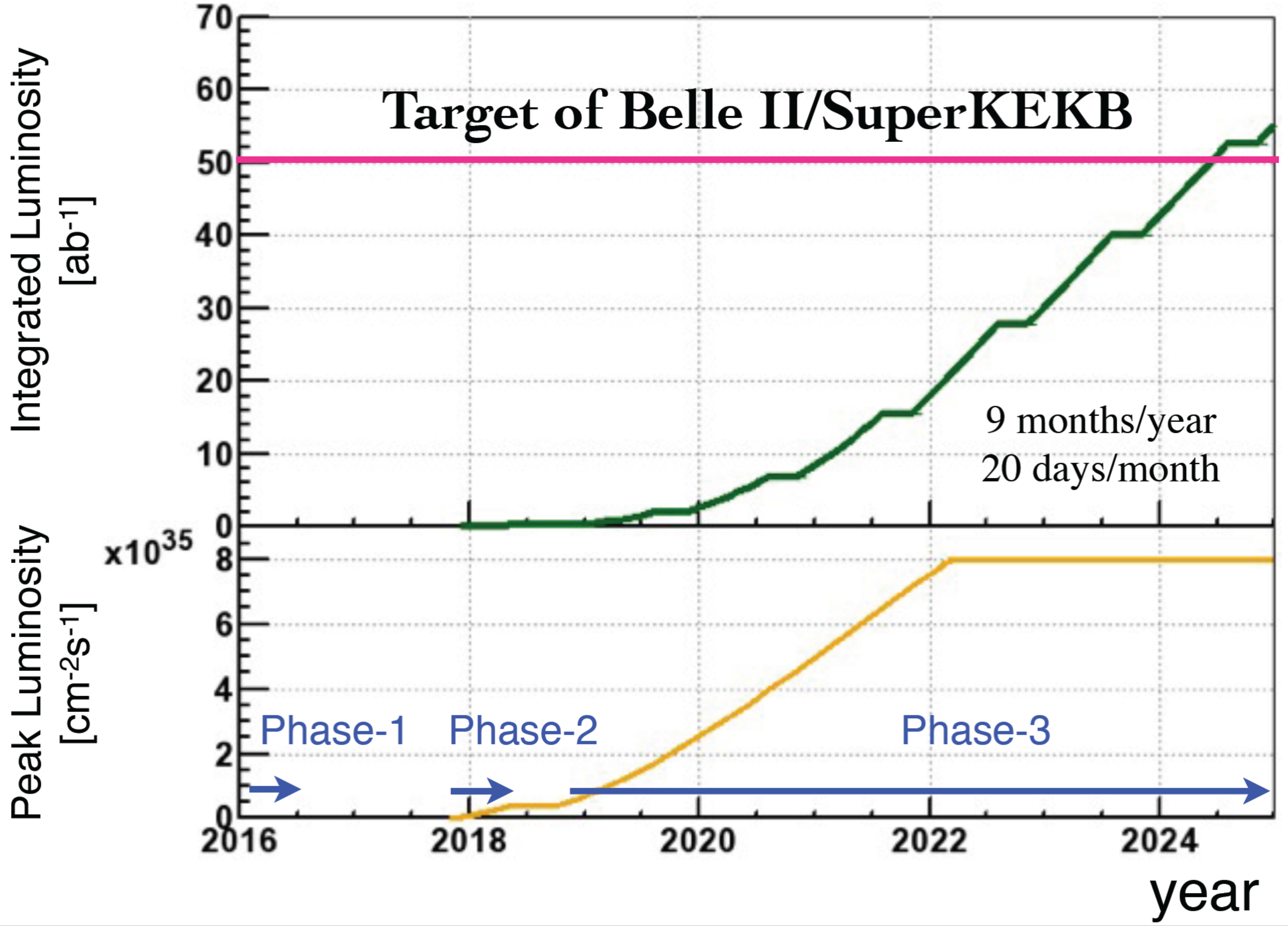


Belle II: 40–50x increase relative to Belle



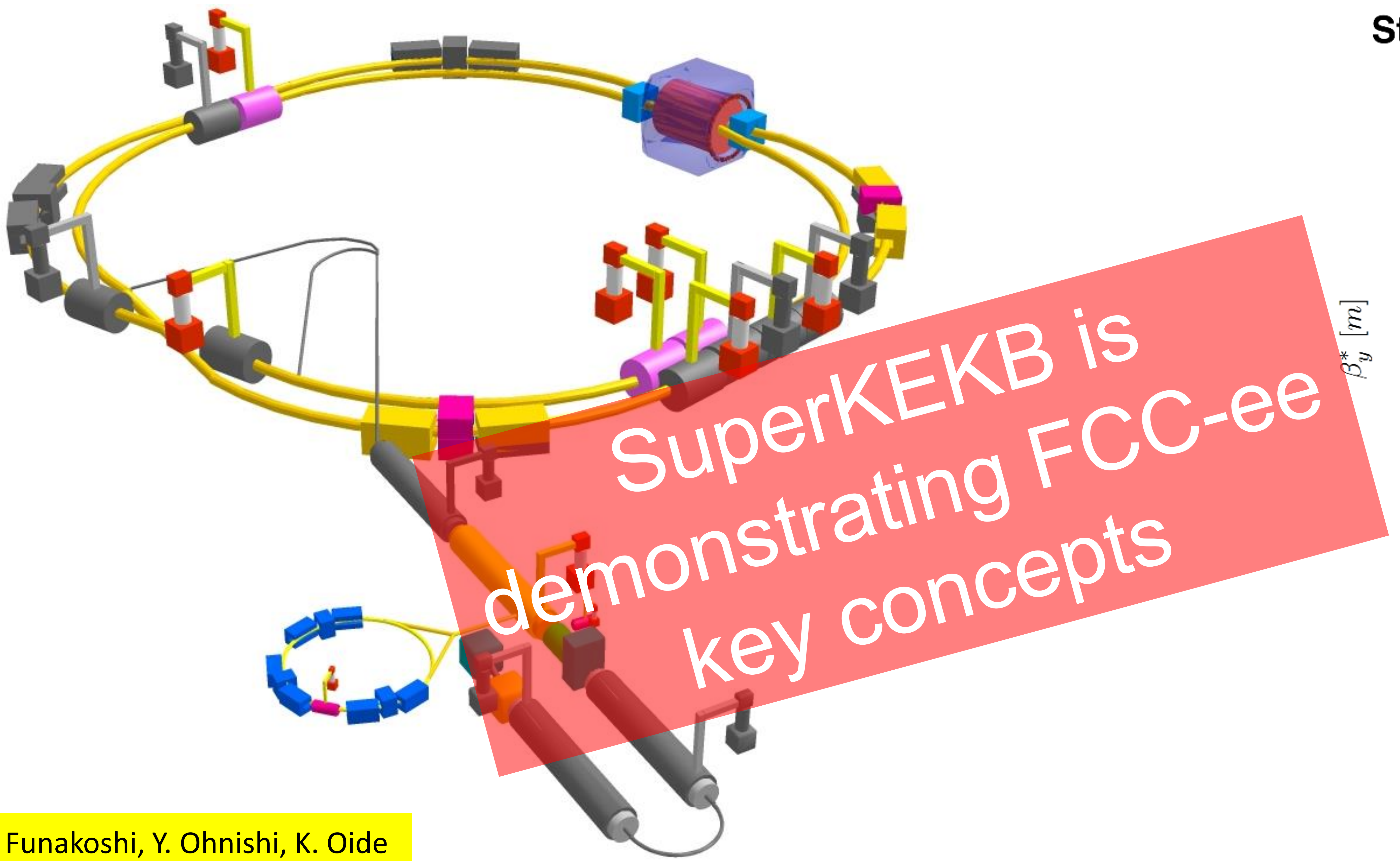
Zupanc (2017)

SuperKEKB luminosity projection



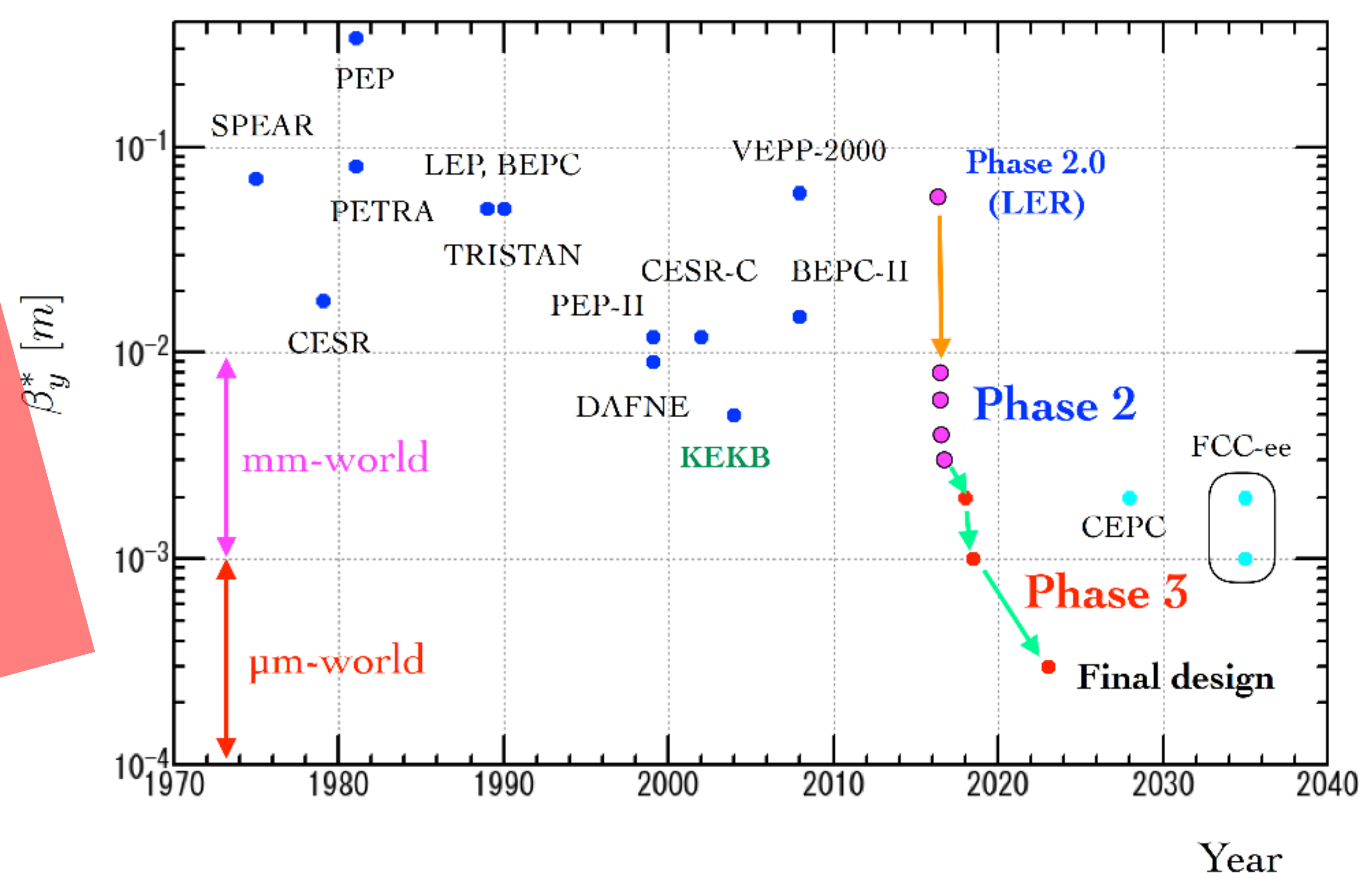
SuperKEKB – pushing luminosity and β*

double ring e^+e^- collider as *B*-factory at 7(e^-) & 4(e^+) GeV; **design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$; β_y^* ~ 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**



Y. Funakoshi, Y. Ohnishi, K. Oide

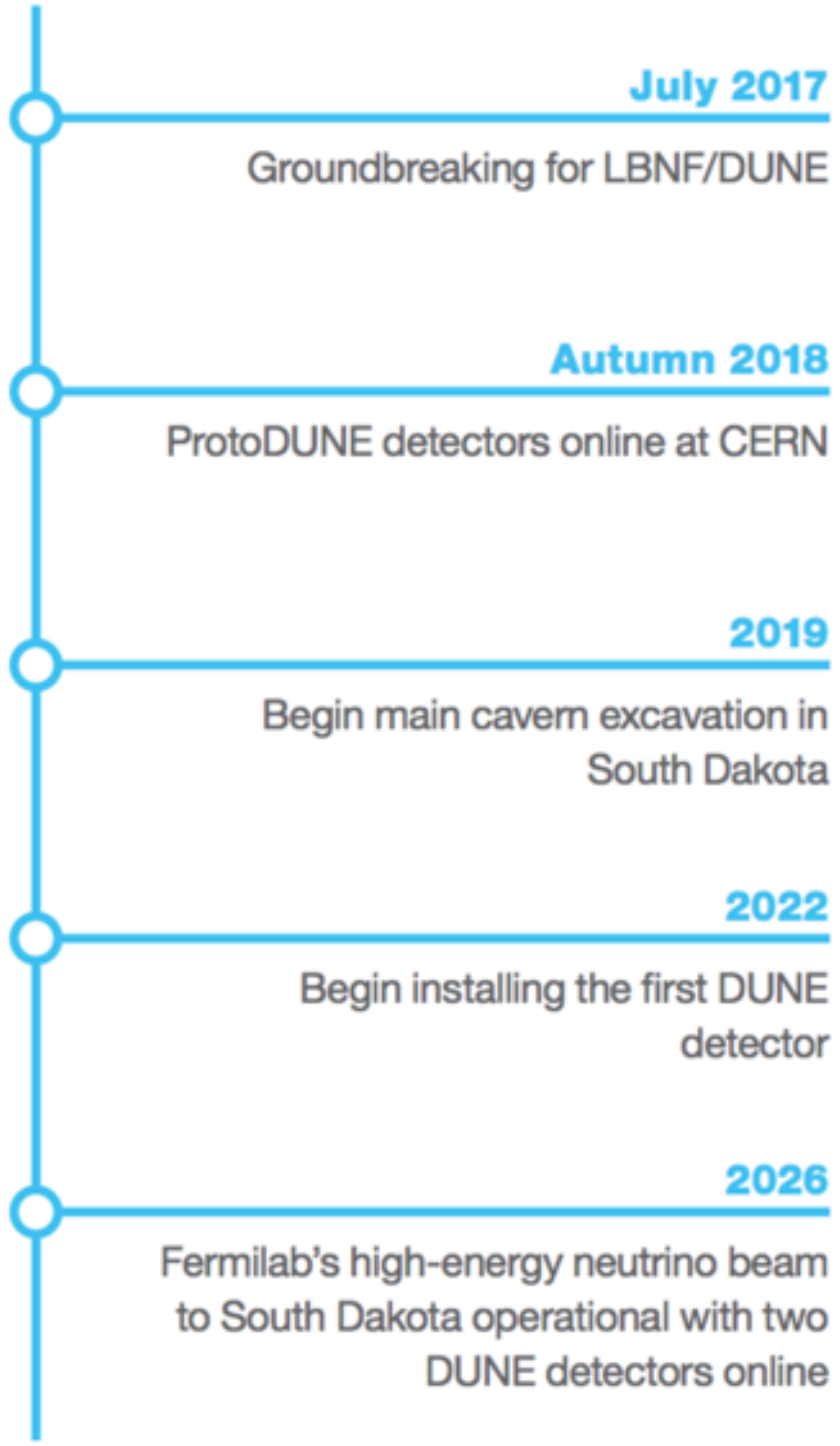
Strategy of beta squeezing for Phase 2 and Phase 3



β_y^* ≤2 mm achieved!

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

DUNE



HYPER-K

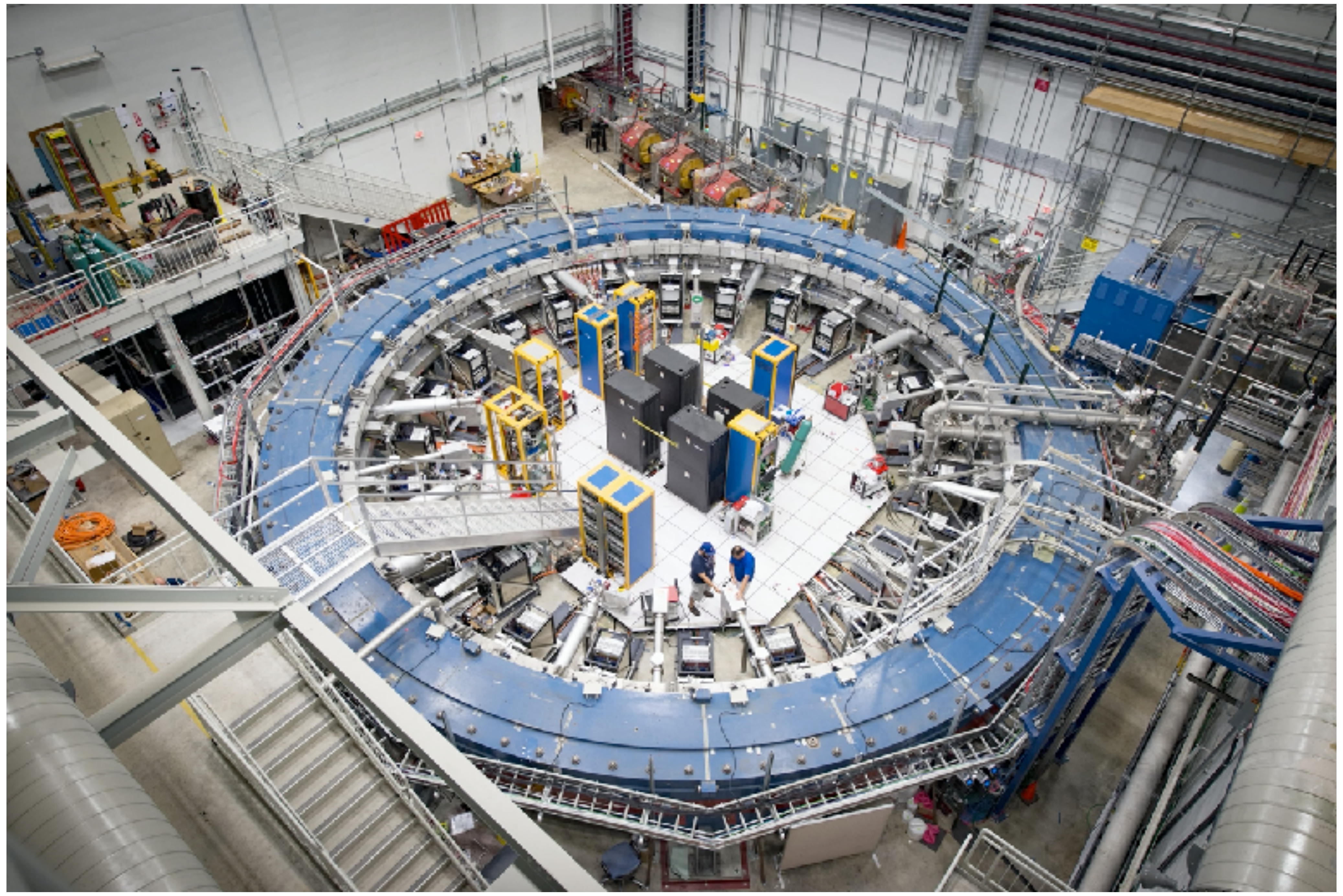
Spring 2020	Final design review of the system
Autumn 2020	Start the design of the system based on the design review
Autumn 2021	Start bidding procedure
Autumn 2022	Start mass production
Autumn 2023	Start final system test
Autumn 2024	Complete mass production
Autumn 2025	Complete system test and get ready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

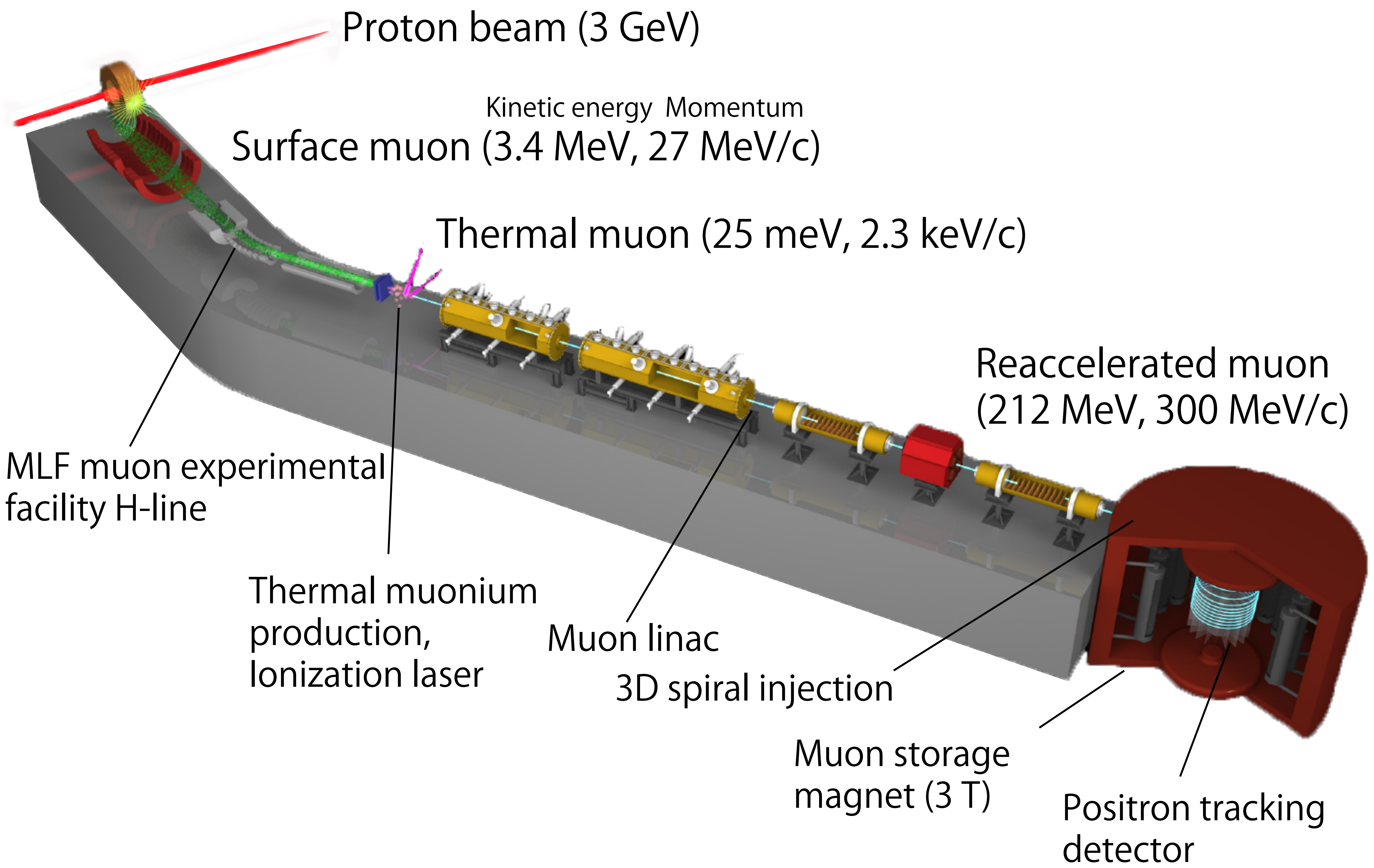
TABLE XXII. Timeline to complete the production for the installation.

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

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

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





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

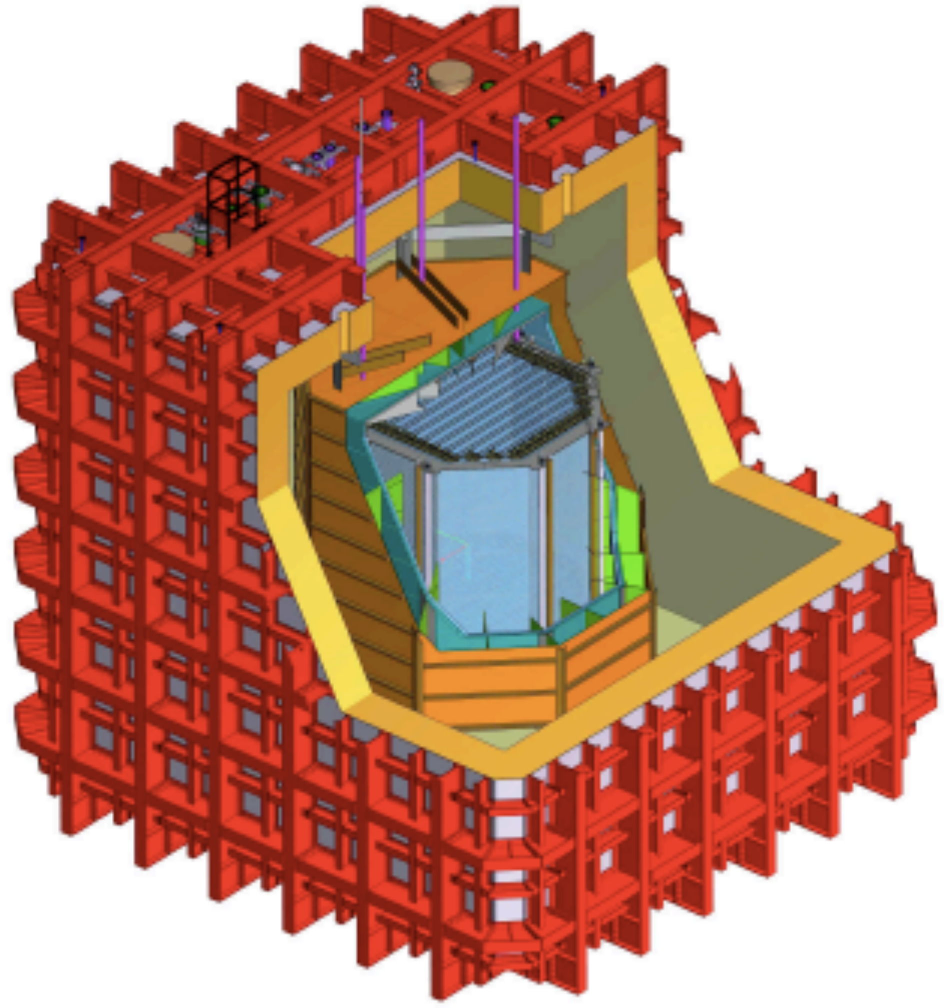
Global Argon Dark Matter Collaboration

DEAP-3600 (running)

DarkSide-50 (running)

miniCLEAN

ArDM

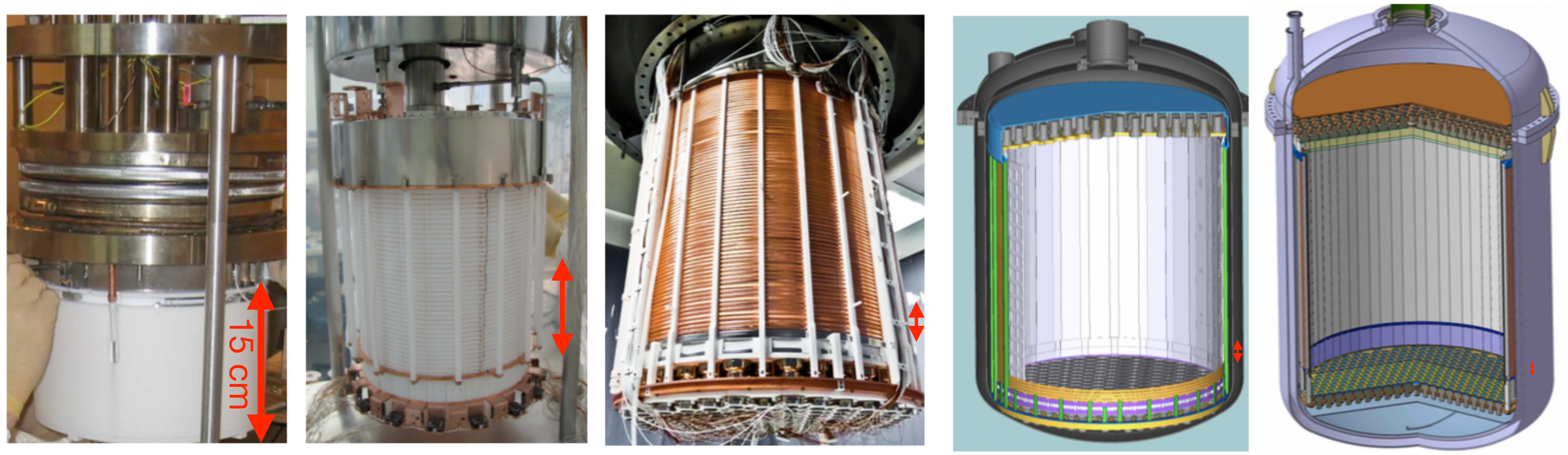


DarkSide-20k 2022~

~300 tonnes

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
- …

LHC physics

The core physics topics at the LHC (colour-coded by directly-probed energy scales)

Topic	Energy scales
Standard-model physics (QCD & electroweak)	100 MeV - 4 TeV
top-quark physics	170 GeV - O(TeV)
Higgs physics	125 GeV - 500 GeV
direct new-particle searches	100 GeV - 8 TeV
flavour physics (bottom & some charm)	1 - 5 GeV
heavy-ion physics	100 MeV - 500 GeV

The core physics topics at the LHC (colour-coded by directly-probed energy scales)

Standard-model physics (QCD & electroweak)
100 MeV - 4 TeV

top-quark physics
170 GeV - O(TeV)

Higgs physics
125 GeV - 500 GeV

direct new-particle searches
100 GeV - 8 TeV

flavour physics (bottom & some charm)
1 - 5 GeV

heavy-ion physics
100 MeV - 500 GeV

The core physics topics at the LHC (colour-coded by directly-probed energy scales)

Standard-model physics (QCD & electroweak)
100 MeV - 4 TeV

top-quark physics
170 GeV - O(TeV)

Higgs physics
125 GeV - 500 GeV

direct new-particle searches
100 GeV - 8 TeV

Key physics goals (my view)

1. Establish the structure of the Higgs sector of the SM
2. Search for signs of physics beyond the SM, direct (incl. dark matter candidates, SUSY, etc.) and indirect
3. Measure SM parameters, proton structure (PDFs), establish theory-data comparison methods, etc.

direct new-particle searches

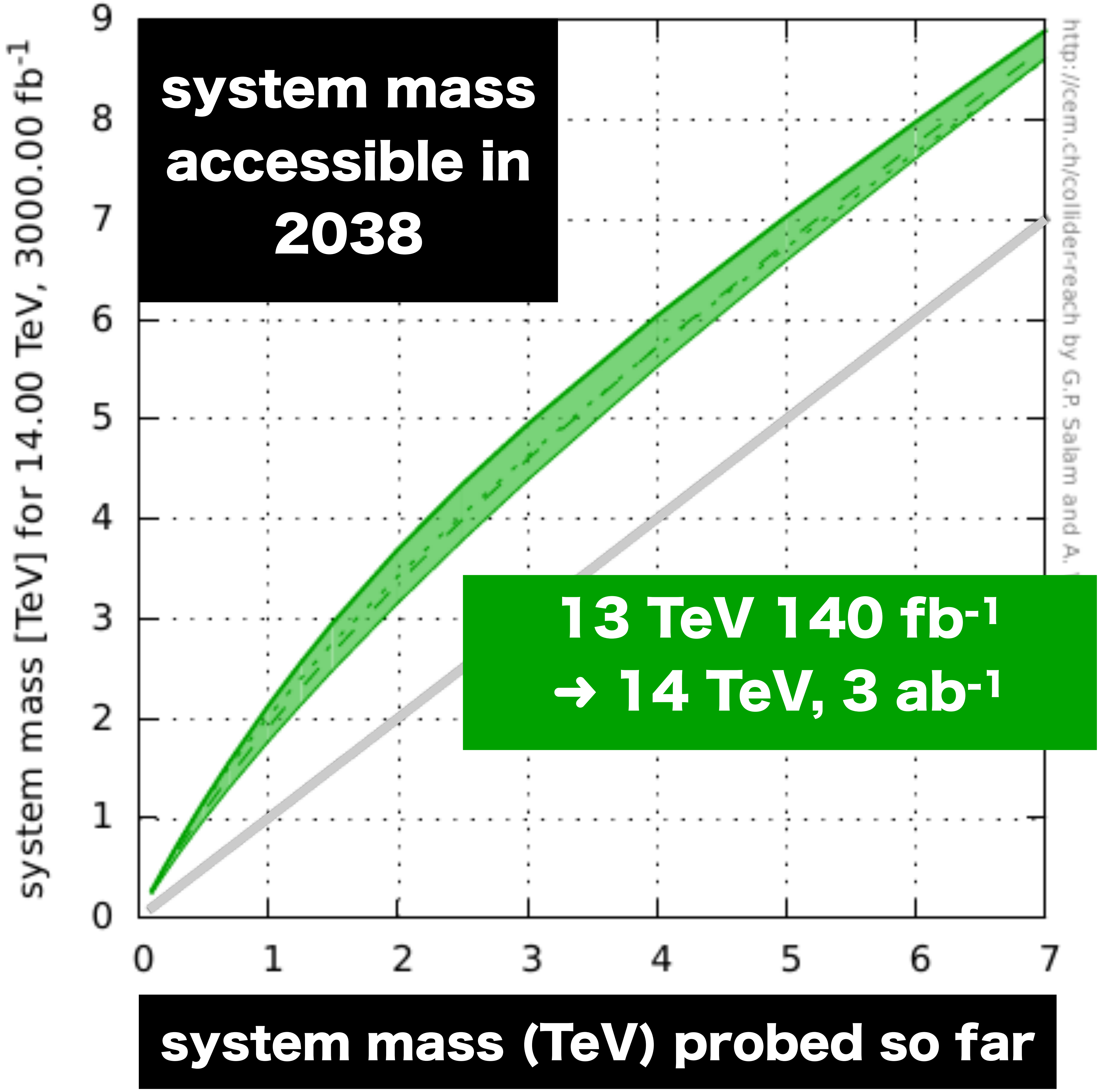
direct new-particle searches

100 GeV - 8 TeV

Long motivated by electroweak hierarchy problem, WIMP miracle

The essence of energy-frontier exploration

LHC direct search prospects (e.g. SUSY, Z′, etc.)

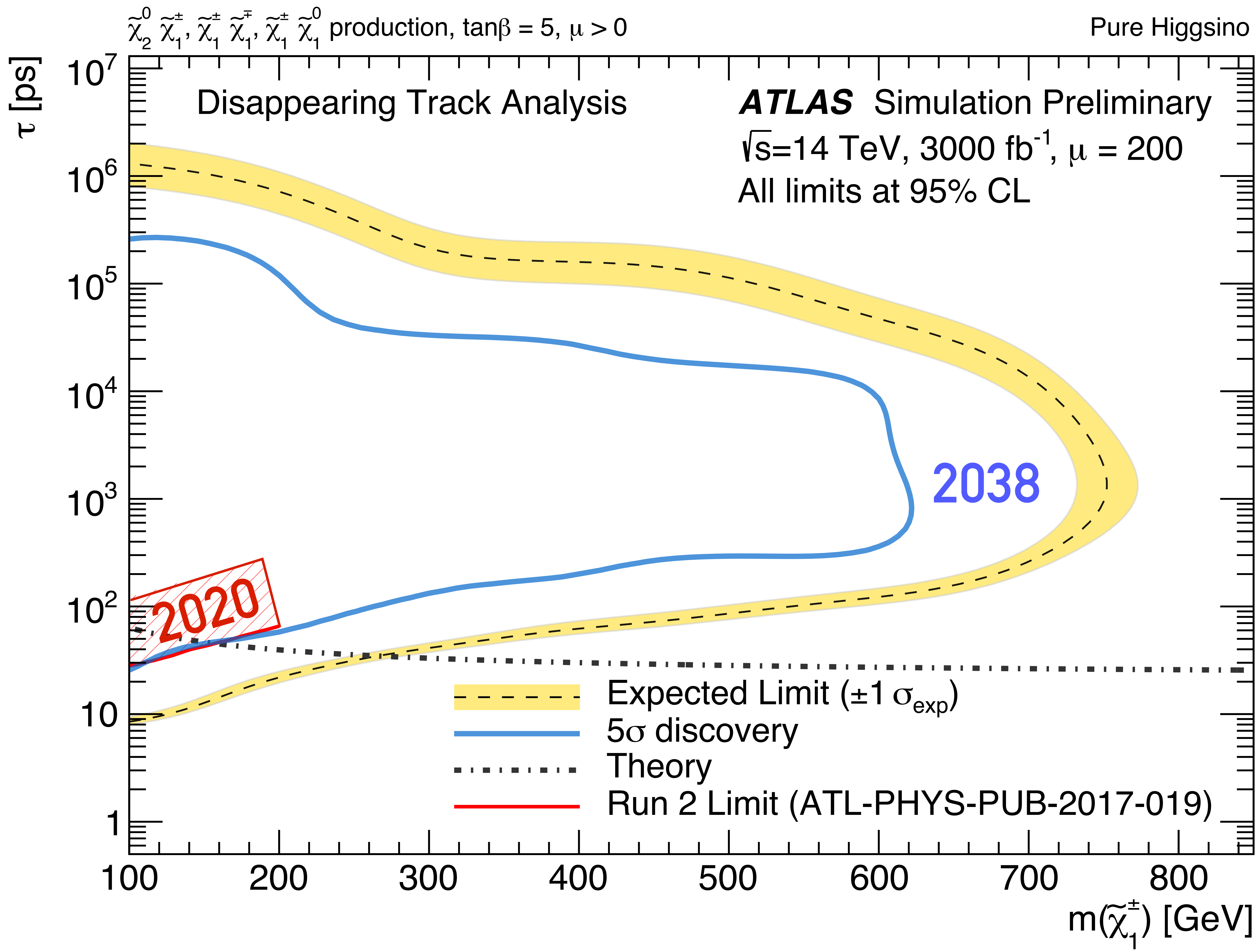


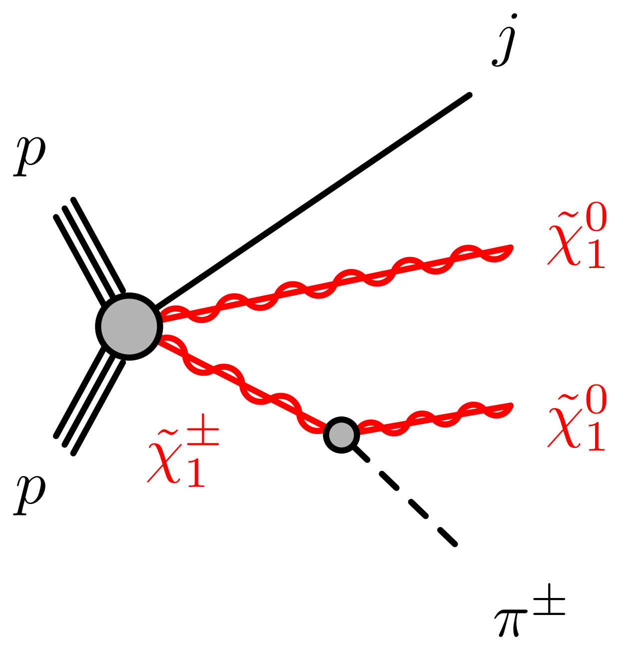
- ➤ Roughly 1.5 – 2 TeV increase in mass reach over next 18 years
- ➤ Proportionally more significant for searches at lower end of mass scale

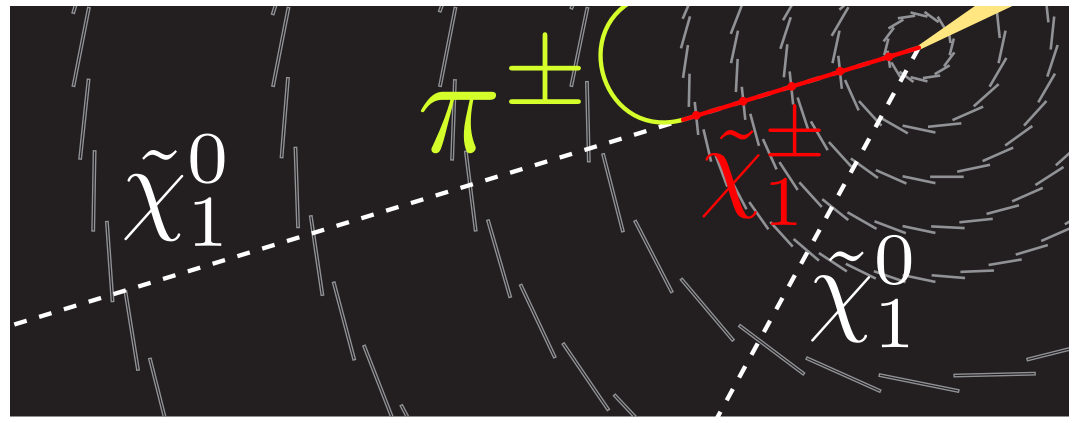
Sequential SM Z' exclusion reach
long-term pp(bar) view:
phases of fast, then slow energy frontier increase are normal
100 TeV pp, 30ab-1, from 2043
100 TeV pp
30ab-1 from 2063
40 TeV pp
12ab-1 from 2043
14 TeV pp, 3ab-1
13 TeV pp
8 TeV pp
7 TeV pp
1.96 TeV pp̄
1.80 TeV pp̄
0.63 TeV pp̄
Z'SSM limit [TeV]
year in which data recorded
Z' → l+l-
points: UA1/CDF/D0/ATLAS/CMS
lines: collider-reach extrapolation
year adjusted when only one lepton channel used
GPS + AW 2019 (with http://cern.ch/collider-reach)
100
70
50
30
20
10
7
5
3
2
1
0.7
0.5
0.3
0.2
0.1
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090


Sequential SM Z' exclusion reach
long-term pp(bar) view:
phases of fast, then slow energy frontier increase are normal
average increase in reach roughly × 2 / decade
100 TeV pp, 30ab-1, from 2043
100 TeV pp
30ab-1 from 2063
40 TeV pp
12ab-1 from 2043
14 TeV pp, 3ab-1
13 TeV pp
8 TeV pp
7 TeV pp
1.96 TeV pp̄
1.80 TeV pp̄
0.63 TeV pp̄
year adjusted when only one lepton channel used
Z'SSM limit [TeV]
year in which data recorded
GPS + AW 2019 (with http://cern.ch/collider-reach)

electroweak SUSY partners: projections

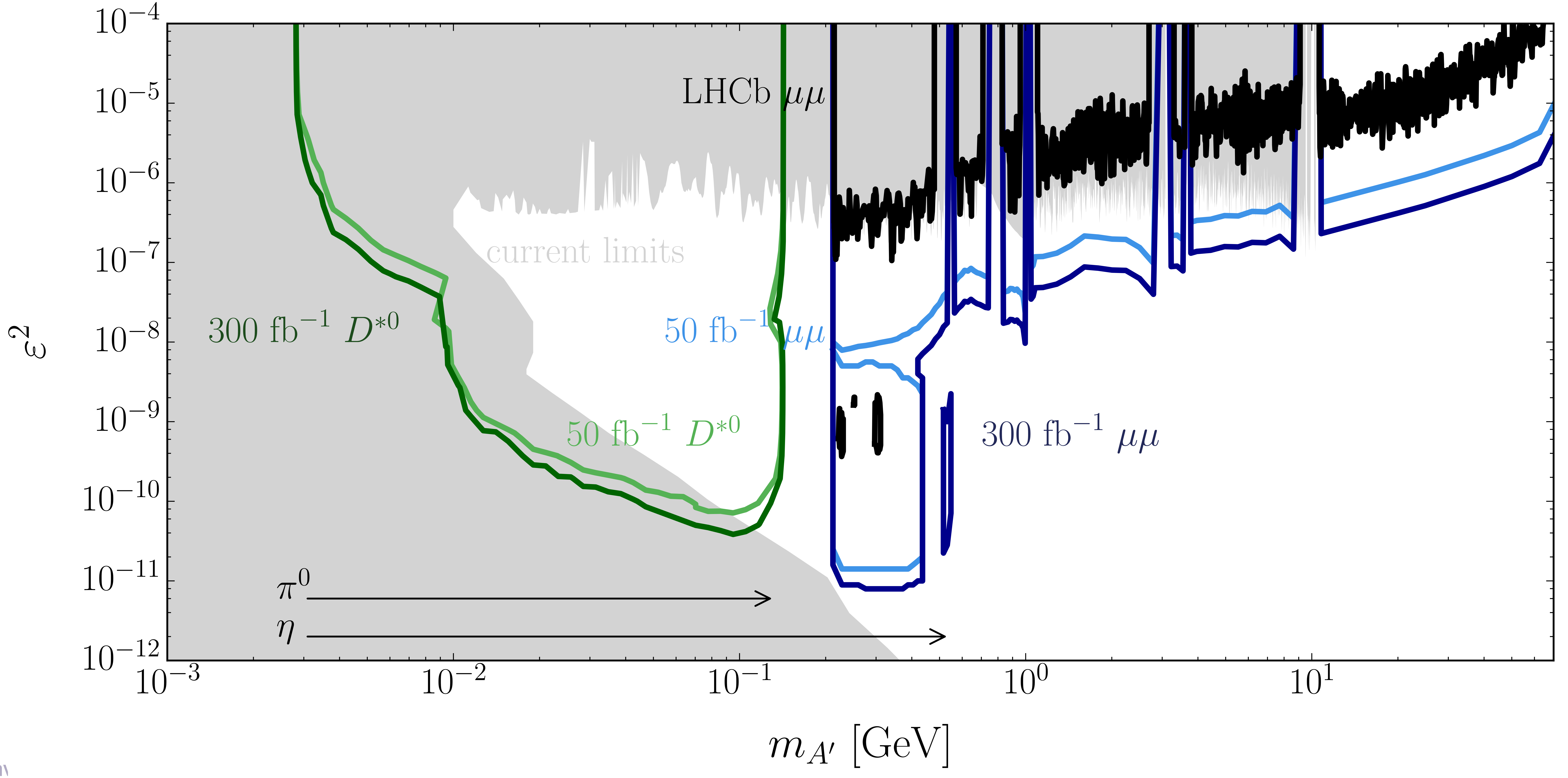




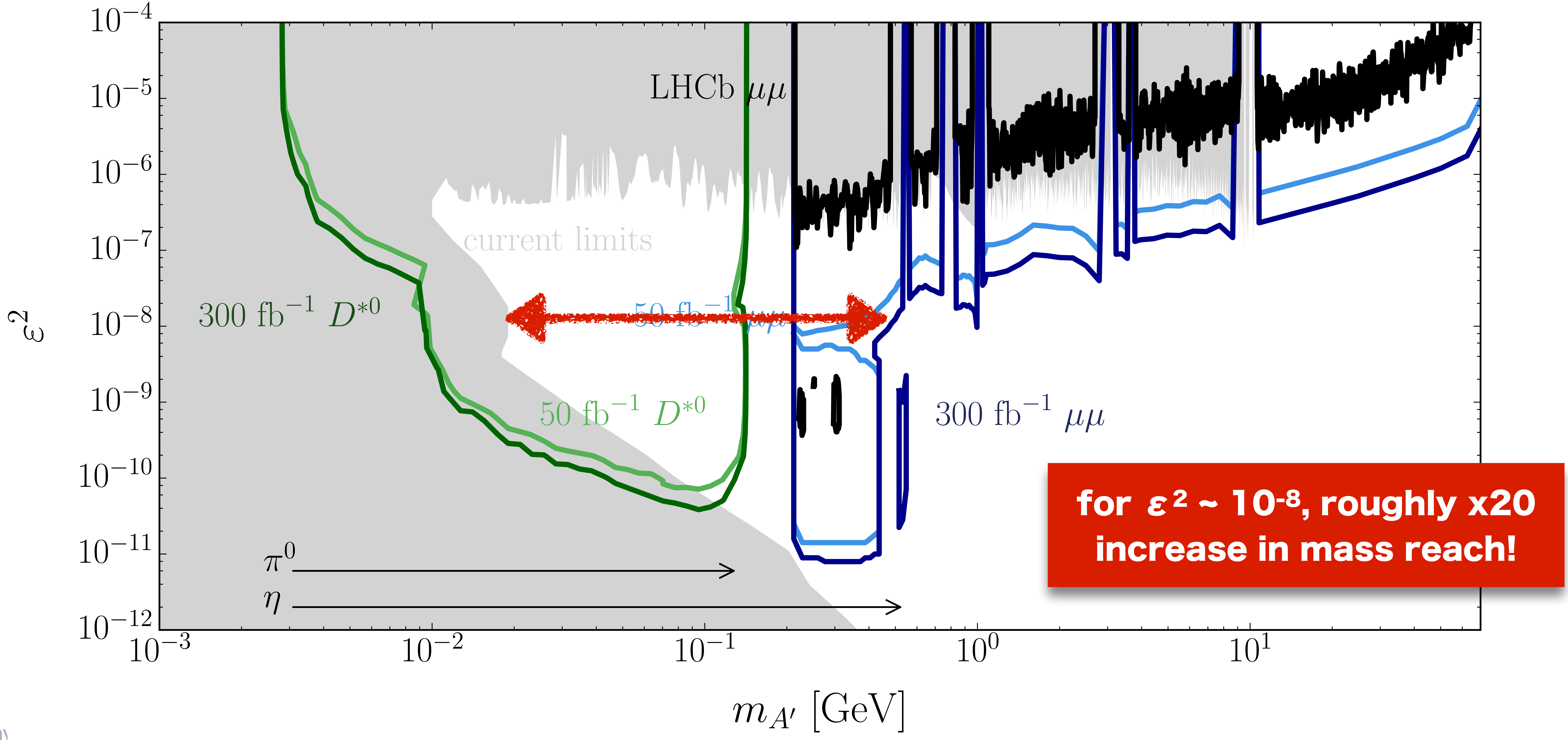


LHC lumi increase & detector upgrades bring unprecedented reach for processes with small cross sections (& sometimes weird signatures — here, disappearing tracks)

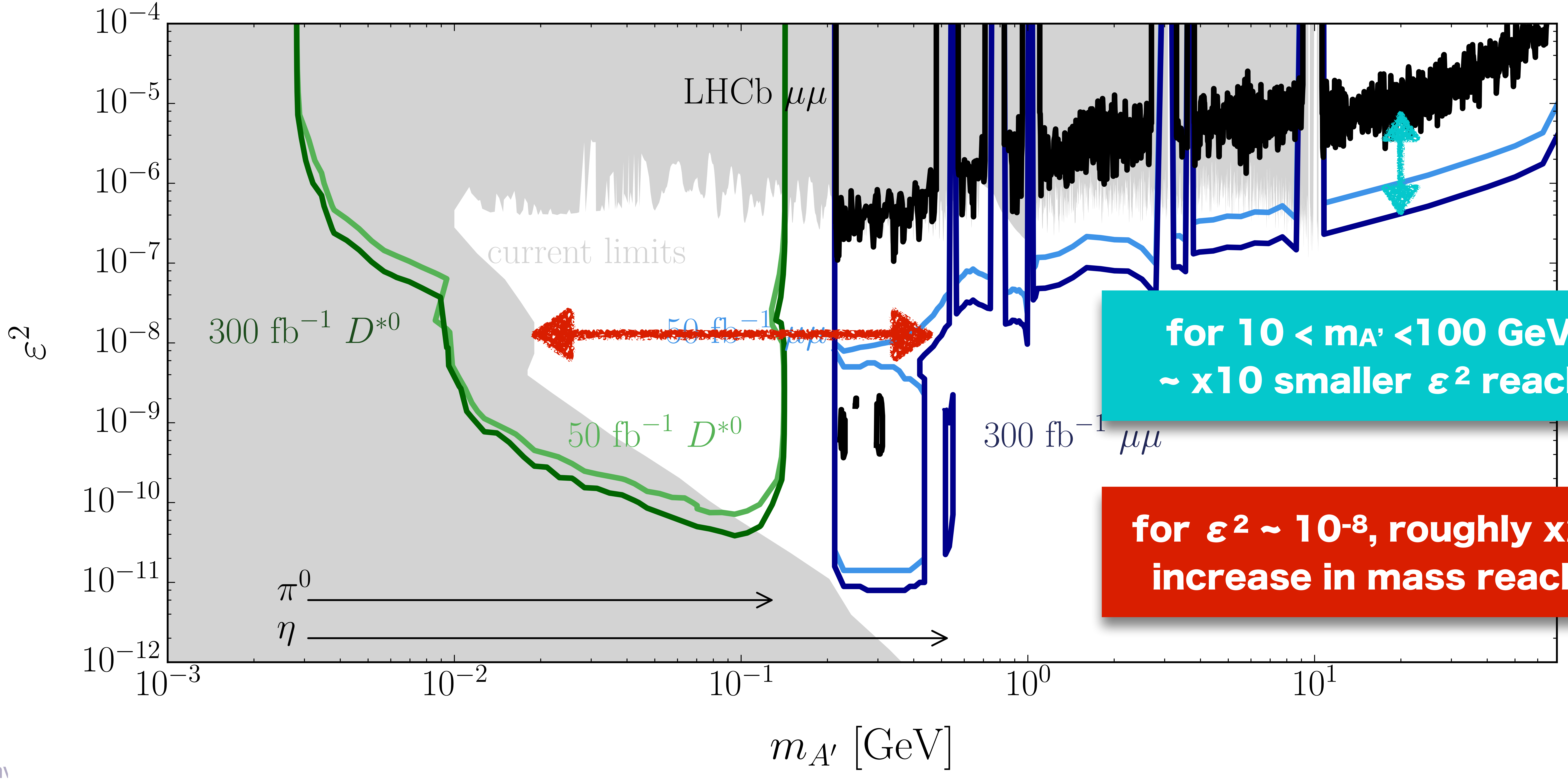
extreme lower end: A′ searches at LHCb



extreme lower end: A′ searches at LHCb



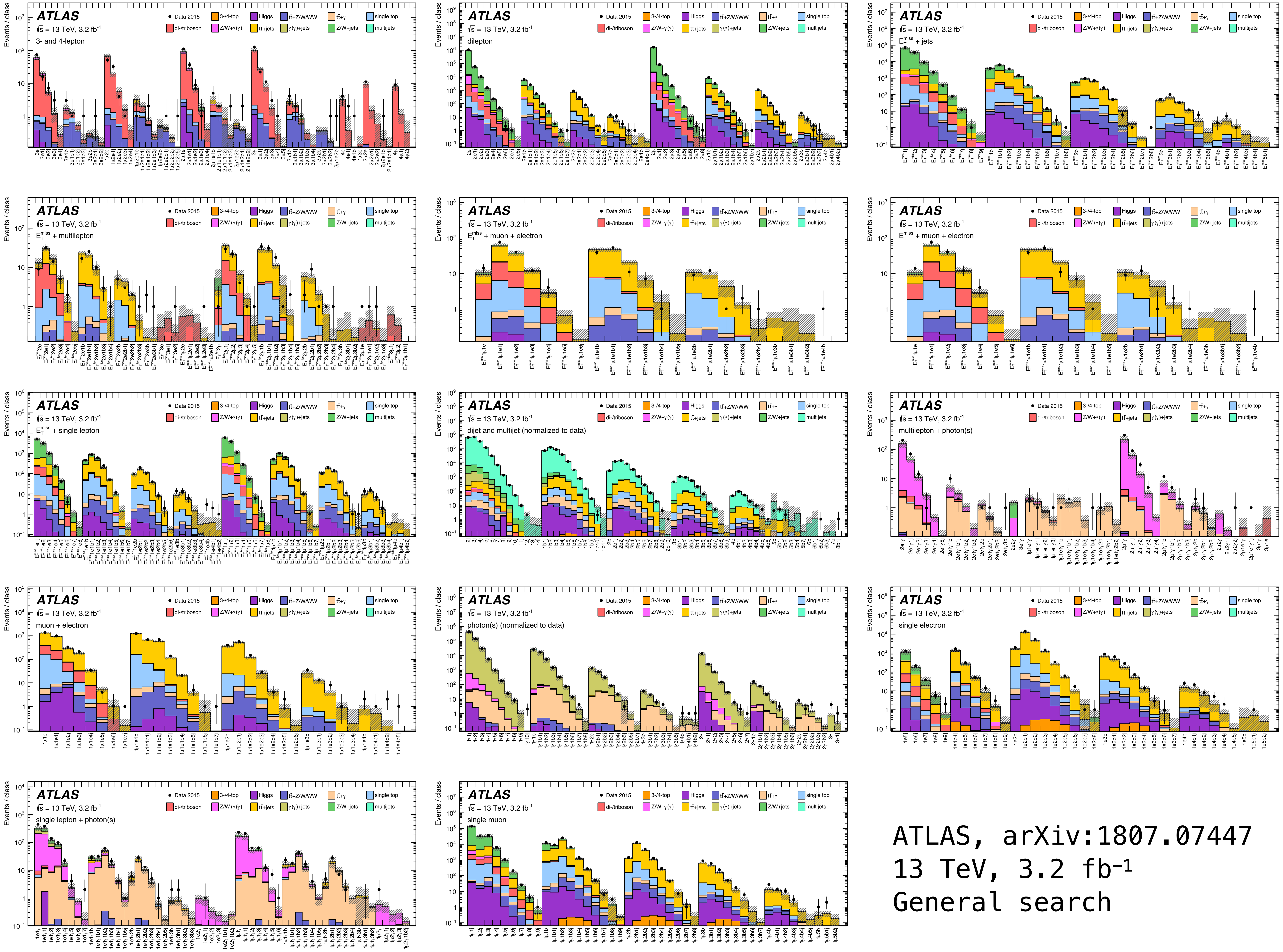
extreme lower end: A′ searches at LHCb



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

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

LHC searches are broad-band (here, a "general search" with 704 event classes, 10^5 bins)



ATLAS, arXiv:1807.07447
13 TeV, 3.2 fb⁻¹
General search

LHC experiments explore vast array of signatures across broad phase-space.

This search is especially reliant on theory predictions, because it's so general.

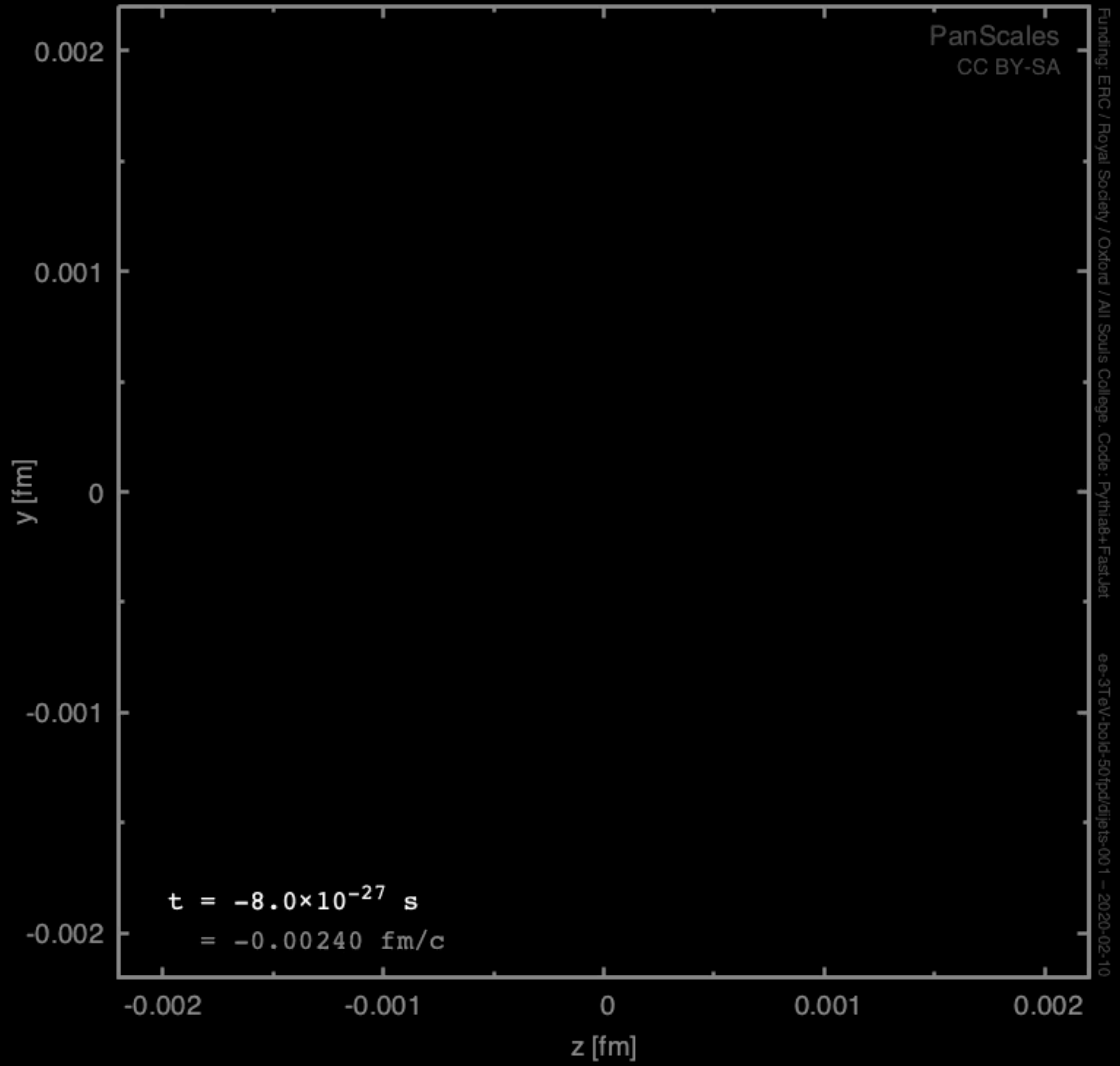
(Other searches often have a mix of theory and "data-driven" background estimates)

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z / W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + WW$	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + \gamma$	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
$t\bar{t} + b\bar{b}$	Sherpa 2.2.0	NLO	Sherpa 2.2.0	NLO	NLO CT10f4	Sherpa default
Single-top (t-channel)	Powheg-Box v1	NLO	Pythia 6.428	app. NNLO	NLO CT10f4	Perugia 2012
Single-top (s- and Wt-channel)	Powheg-Box v2	NLO	Pythia 6.428	app. NNLO	NLO CT10	Perugia 2012
tZ	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
3-top	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
4-top	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
WW	Sherpa 2.1.1	0j@NLO + 1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
WZ	Sherpa 2.1.1	0j@NLO + 1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
ZZ	Sherpa 2.1.1	0,1j@NLO + 2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
Multijets	Pythia 8.186	LO	Pythia 8.186	data	NNPDF2.3LO	A14
Higgs (ggF/VBF)	Powheg-Box v2	NLO	Pythia 8.186	NNLO	NLO CT10	AZNLO
Higgs ($t\bar{t}H$)	MG5_aMC@NLO 2.2.2	NLO	Herwig++	NNLO	NLO CT10	UEEE5
Higgs (W/ZH)	Pythia 8.186	LO	Pythia 8.186	NNLO	NNPDF2.3LO	A14

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z / W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + WW$	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + \gamma$	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
$t\bar{t} + b\bar{b}$	Sherpa 2.2.0	NLO	Sherpa 2.2.0	NLO	NLO CT10f4	Sherpa default
Single-top (t-channel)	Powheg-Box v1	NLO	Pythia 6.428	app. NNLO	NLO CT10f4	Perugia 2012
Single-top (s- and Wt-channel)	Powheg-Box v2	NLO	Pythia 6.428	app. NNLO	NLO CT10	Perugia 2012
tZ	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
3-top	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	LO	NNPDF2.3LO	A14
4-top	MG5_aMC@NLO 2.2.2	LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
WW	Sherpa 2.1.1	0j@NLO + 1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
WZ	Sherpa 2.1.1	0j@NLO + 1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
ZZ	Sherpa 2.1.1	0,1j@NLO + 2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
Multijets	Pythia 8.186	LO	Pythia 8.186	data	NNPDF2.3LO	A14
Higgs (ggF/VBF)	Powheg-Box v2	NLO	Pythia 8.186	NNLO	NLO CT10	AZNLO
Higgs ($t\bar{t}H$)	MG5_aMC@NLO 2.2.2	NLO	Herwig++	NNLO	NLO CT10	UEEE5
Higgs (W/ZH)	Pythia 8.186	LO	Pythia 8.186	NNLO	NNPDF2.3LO	A14

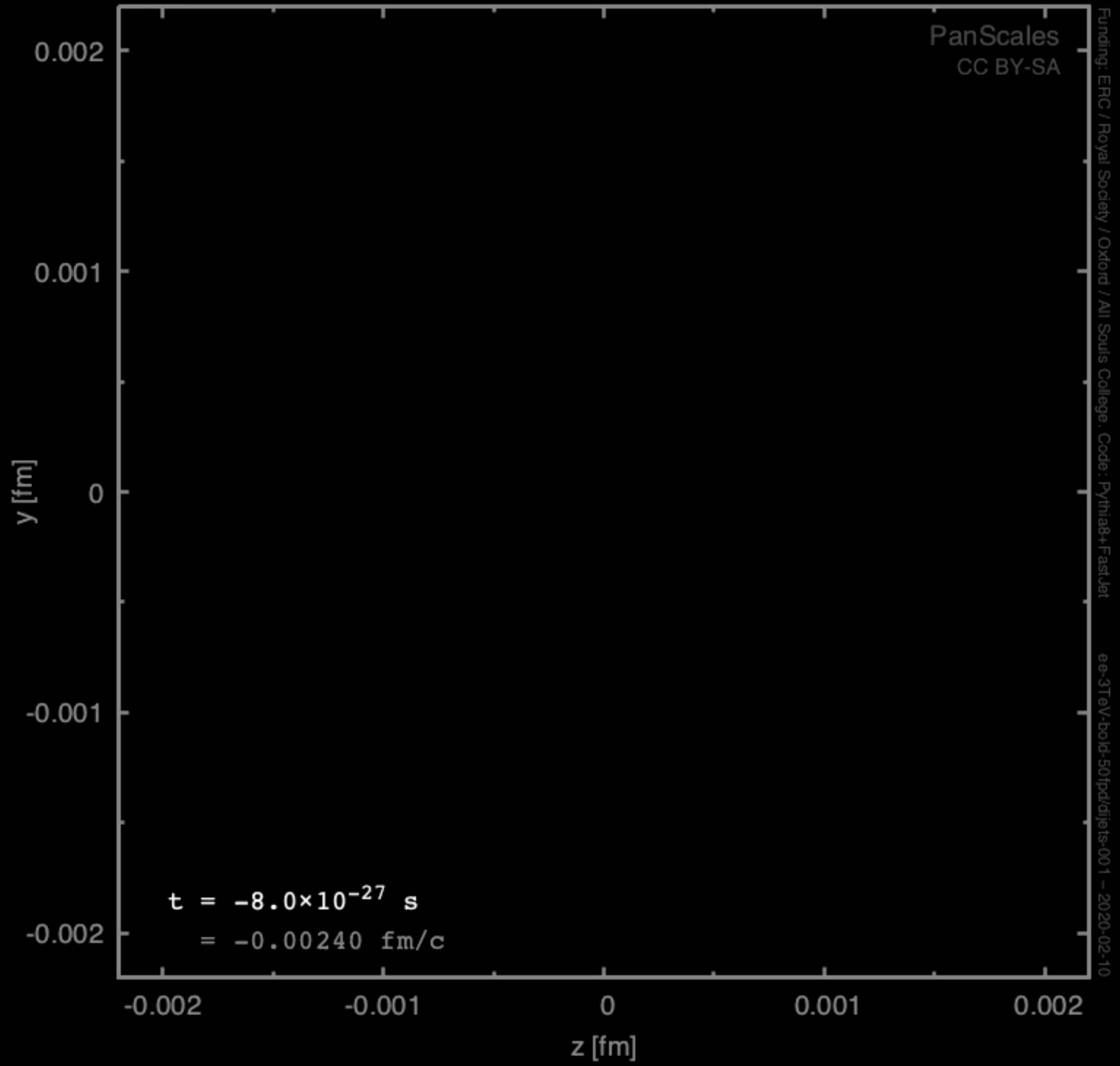


incoming beam particle

intermediate particle

final particle

Event evolution spans 7 orders of magnitude in space-time



incoming beam particle

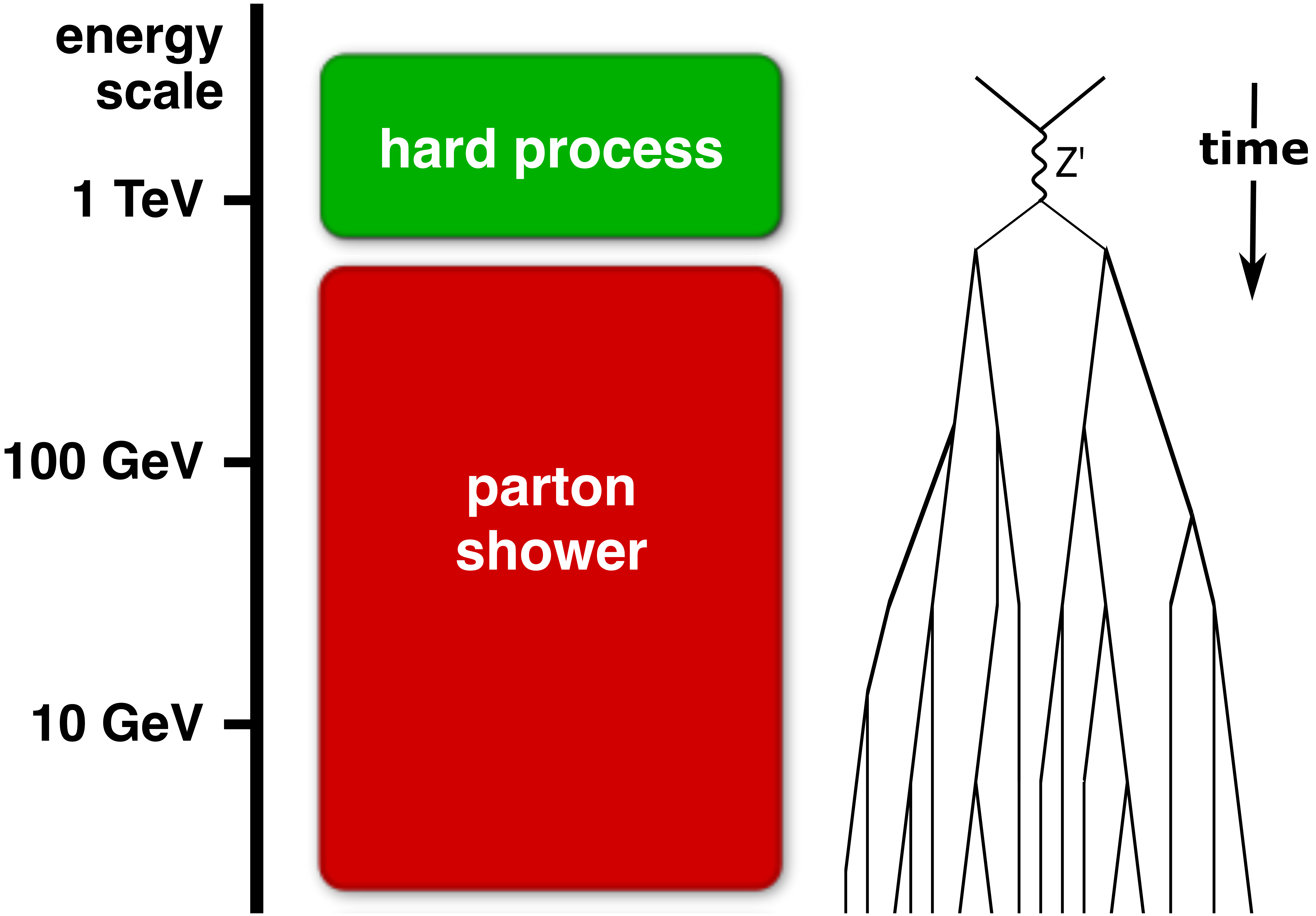
intermediate particle

final particle

Event evolution spans 7 orders of magnitude in space-time

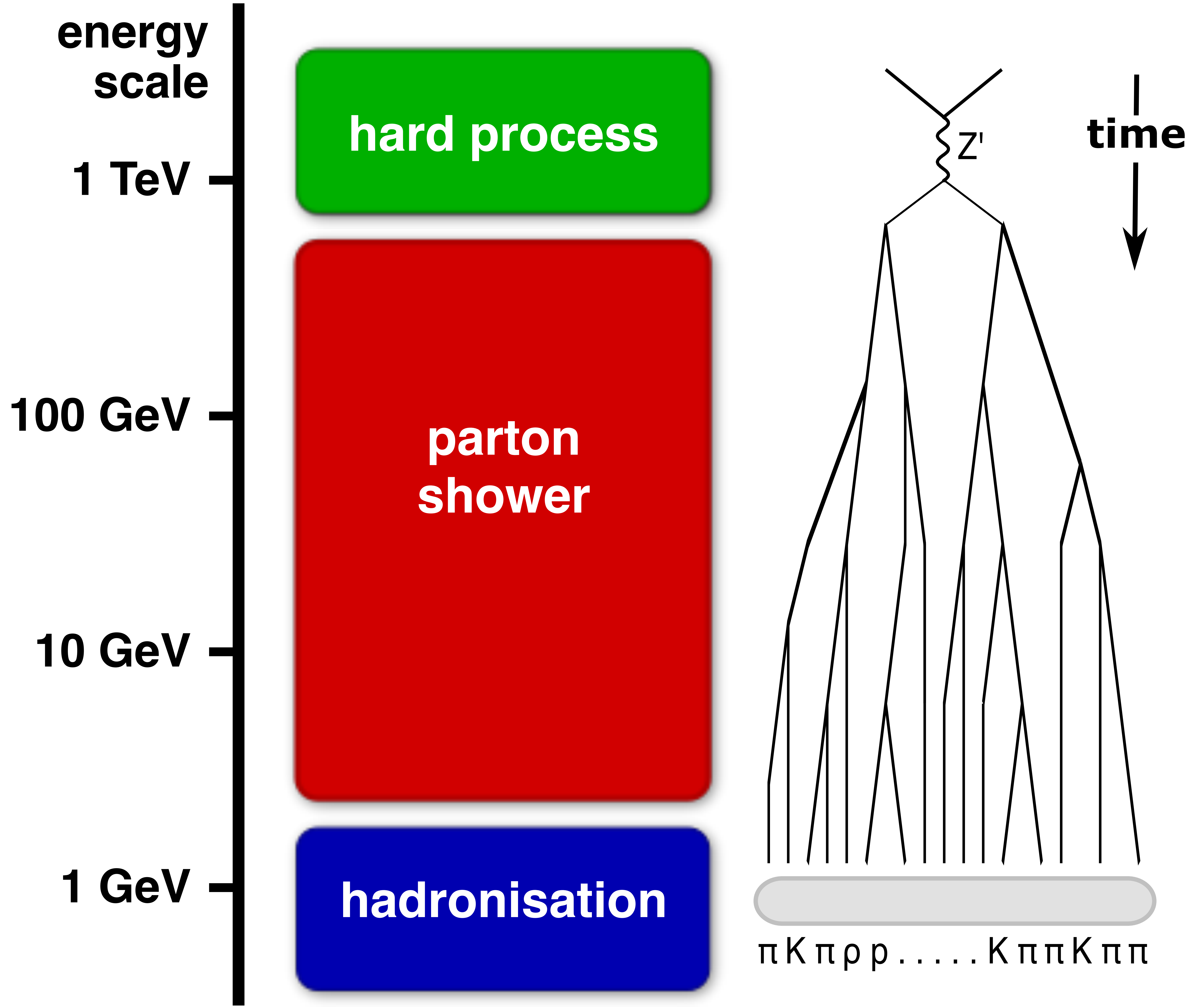
Amplitudes are most critical here

schematic view of key components of QCD predictions and Monte Carlo event simulation



Amplitudes are most critical here

schematic view of key components of QCD predictions and Monte Carlo event simulation



Amplitudes are most critical here

schematic view of key components of QCD predictions and Monte Carlo event simulation

pattern of particles in MC can be directly compared to pattern in experiment

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z / W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14

theory (hadron-level + detector sim) compared to data

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z / W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14

The sets of amplitudes being used at the hard scale

theory (hadron-level + detector sim) compared to data

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z / W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14

the parton shower (from hard scale down to GeV scale)

The sets of amplitudes being used at the hard scale

theory (hadron-level + detector sim) compared to data

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z (\to \ell^+\ell^-)$ + jets	Sherpa 2.1.1	0,1,2j@NLO + 3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W (\to q\bar{q})$ + jets	Sherpa 2.1.1	1,2,3,4j@LO	Sherpa 2.1.1	NNLO	NLO CT10	Sherpa default
$Z / W + \gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
$Z / W + \gamma\gamma$	Sherpa 2.1.1	0,1,2,3j@LO	Sherpa 2.1.1	NLO	NLO CT10	Sherpa default
γ + jets	Sherpa 2.1.1	0,1,2,3,4j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma$ + jets	Sherpa 2.1.1	0,1,2j@LO	Sherpa 2.1.1	data	NLO CT10	Sherpa default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	Pythia 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	Powheg-Box v2	NLO	Pythia 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	Pythia 8.186	NLO	NNPDF2.3LO	A14

The matching between amplitudes and parton shower

the parton shower (from hard scale down to GeV scale)

The sets of amplitudes being used at the hard scale

theory (hadron-level + detector sim) compared to data

Calculations used in 1807.07447 (ATLAS general search)

Physics process	Generator	ME accuracy	Parton shower	Cross-section normalization	PDF set	Tune
$W (\to \ell\nu)$ + jets	SHERPA 2.1.1	0,1,2j@NLO + 3,4j@LO	SHERPA 2.1.1	NNLO	NLO CT10	SHERPA default
$Z (\to \ell^+\ell^-)$ + jets	SHERPA 2.1.1	0,1,2j@NLO + 3,4j@LO	SHERPA 2.1.1	NNLO	NLO CT10	SHERPA default
$Z / W (\to q\bar{q})$ + jets	SHERPA 2.1.1	1,2,3,4j@LO	SHERPA 2.1.1	NNLO	NLO CT10	SHERPA default
$Z / W + \gamma$	SHERPA 2.1.1	0,1,2,3j@LO	SHERPA 2.1.1	NLO	NLO CT10	SHERPA default
$Z / W + \gamma\gamma$	SHERPA 2.1.1	0,1,2,3j@LO	SHERPA 2.1.1	NLO	NLO CT10	SHERPA default
γ + jets	SHERPA 2.1.1	0,1,2,3,4j@LO	SHERPA 2.1.1	data	NLO CT10	SHERPA default
$\gamma\gamma$ + jets	SHERPA 2.1.1	0,1,2j@LO	SHERPA 2.1.1	data	NLO CT10	SHERPA default
$\gamma\gamma\gamma$ + jets	MG5_aMC@NLO 2.3.3	0,1j@LO	PYTHIA 8.212	LO	NNPDF23LO	A14
$t\bar{t}$	POWHEG-BOX v2	NLO	PYTHIA 6.428	NNLO+NNLL	NLO CT10	Perugia 2012
$t\bar{t} + W$	MG5_aMC@NLO 2.2.2	0,1,2j@LO	PYTHIA 8.186	NLO	NNPDF2.3LO	A14
$t\bar{t} + Z$	MG5_aMC@NLO 2.2.2	0,1j@LO	PYTHIA 8.186	NLO	NNPDF2.3LO	A14

The matching between amplitudes and parton shower

the parton shower (from hard scale down to GeV scale)

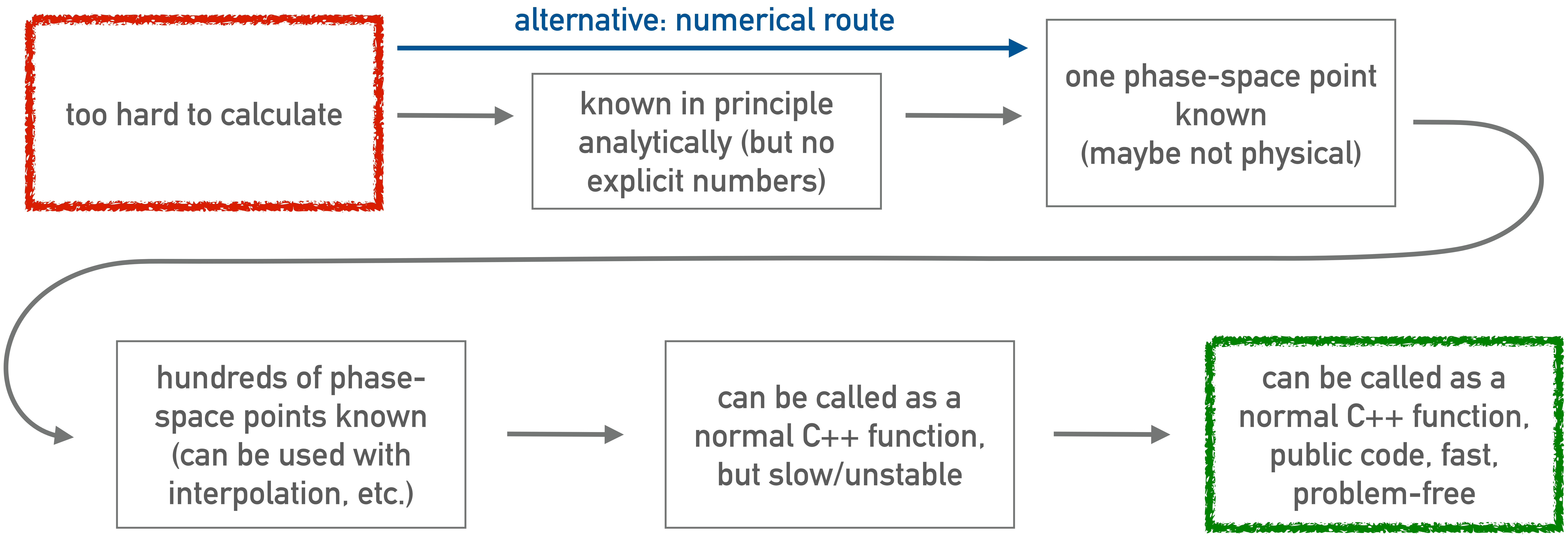
The sets of amplitudes being used at the hard scale

non-perturbative physics:

proton structure (PDFs) and hadronisation models etc.

theory (hadron-level + detector sim) compared to data

stages of an amplitude



Each stage brings important value.
For broad experimental use at the LHC,
we need to get to the last one (+ parton-shower matching etc.)

stages of an amplitude

The amplitudes alone are not enough,
but need to be supplemented with

1) subtraction/slicing schemes

2) parton distribution functions (to same order)

3) splitting functions (to same order)

4) merging/matching with parton showers
(to get hadron-level predictions)

alternative: numerical route

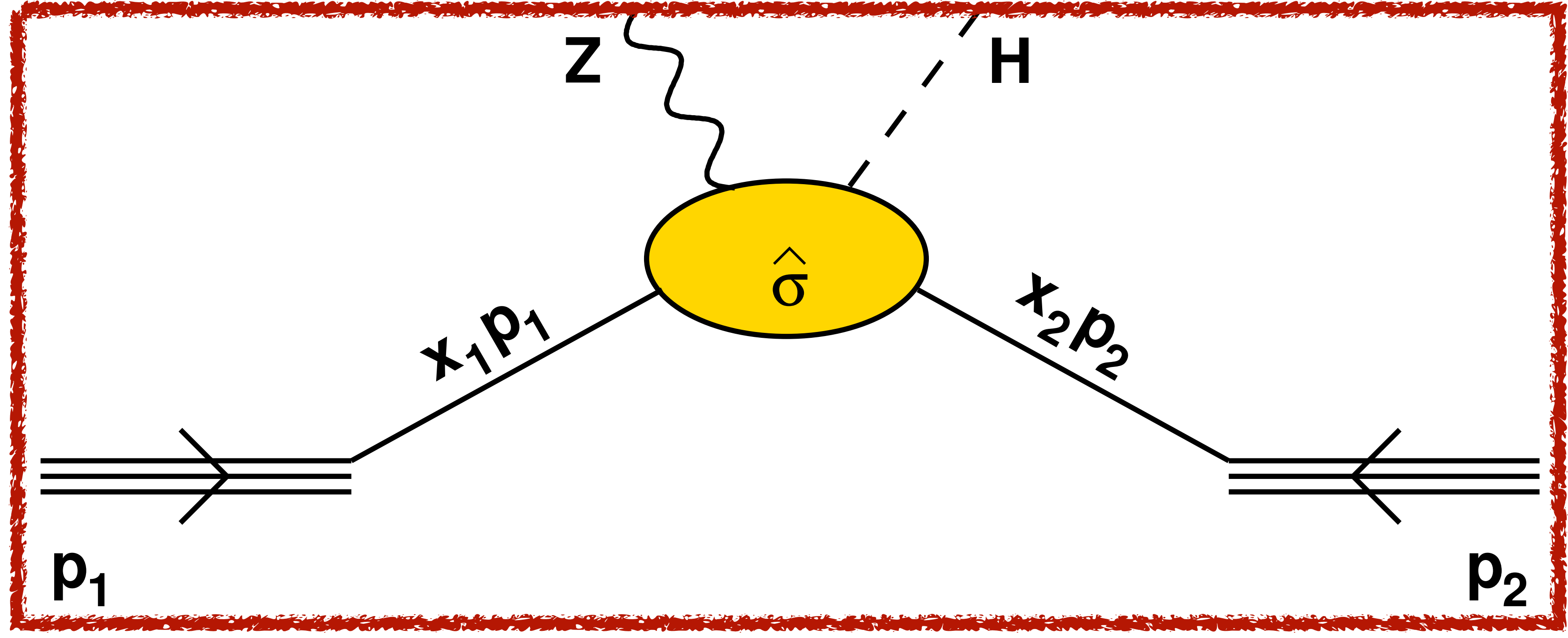
too hard to calculate → known in principle analytically (but no explicit numbers)

one phase-space point known (maybe not physical)

hundreds of phase-space points known (can be used with interpolation, etc.) → can be called as a normal C++ function, but slow/unstable → can be called as a normal C++ function, public code, fast, problem-free

Each stage brings important value.
For broad experimental use at the LHC,
we need to get to the last one (+ parton-shower matching etc.)

Why do you need parton showers etc.?



For **infrared and collinear safe observables**, you can ignore most of the physics between hard scale Q and Λ_{QCD}

$$\sigma = \sum_{n,i,j} \alpha_s^n(\mu) \int dx_1 dx_2\, \hat{\sigma}_{n,ij}(x_1, x_2, \mu)\, f_{i/p}(x_1, \mu)\, f_{j/p}(x_2, \mu) \;+\; \mathcal{O}\left(\frac{\Lambda^m}{Q^{2+m}}\right)$$

perturbative expansion at hard scale μ~Q

amplitudes + subtraction / slicing

proton structure (PDFs)

non-perturbative (higher-twist) effects

The physics at intermediate and low scales is higher-order or higher twist in "proper" observables, i.e. numerically subdominant.

But detector effects can have up to O(1) impact, and to understand those effects you need full hadron-level description of collider events (i.e. not infrared-collinear safe).

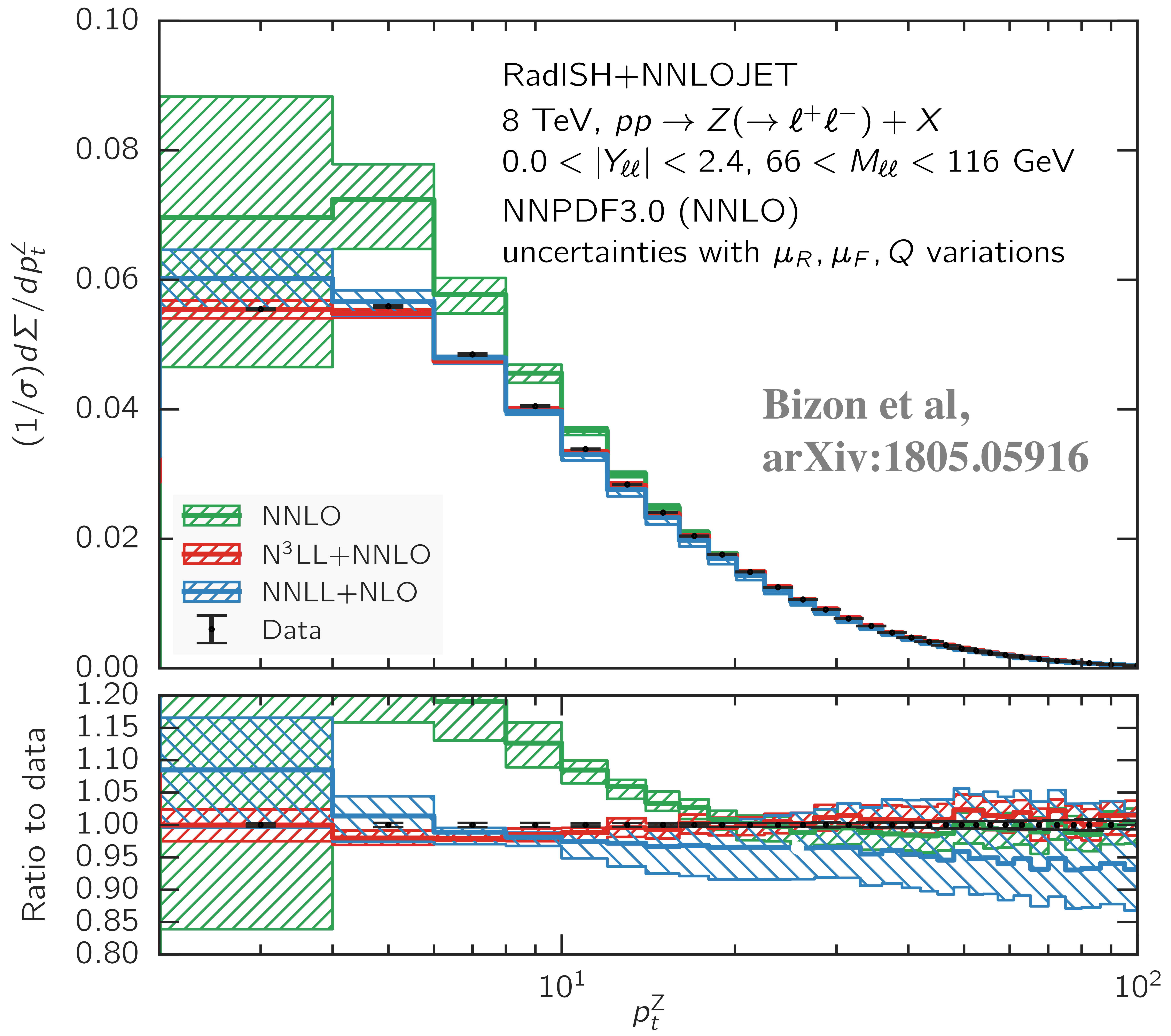
Standard-model physics (QCD & electroweak)

100 MeV - 4 TeV

This is where we measure SM parameters (e.g. top-quark mass), learn about basic non-perturbative inputs (parton distribution functions — PDFs) and test many of our methods

[it's also one of many places where we validate the SM and look for deviations]

SM measurements



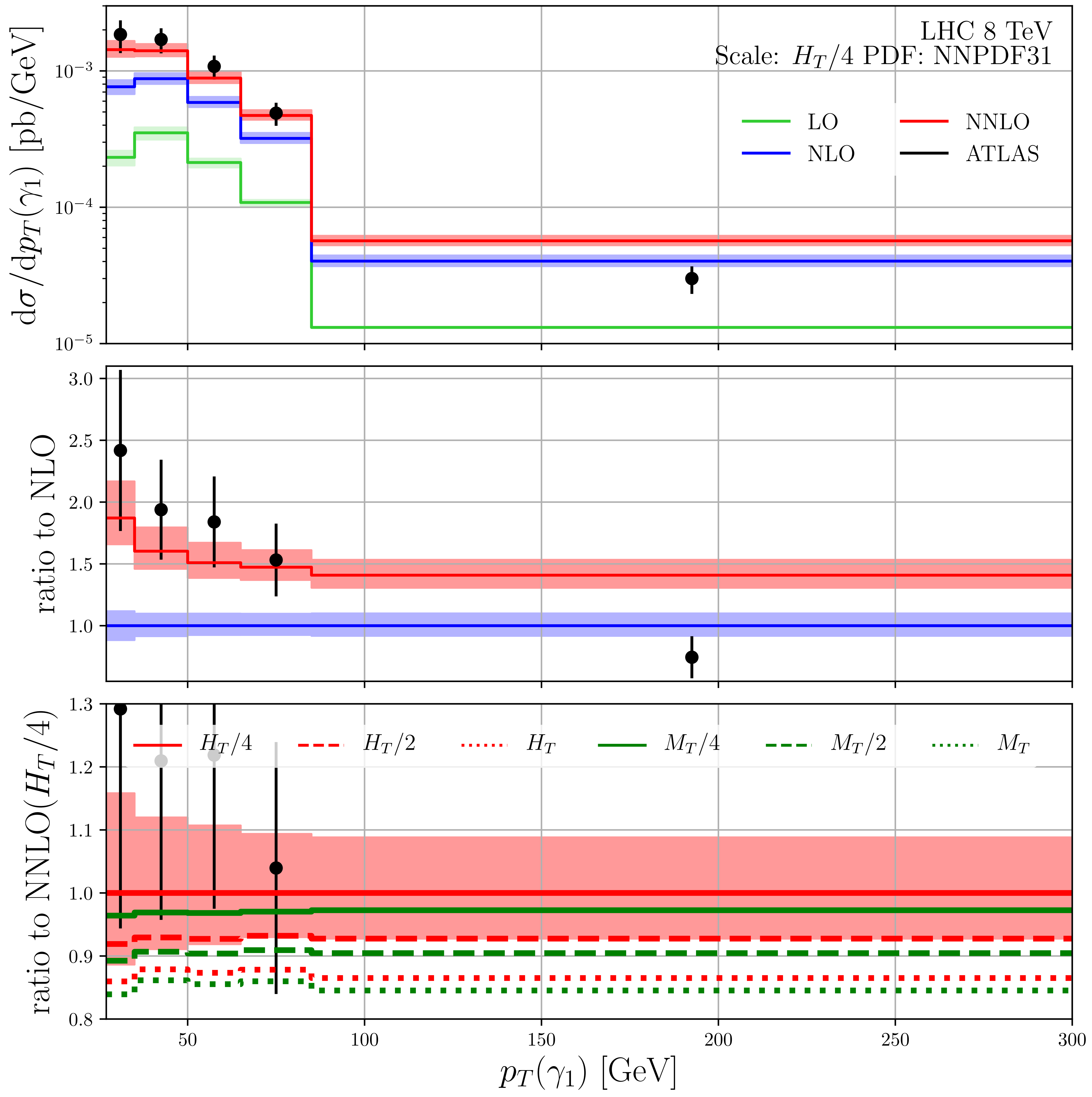
Z-boson transverse momentum

- "unfolded" measurement, i.e. as if experiments could directly measure the electrons and muons from Z decay.
- The observable is infrared and collinear safe (i.e. finite in perturbation theory)
- < 1% uncertainties in the data
- ~2% uncertainty on theory, thanks to past 5-years' advances in fixed-order predictions (Z+jet @ NNLO) and resummation (N3LL)
- agreement is very good

Key demonstration that LHC data & theory can successfully achieve high precision

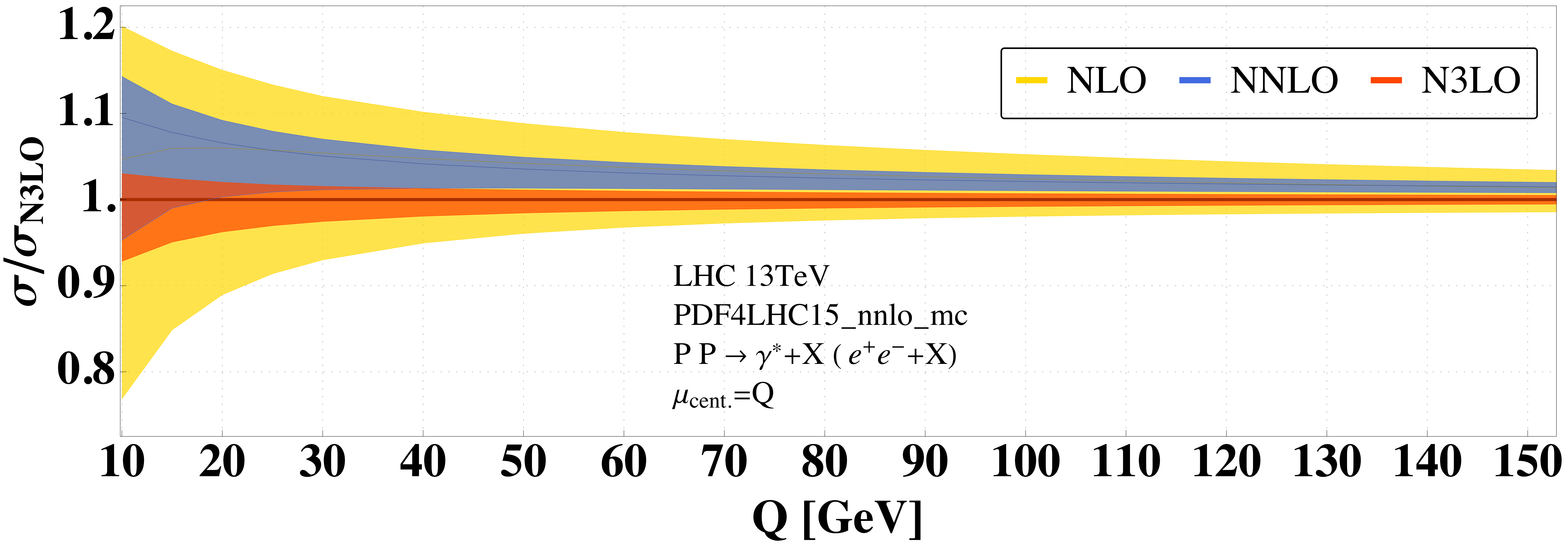
NB: two-loop amplitudes date to ~2002

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



➤ Chawdhry, Czakon, Mitov & Poncelet, arXiv:1911.00479

Drell-Yan at N3LO (Duhr, Dulat & Mistlberger, 2001.07717)

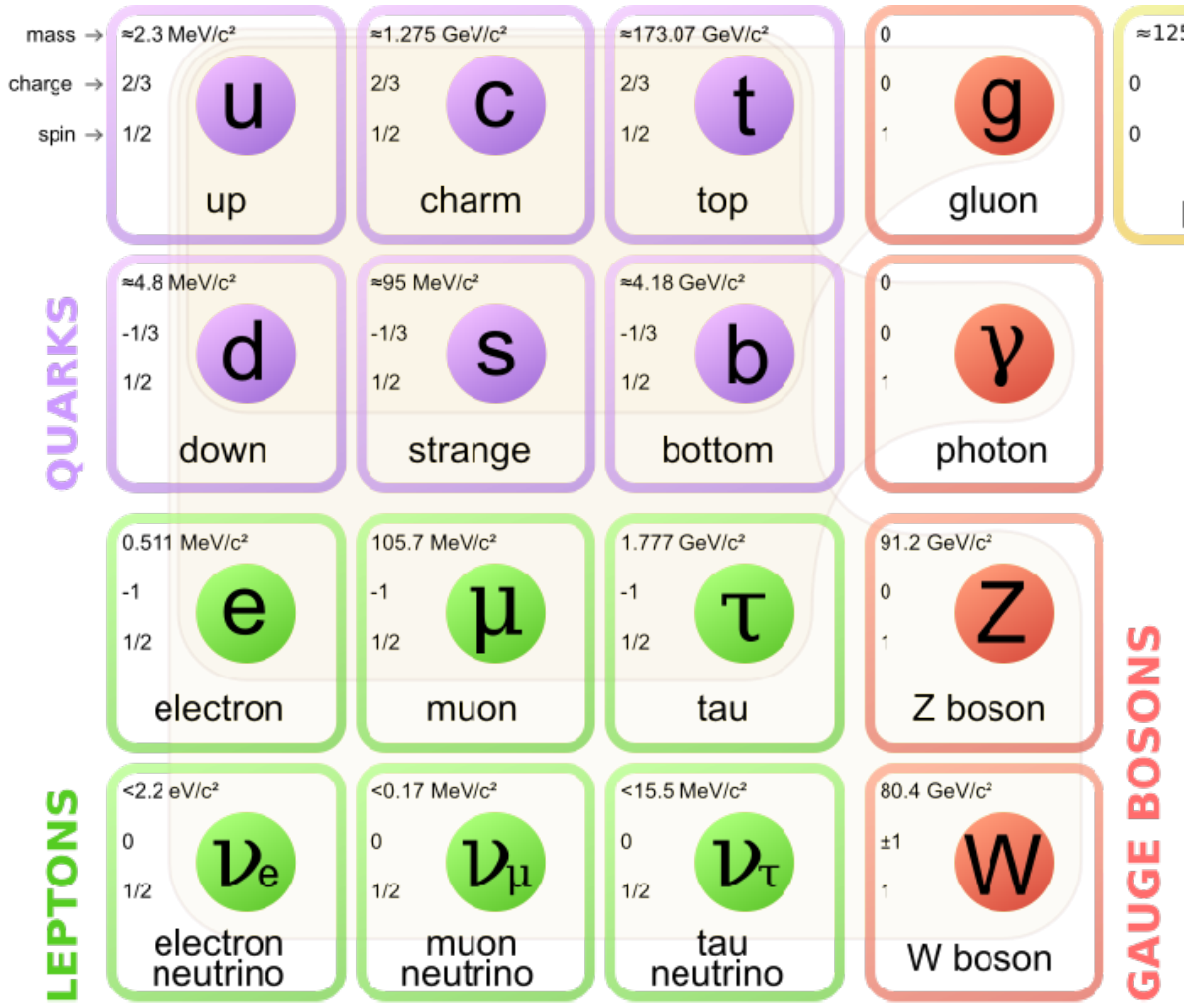


Higgs physics

Higgs physics

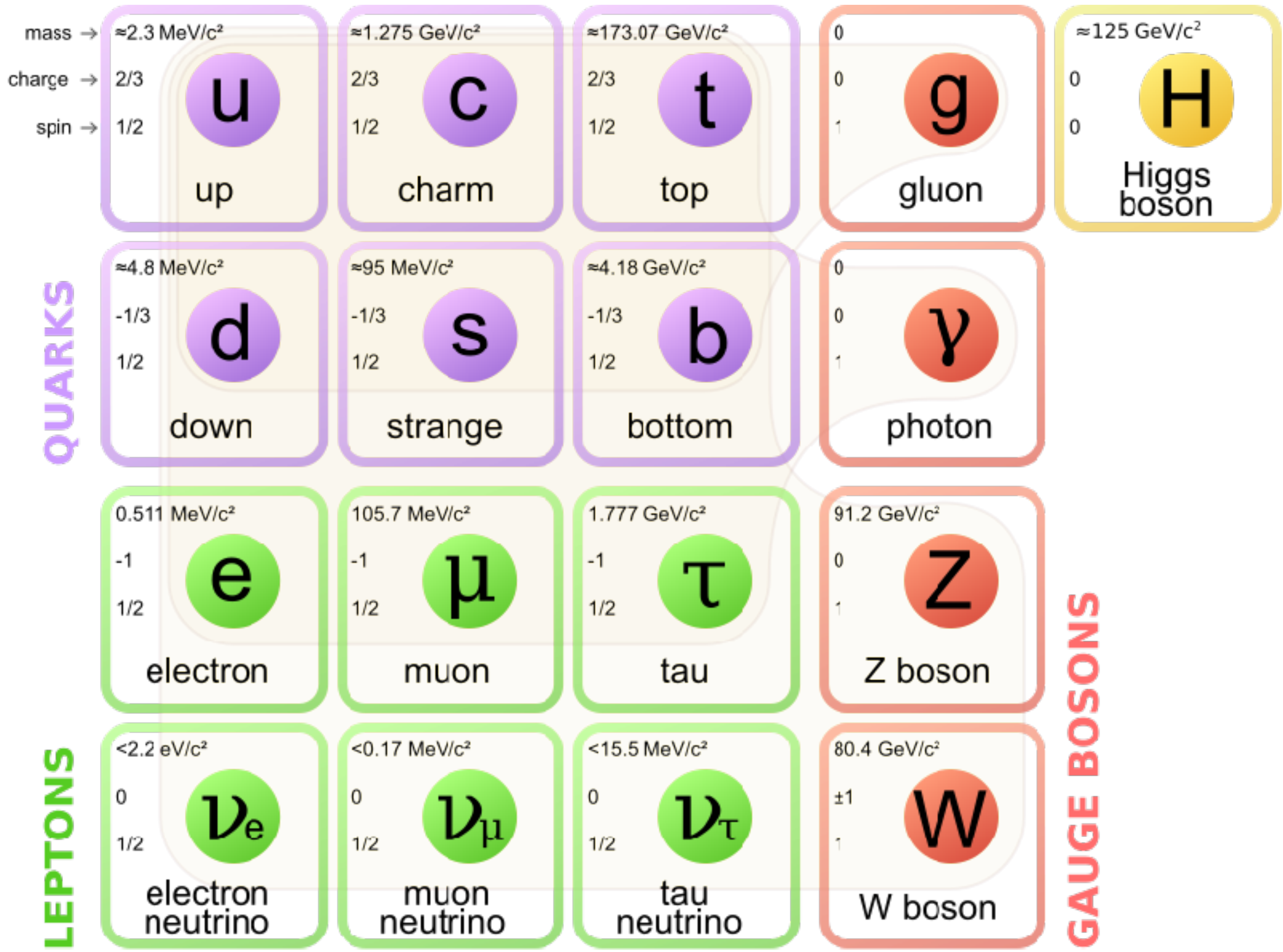
125 GeV - 500 GeV

the Standard Model is **not** complete



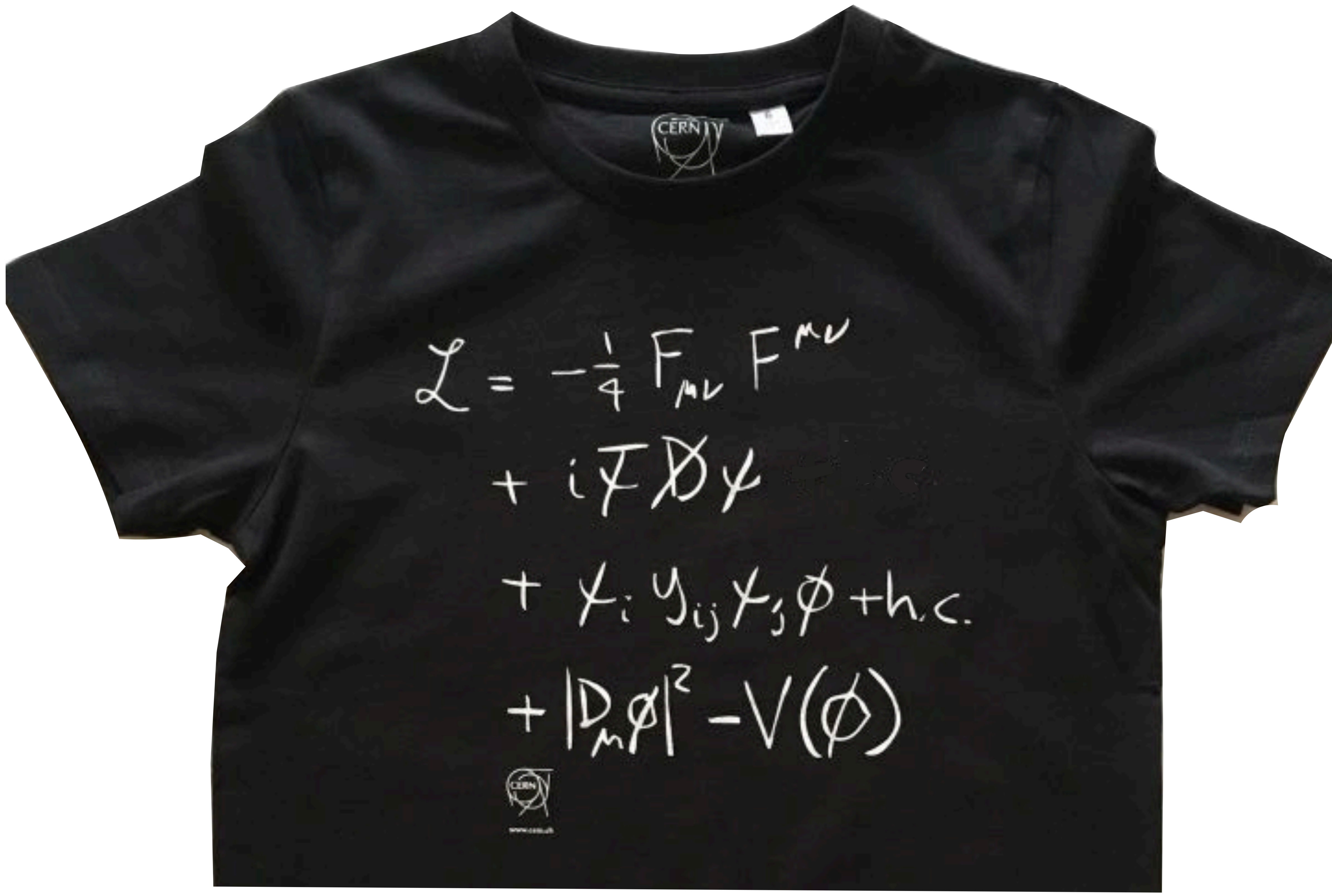
particles

the Standard Model is not complete



particles

+

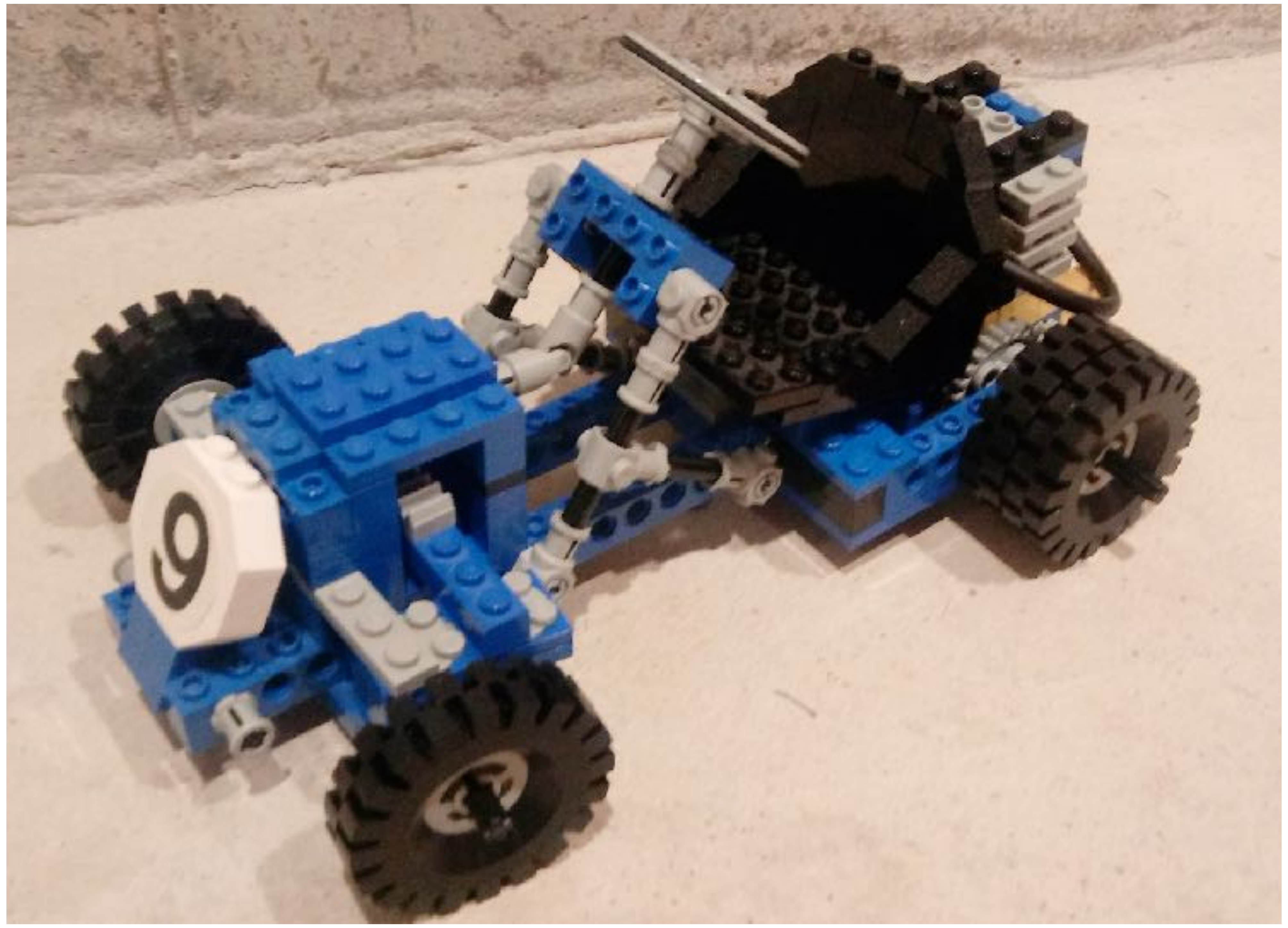


interactions

particles

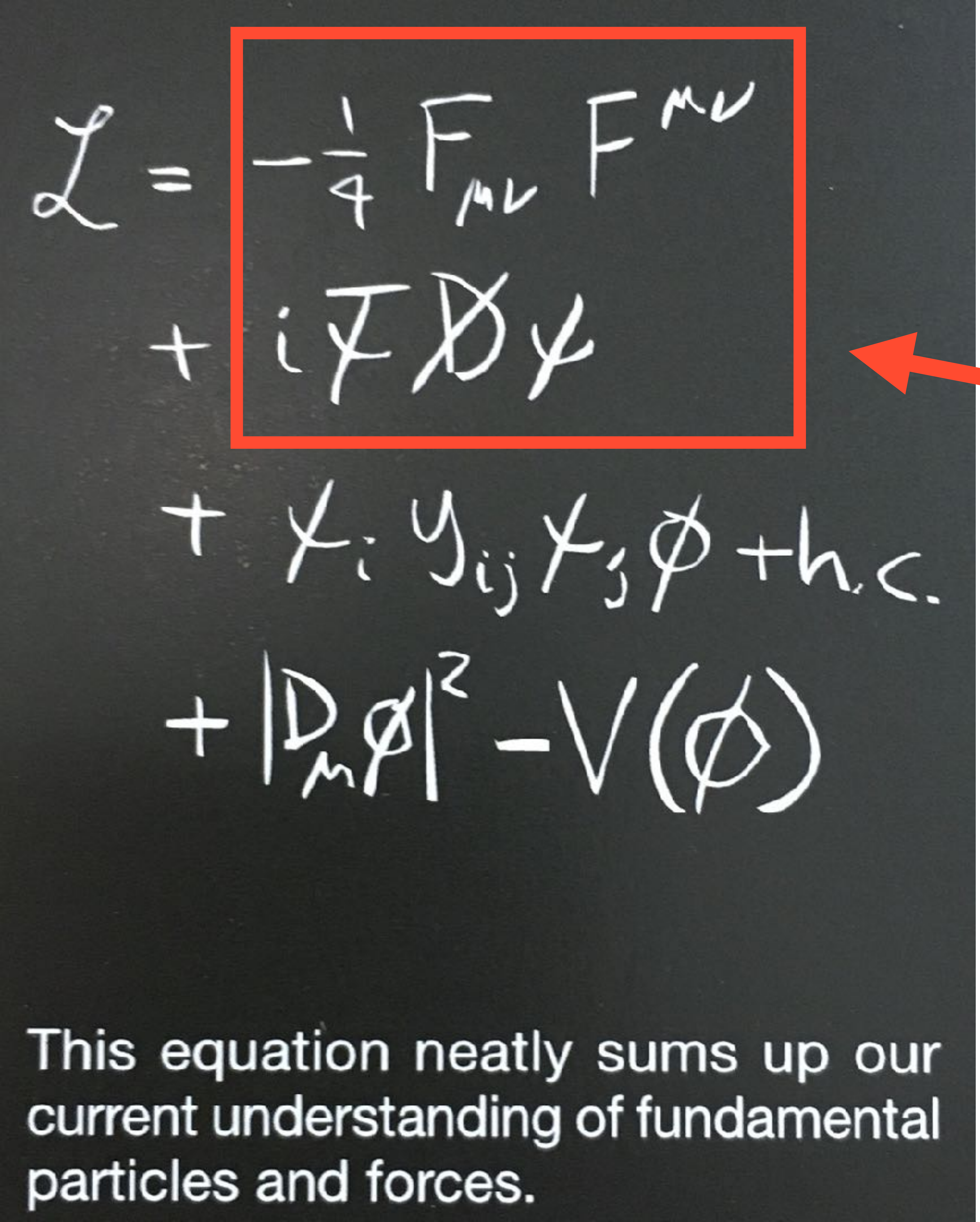
https://www.piqsels.com/en/public-domain-photo-fqrgz

particles + interactions



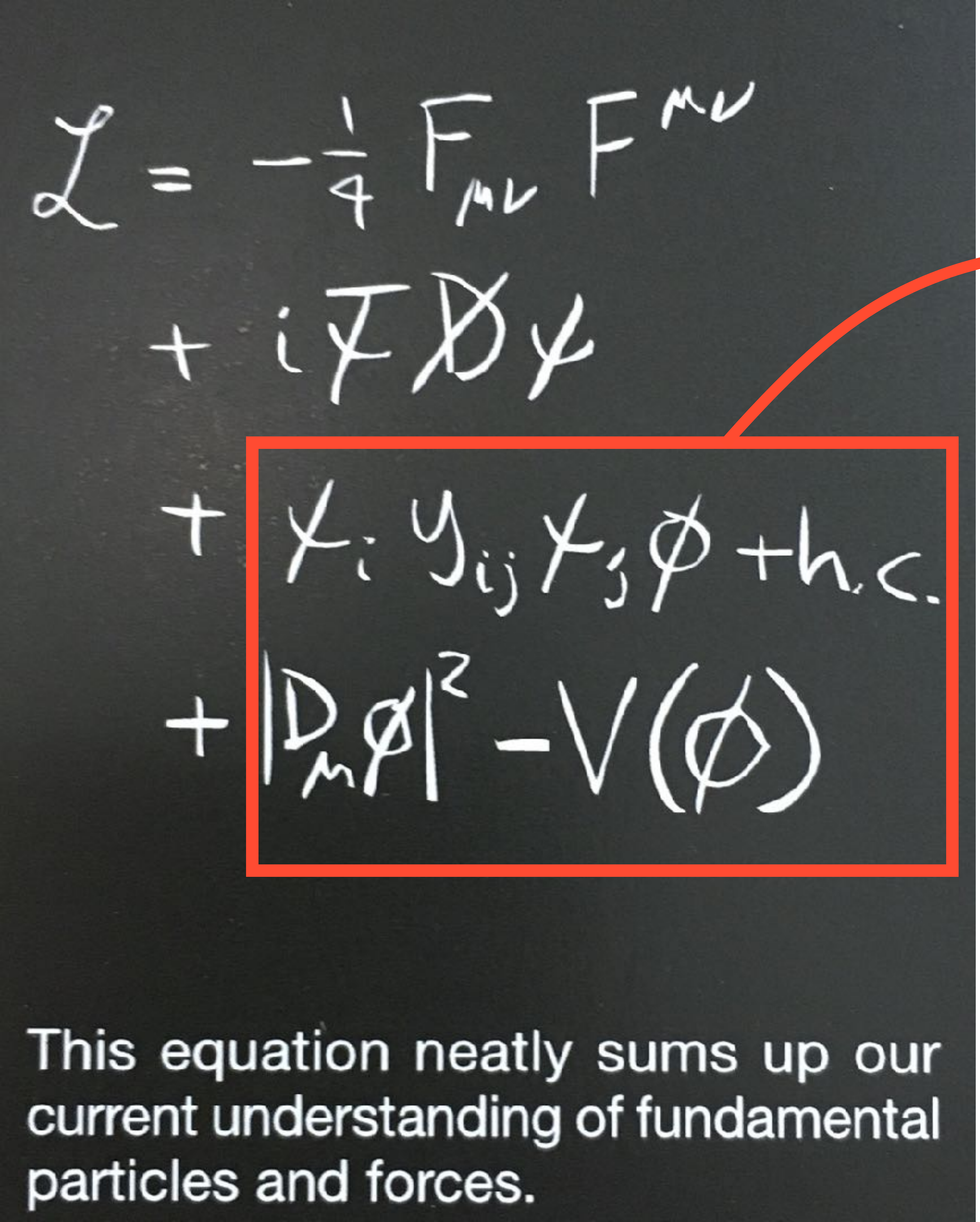
https://commons.wikimedia.org/wiki/File:LEGO_Expert_Builder_948_Go-Kart.jpg, CC-BY-SA-4.0

Some interactions extensively tested



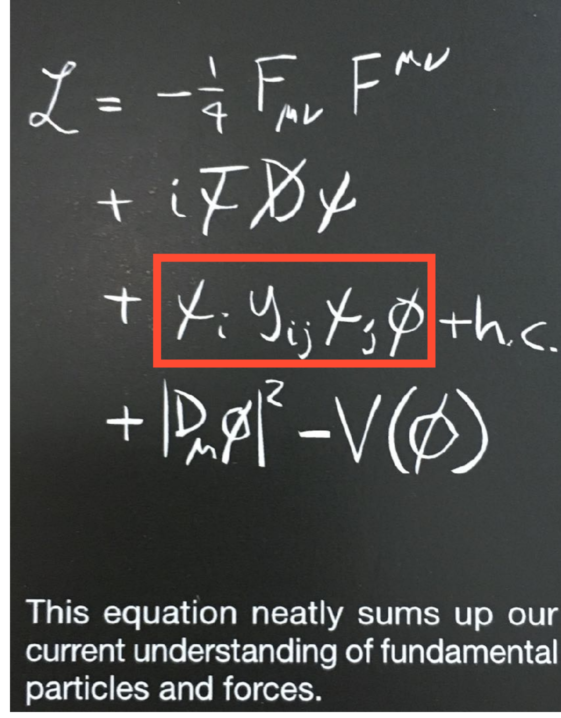
Many parts of the gauge sector have been tested to high accuracy (e.g. QED)

Higgs sector



until 7 years ago none of these terms had ever been directly observed.

Why do Yukawa couplings matter?
(1) Because, within SM conjecture, they're what give masses to all quarks



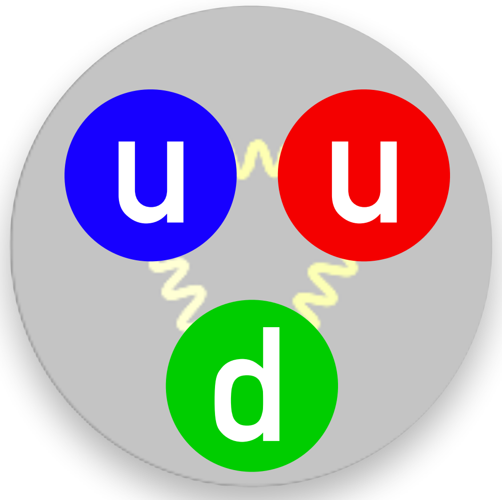
Up quarks (mass ~ 2.2 MeV) are lighter than
down quarks (mass ~ 4.7 MeV)

proton (up+up+down): 2.2 + 2.2 + 4.7 + … = 938.3 MeV
neutron (up+down+down): 2.2 + 4.7 + 4.7 + … = 939.6 MeV

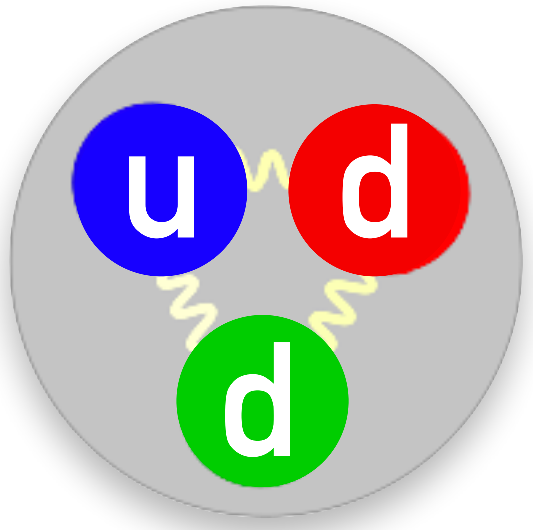
So protons are **lighter** than neutrons,
→ protons are stable.

Which gives us the hydrogen atom,
& chemistry and biology as we know it

proton
mass = 938.3MeV

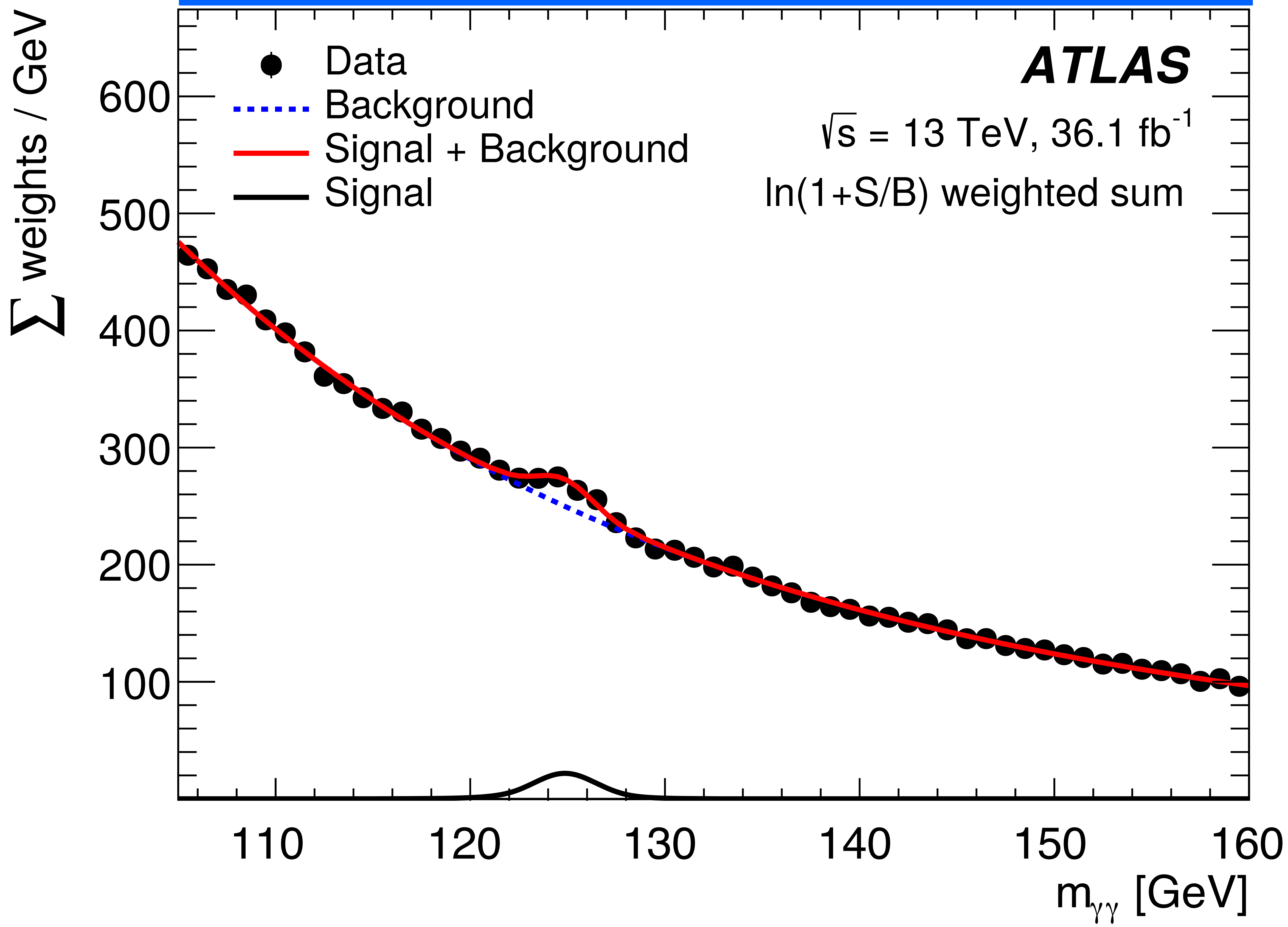


neutron
mass = 939.6MeV

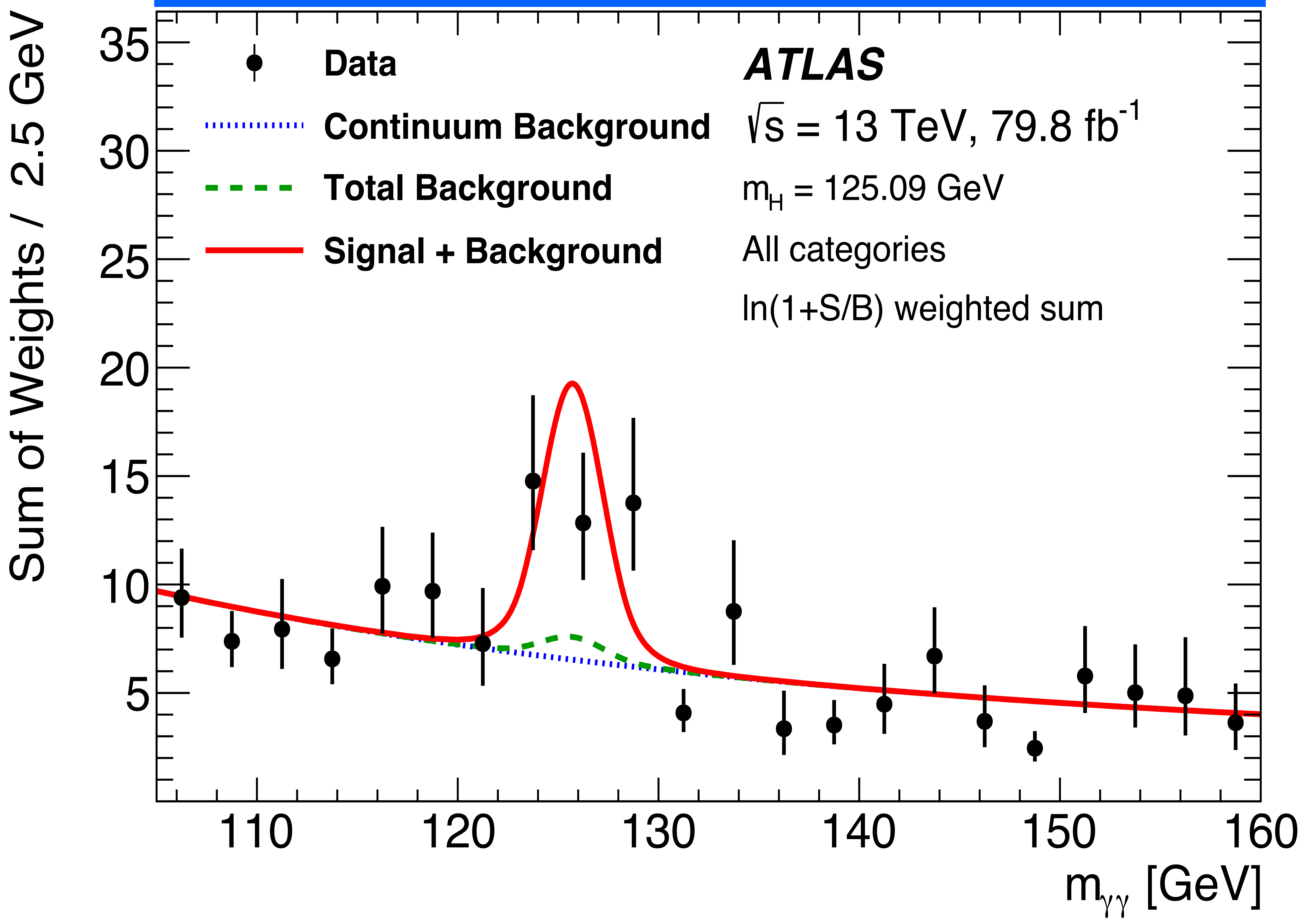


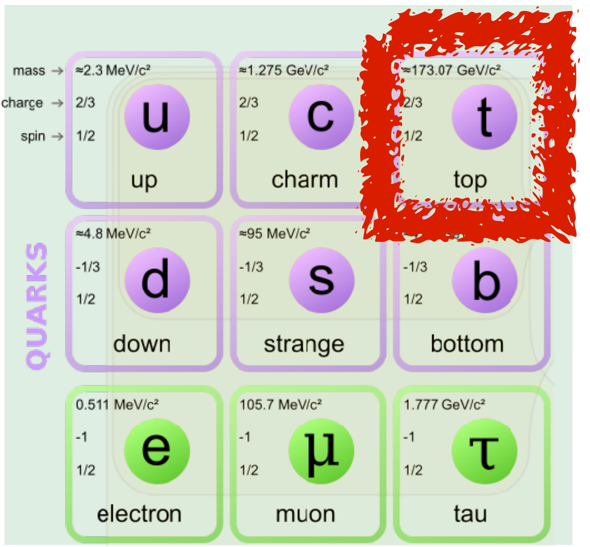
major news of past 2 years: ATLAS & CMS see events with top-quarks & Higgs simultaneously

$H \to \gamma\gamma$ across all events



in events with top quarks





enhanced fraction of Higgs bosons in events with top quarks

→ direct observation of Higgs interaction with tops

(consistent with SM to c. ±20%)

metric for success going forwards [one possible view]

- **Long term (≡ new colliders):**
  can we observe Higgs self coupling?
  I.e. get an experimental window on the Higgs potential, which underpins the rest of the SM

- Medium term:
  evolve today's c. 10-20% constraints on Higgs sector towards accuracy
  (we wouldn't consider QED established if it had only been tested to 10%)

- **Bonuses:**
  maximise our sensitivity to new physics at colliders and smaller experiments,
  (what form it takes and whether it's even accessible is in Nature's hands, not ours)

metric for success going forwards [one possible view]

- **Long term (≡ new colliders):**
  can we observe Higgs self coupling?
  I.e. get an experimental window on the Higgs potential, which underpins the rest of the SM
- **Medium term:**
  evolve today's c. 10-20% constraints on Higgs sector towards accuracy
  (we wouldn't consider QED established if it had only been tested to 10%)
- **Bonuses:**
  maximise our sensitivity to new physics at colliders and smaller experiments,
  (what form it takes and whether it's even accessible is in Nature's hands, not ours)

e.g. CMS 1804.02610 on ttH (~80 fb^{-1})

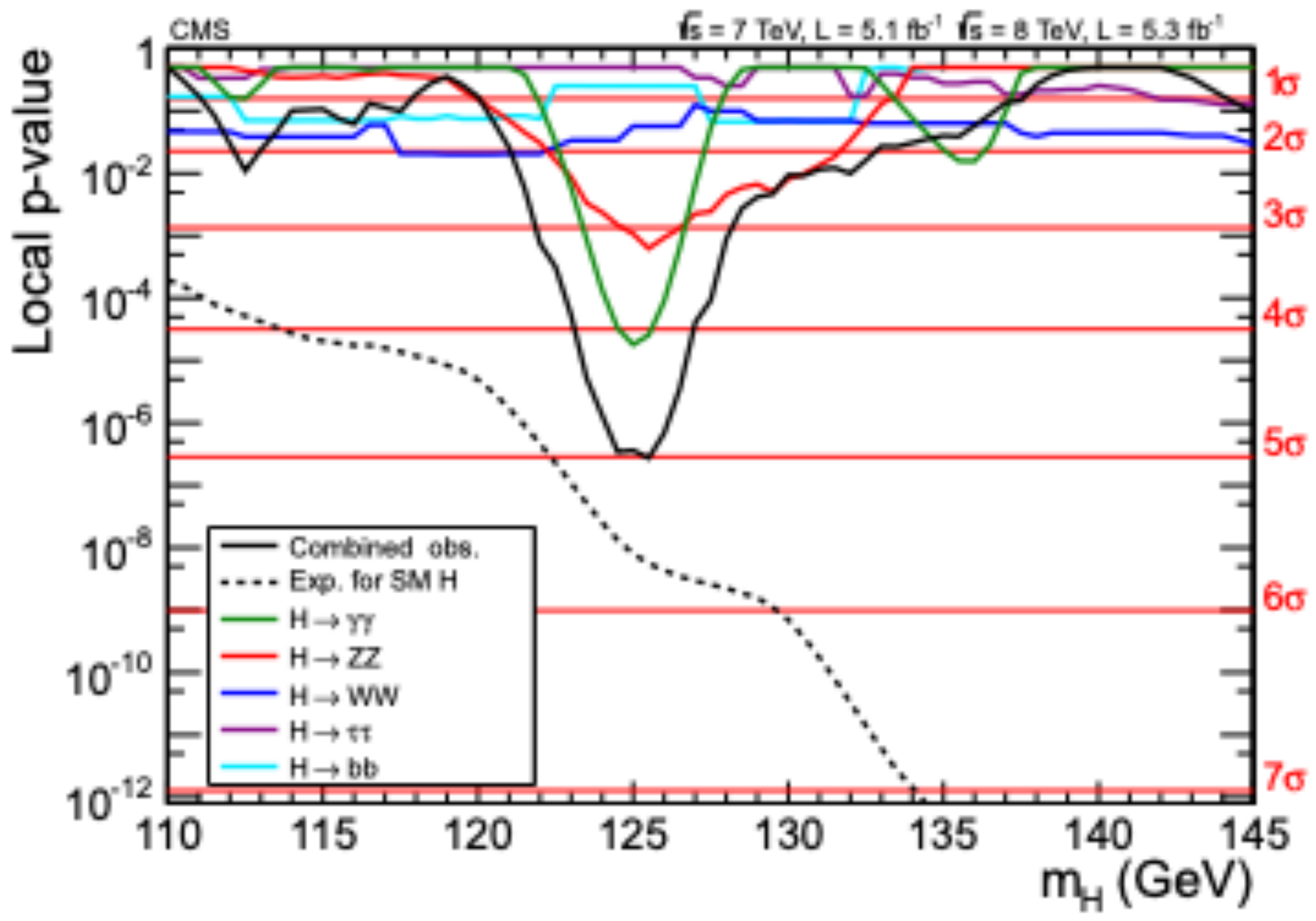
Parameter	Best fit	Uncertainty Stat	Expt	Thbgd	Thsig
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$	$^{+0.16}_{-0.16}$	$^{+0.17}_{-0.15}$	$^{+0.14}_{-0.13}$	$^{+0.15}_{-0.07}$

- overall on ttH, theory systematics are about the same as statistical and experimental systematics
- statistical error has potential to go down by $\times 6$ at the HL-LHC (factor ~ 40 in data)
- useless if theory doesn't keep up.
- both signals and backgrounds matter

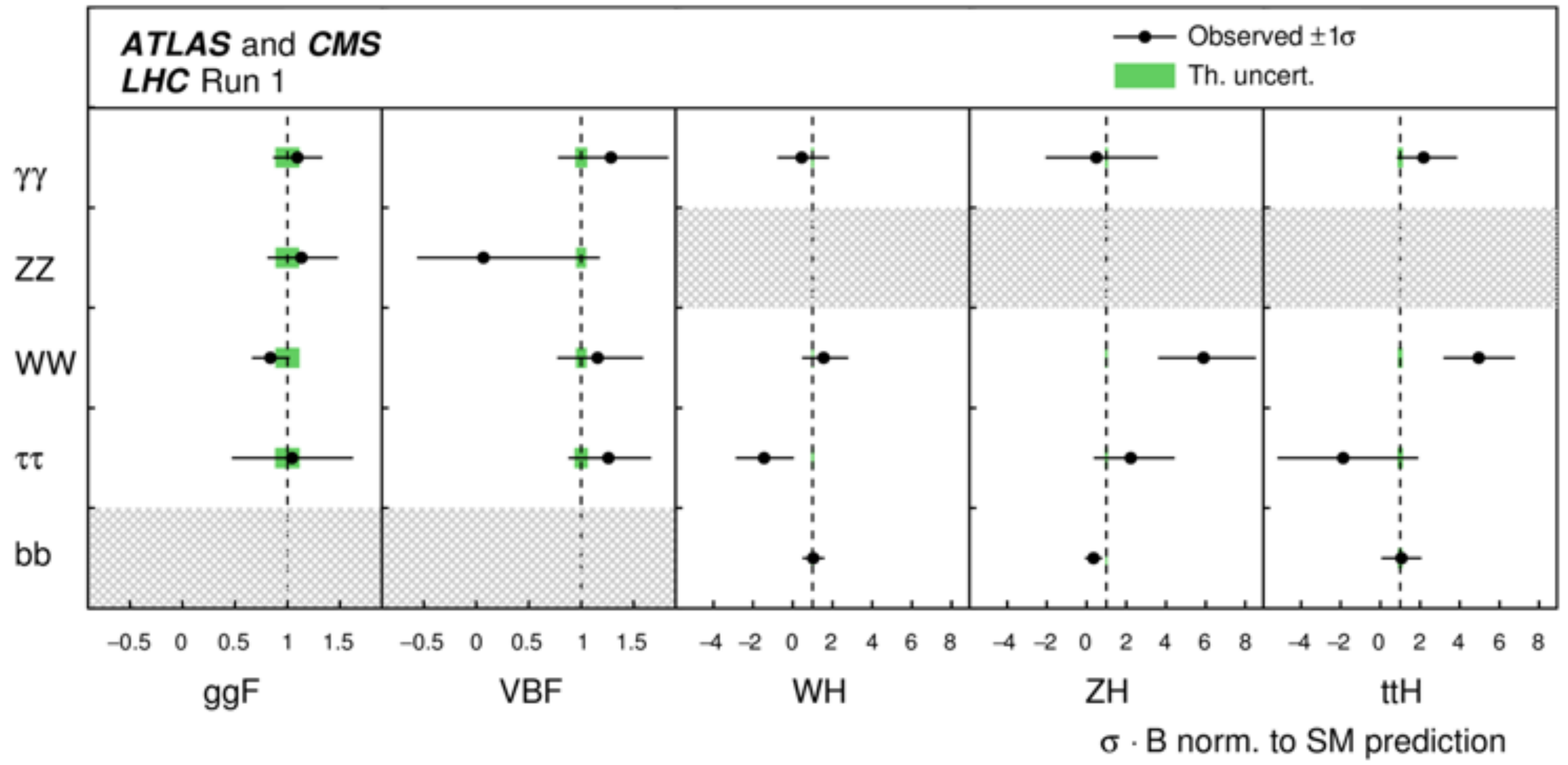
LHC – FROM 5 SIGMA TO DIFFERENTIAL IN 360 WEEKS

Andre David @ZPW

July 2012

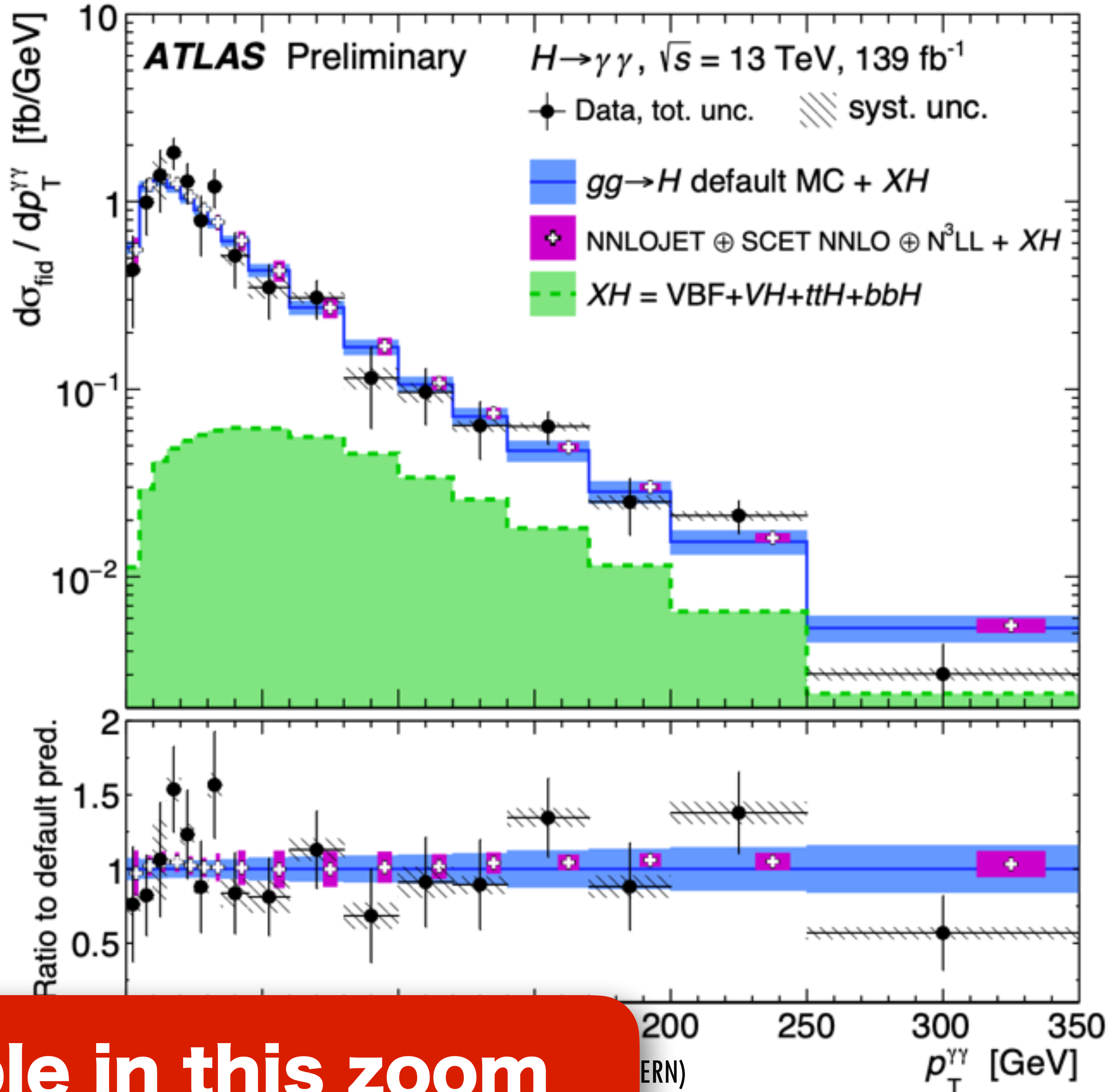


Run1 CMS-ATLAS combination



Some **Run 2** milestones:

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



+ theory calculations from many people in this zoom

EFT (expressive formulation of constraints) or not?

- First observe a given channel, e.g. H $\to b\bar{b}$
- Once you've observed it, if it agrees roughly ($\pm 20\%$) with SM, then consider going 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

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

BSM effects SM particles

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.

top-quark physics

170 GeV – O(TeV)

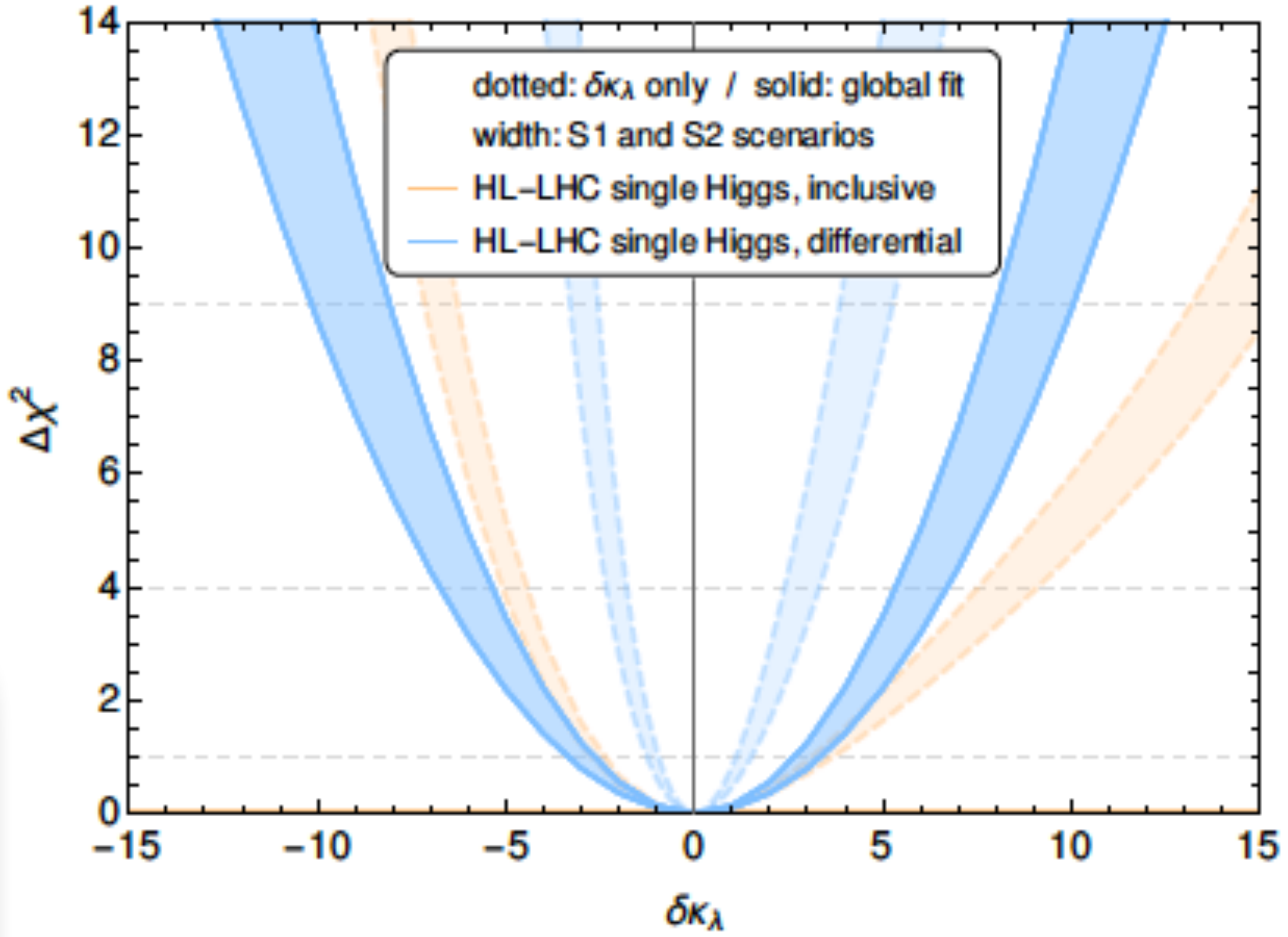
Higgs physics

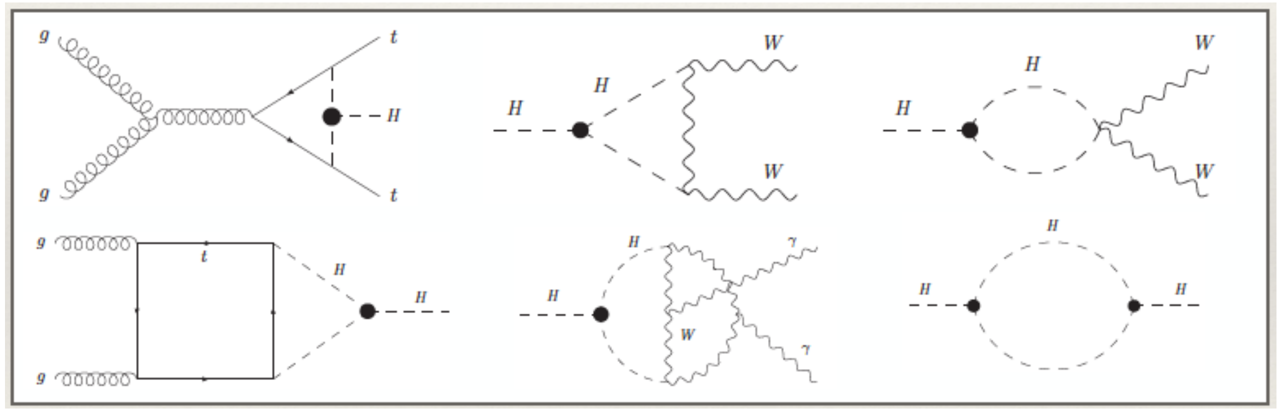
125 GeV – 500 GeV

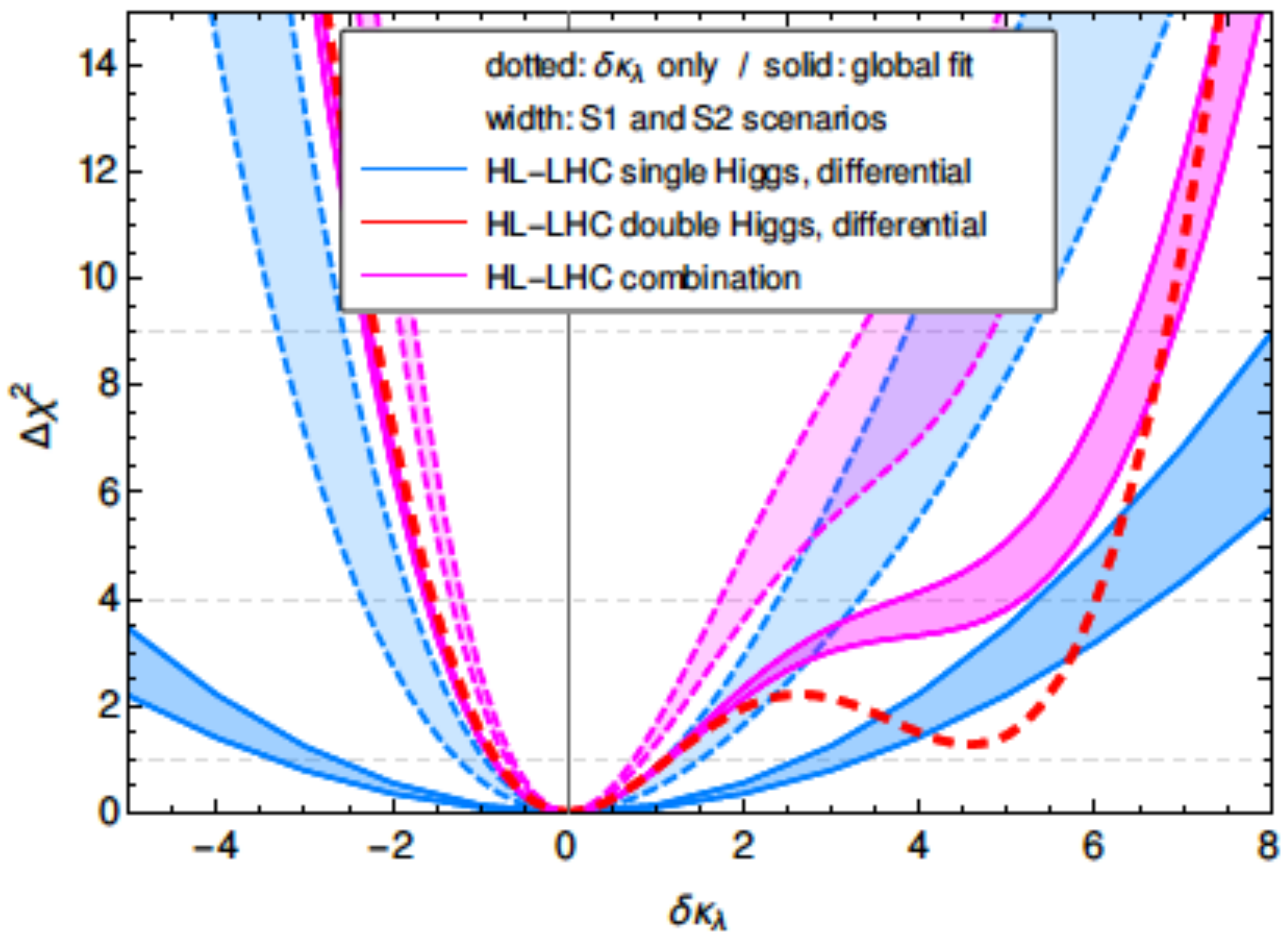
these two sectors are intimately connected with each other

Top-Higgs interplay in HH

Future prospects for Higgs self-coupling:





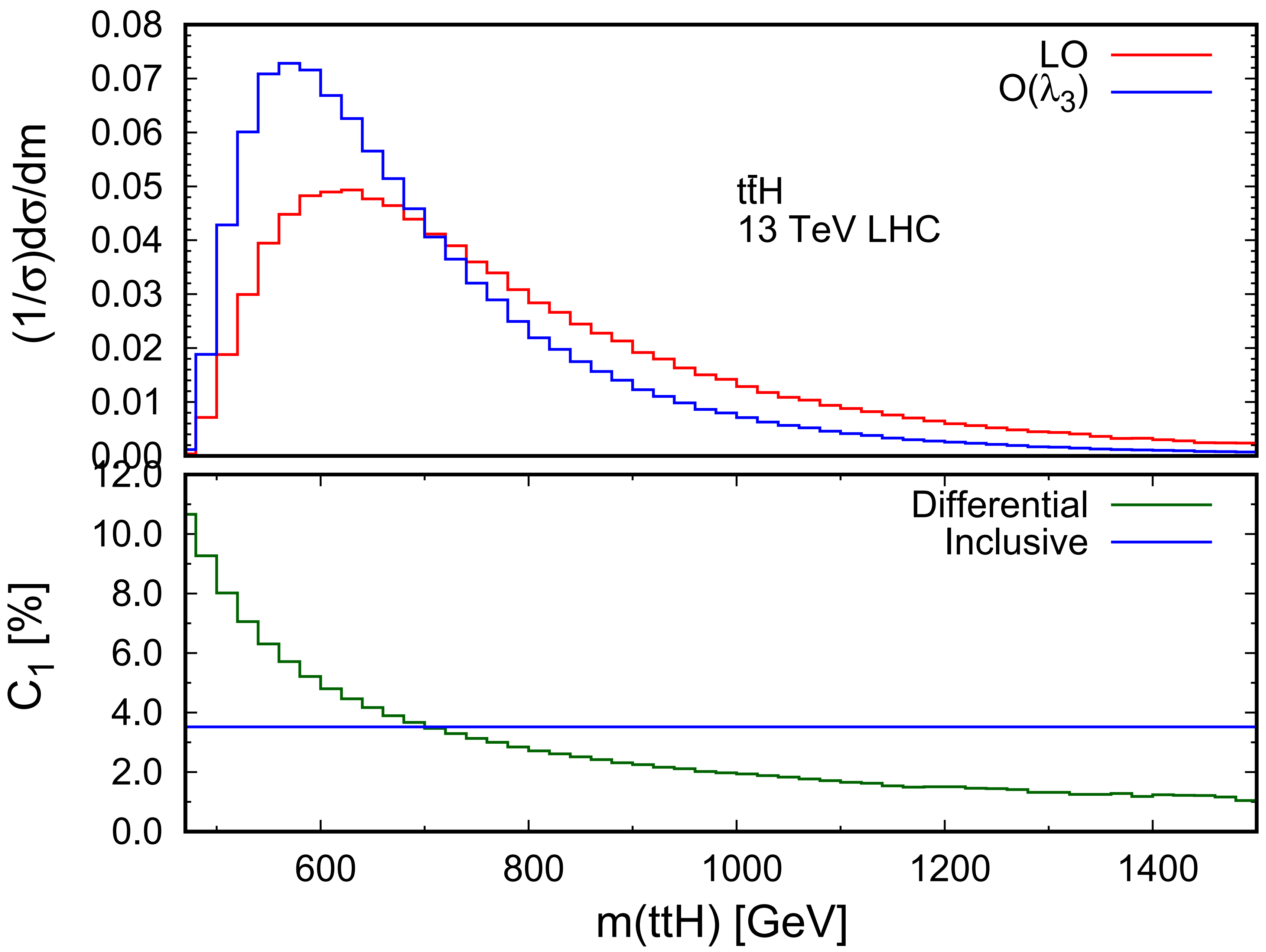


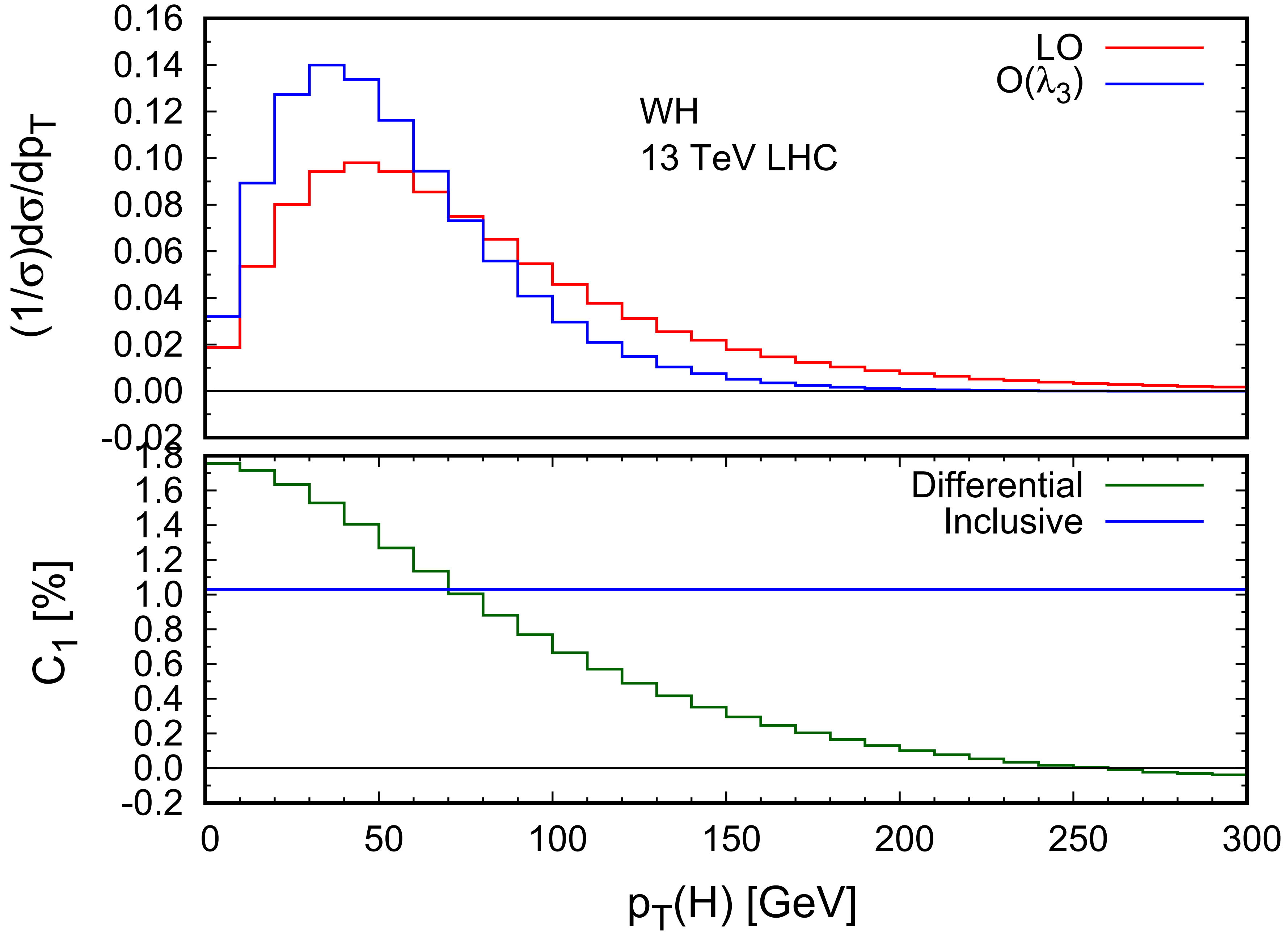
Di Vita et al. arXiv:1704.01953 and HH white paper

Eleni Vryonidou @ ZPW

Degeneracy with Yukawa and contact ggH operators worsens HHH sensitivity

C1: kinematic dependence



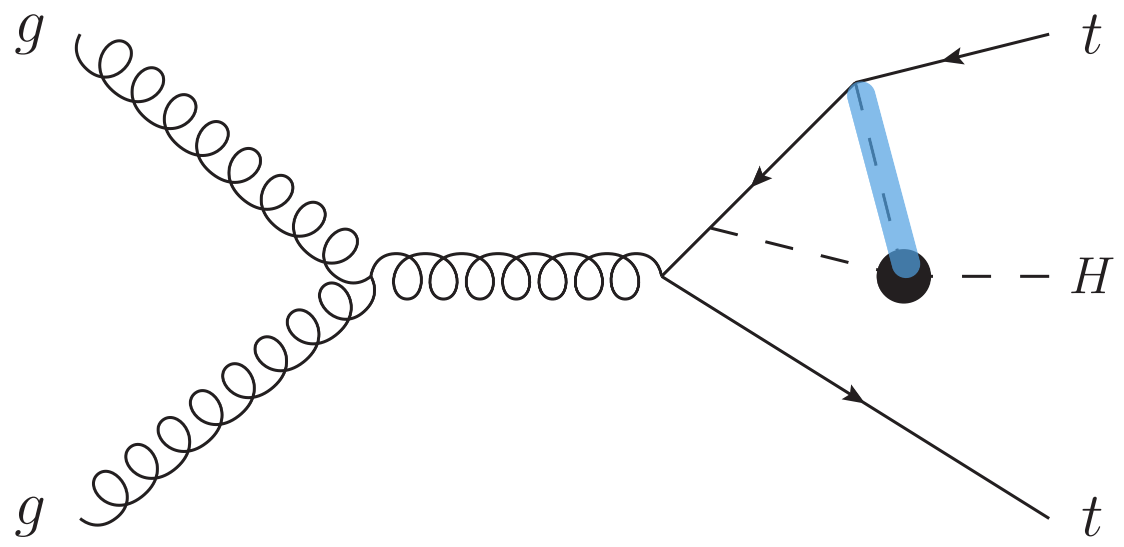


Davide Pagani @ ZPW

complementary to direct searches for HH

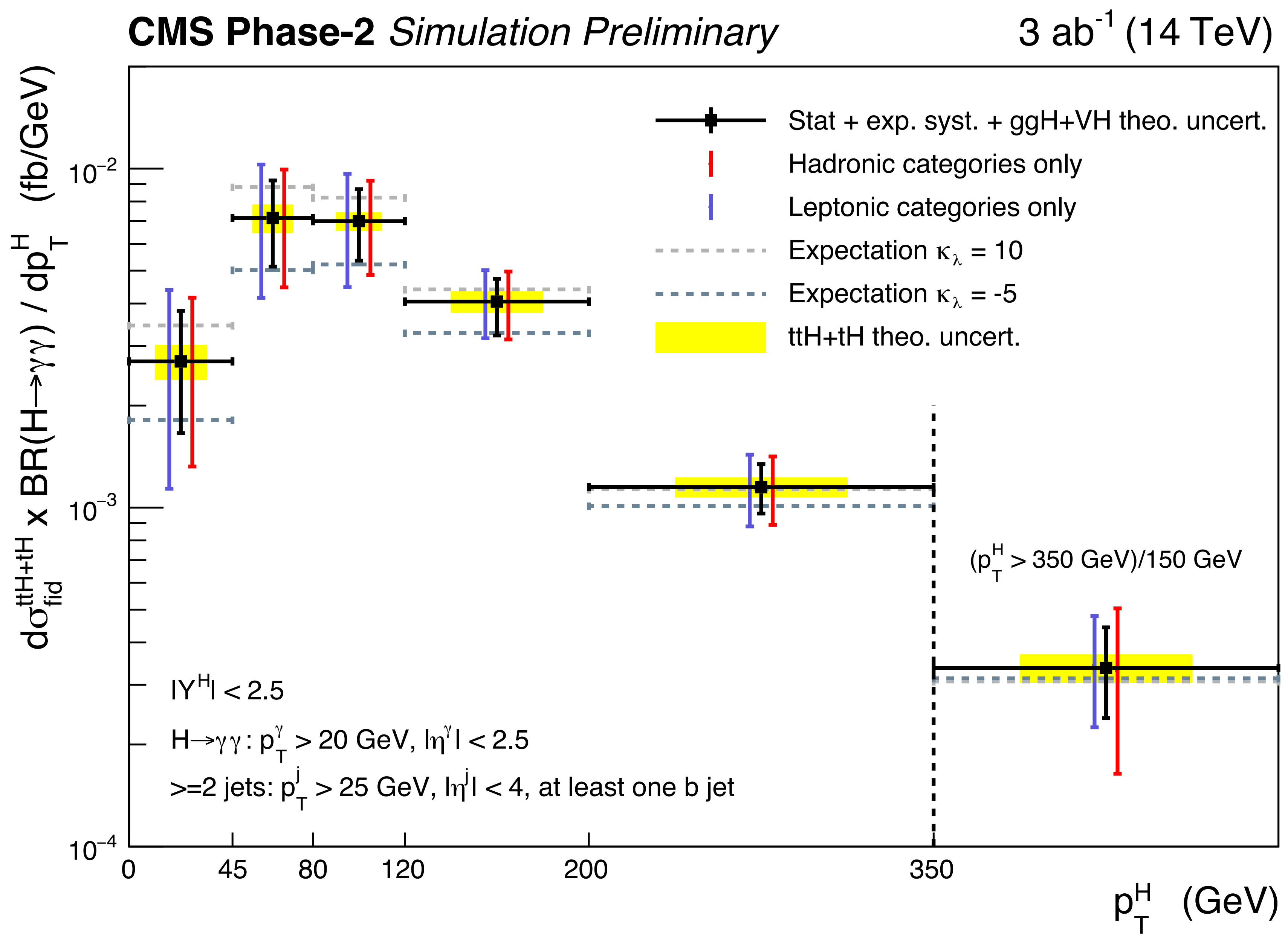
Maltoni, DP, Shivaji, Zhao '17

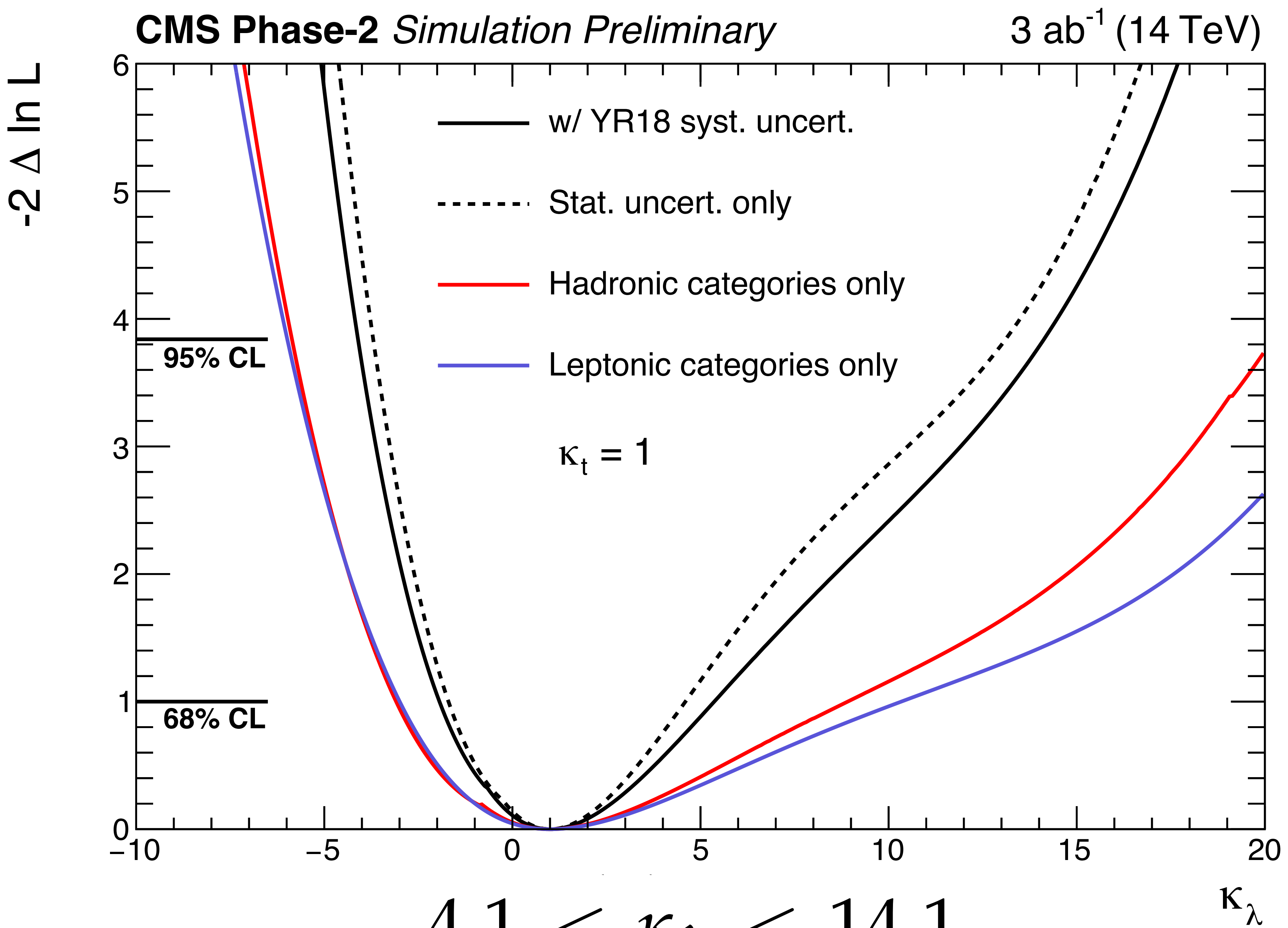
Contributions to ttH and HV processes can be seen as induced by a Yukawa potential, giving a Sommerfeld enhancement at the threshold.



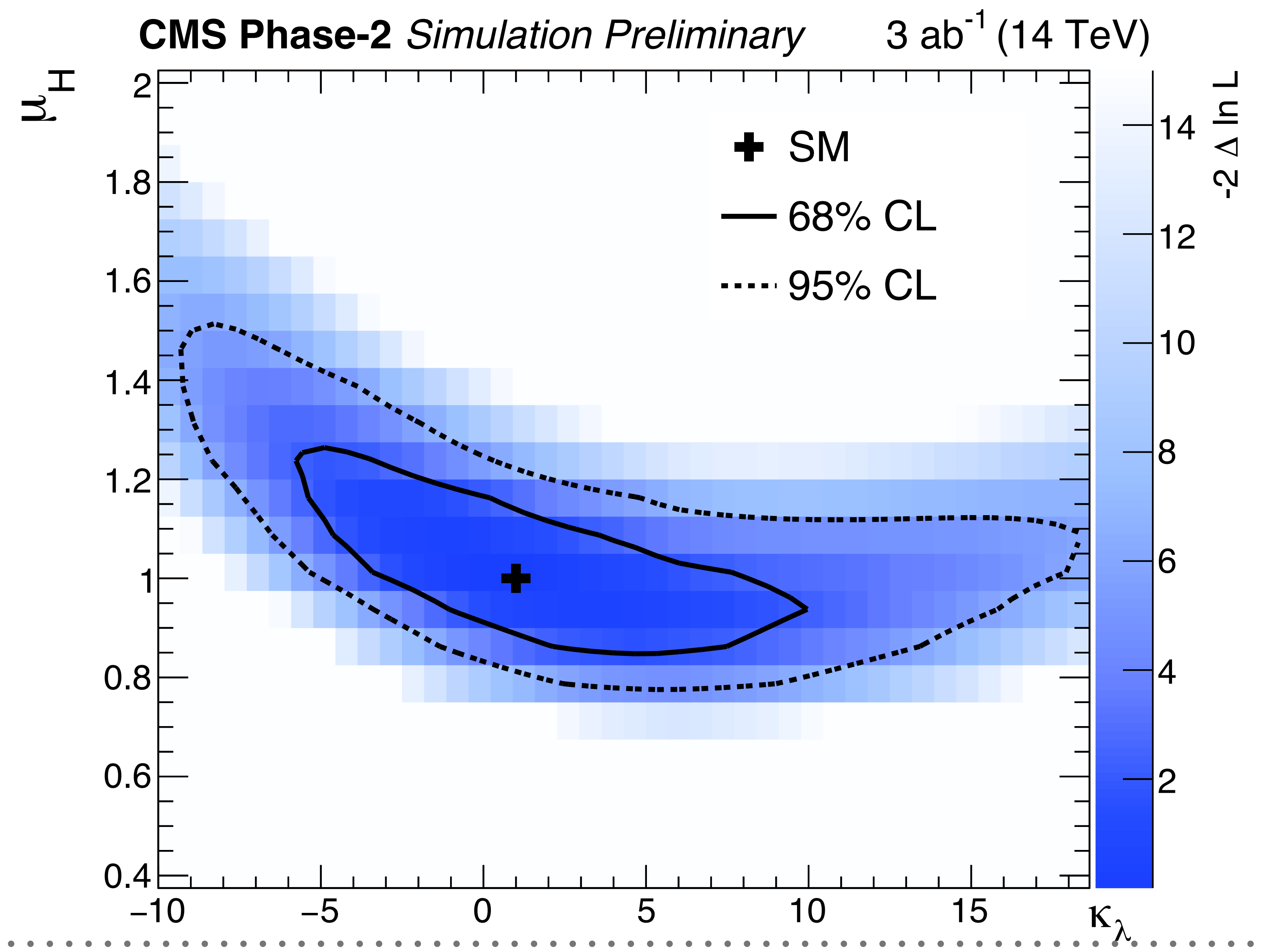
32

First experimental projections





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



33

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

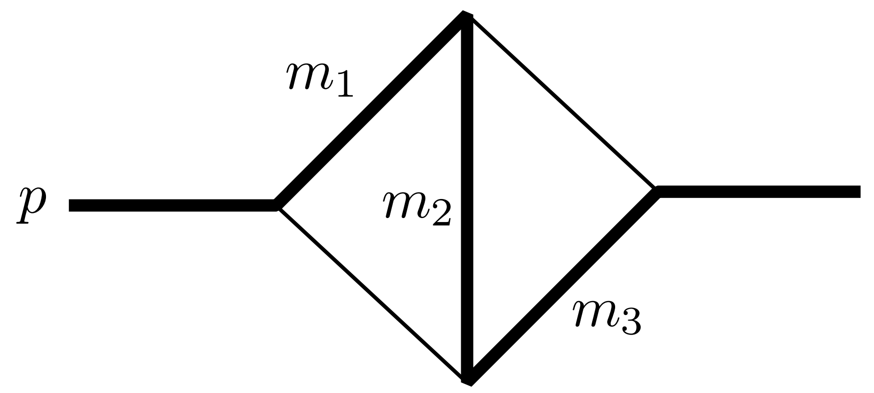
Davide Pagani @ ZPW

complementary to direct searches for HH

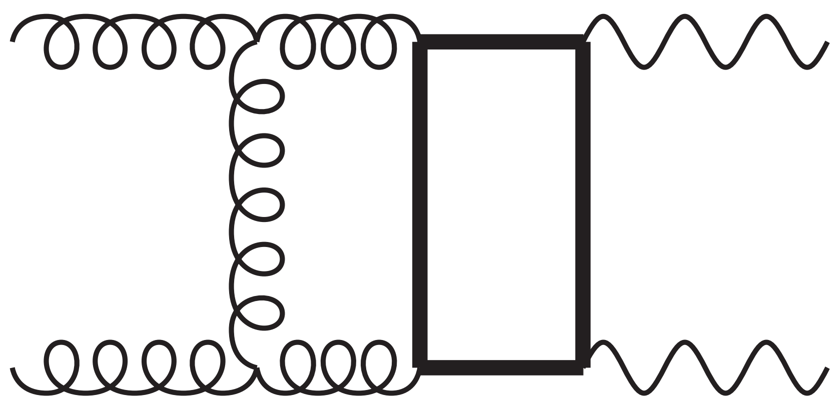
only the start of studying its potential

TOWARDS HIGGS AND TOPS @ NNLO

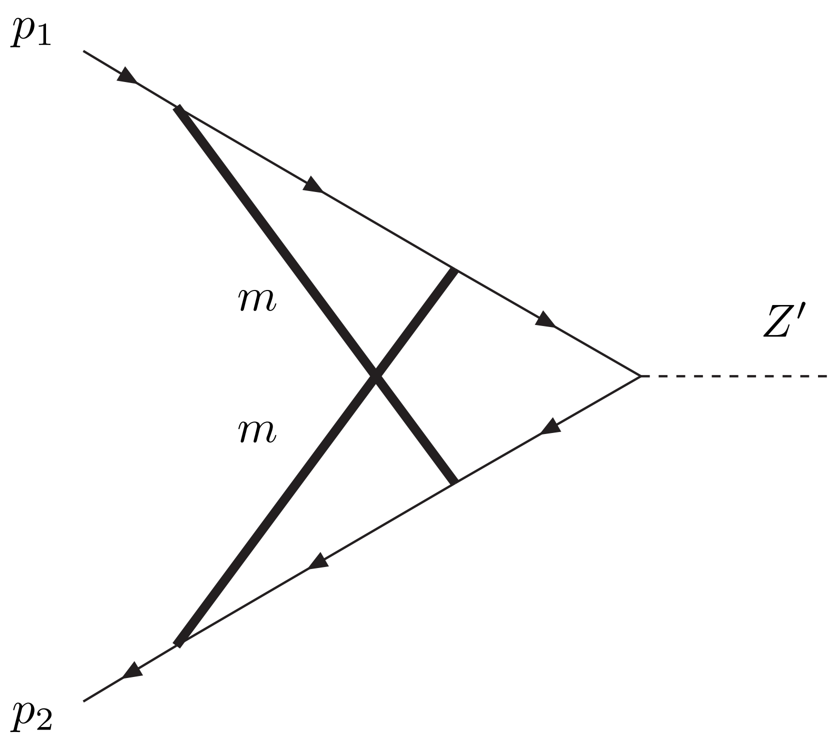
Lorenzo Tancredi @ ZPW



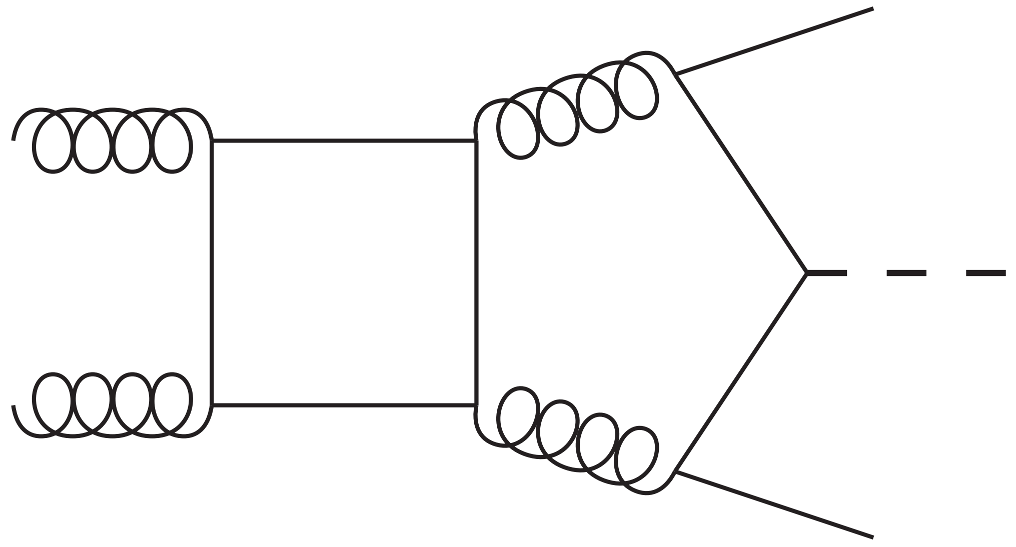
Kite integral (self-energies…)



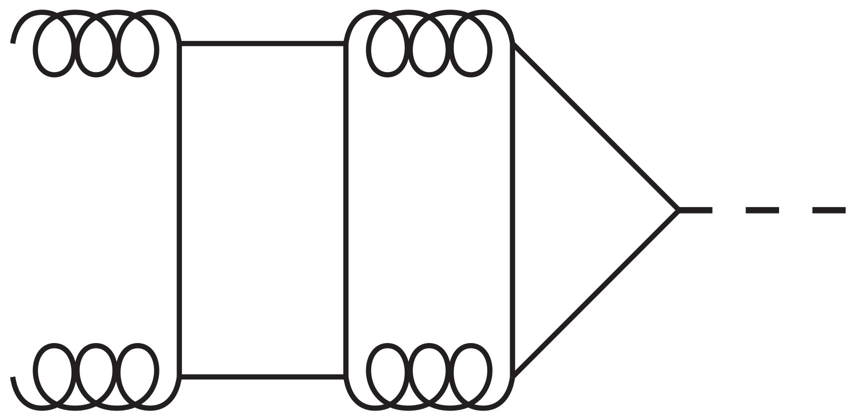
QCD with top quarks



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** !

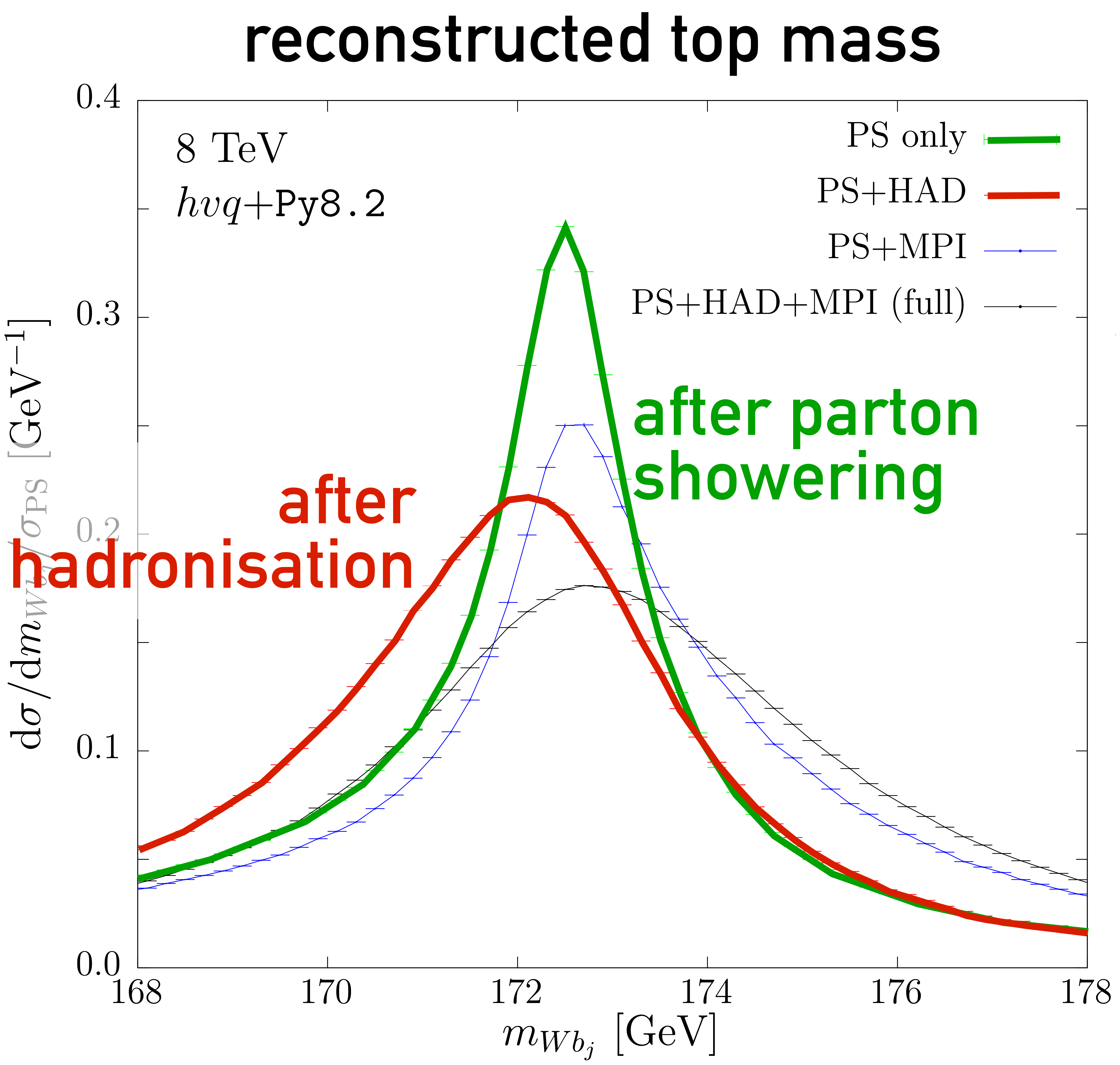
top-quark physics

170 GeV – O(TeV)

top mass

A plot shown many times

Degrassi et al. 2012



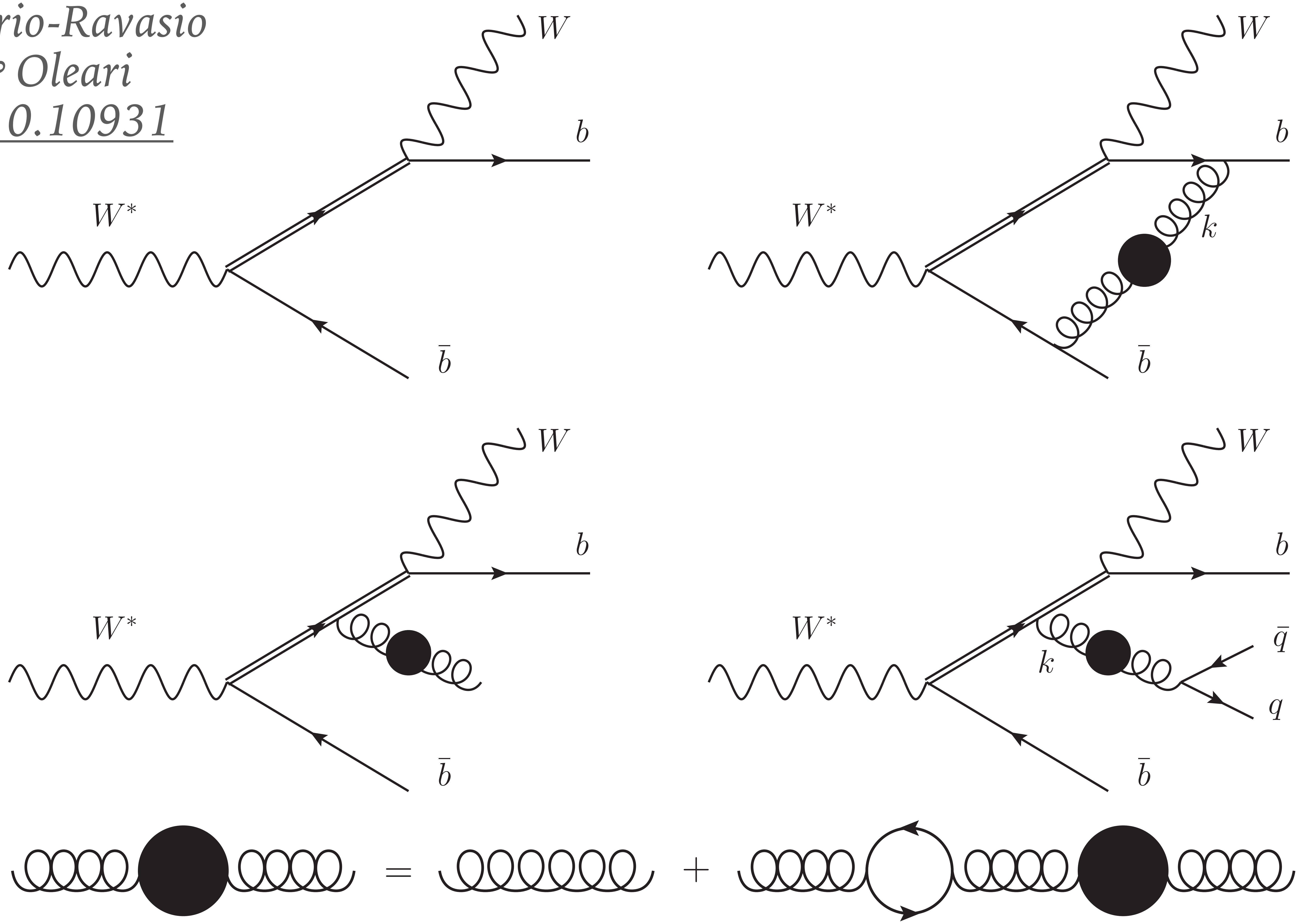
hadron-level effects

- ultimately, it is hadrons that get measured
- for utmost precision (≲ 1 GeV) we need some handle on non-perturbative effects
- long-standing discussion about pole mass v. MSbar mass (and associated non-perturbative effects ≡ renormalons)
- but this is only one part of the story

plot from Ferraro Ravasio, Jezo, Nason, Oleari
1801.03944 + *1906.09166*
see also work by Hoang et al

Diagrams up to leading N_f one gluon correction

Nason, Ferrario-Ravasio & Oleari *1810.10931*



revolution in treatment of non-perturbative effects

ultimate impact likely well beyond top physics

Prospects

Nason, Ferrario-Ravasio & Oleari 1810.10931

- 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]

Standard-model physics (QCD & electroweak)

100 MeV - 4 TeV

top-quark physics

170 GeV - O(TeV)

Higgs physics

125 GeV - 500 GeV

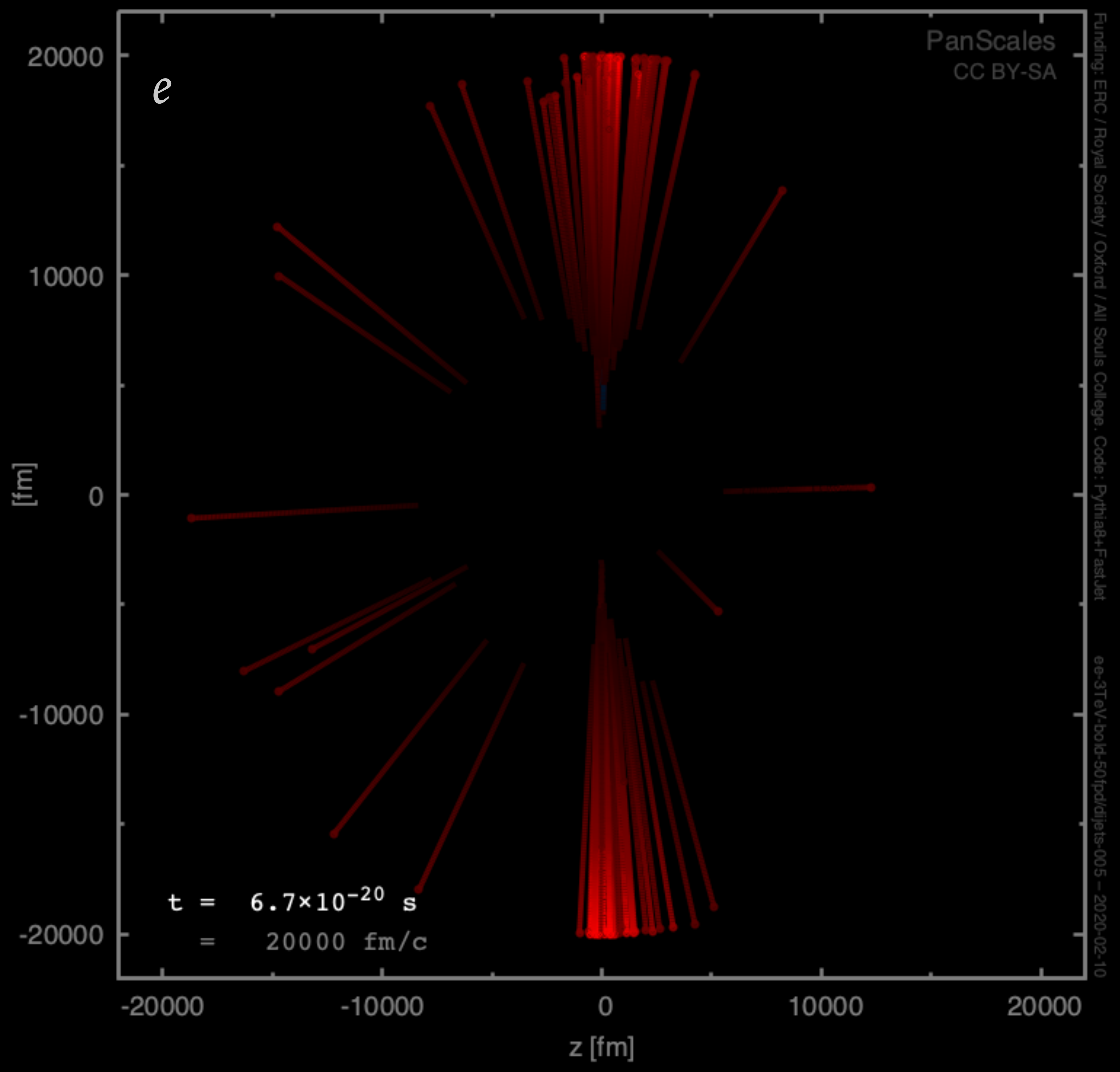
direct new-particle searches

100 GeV - 8 TeV

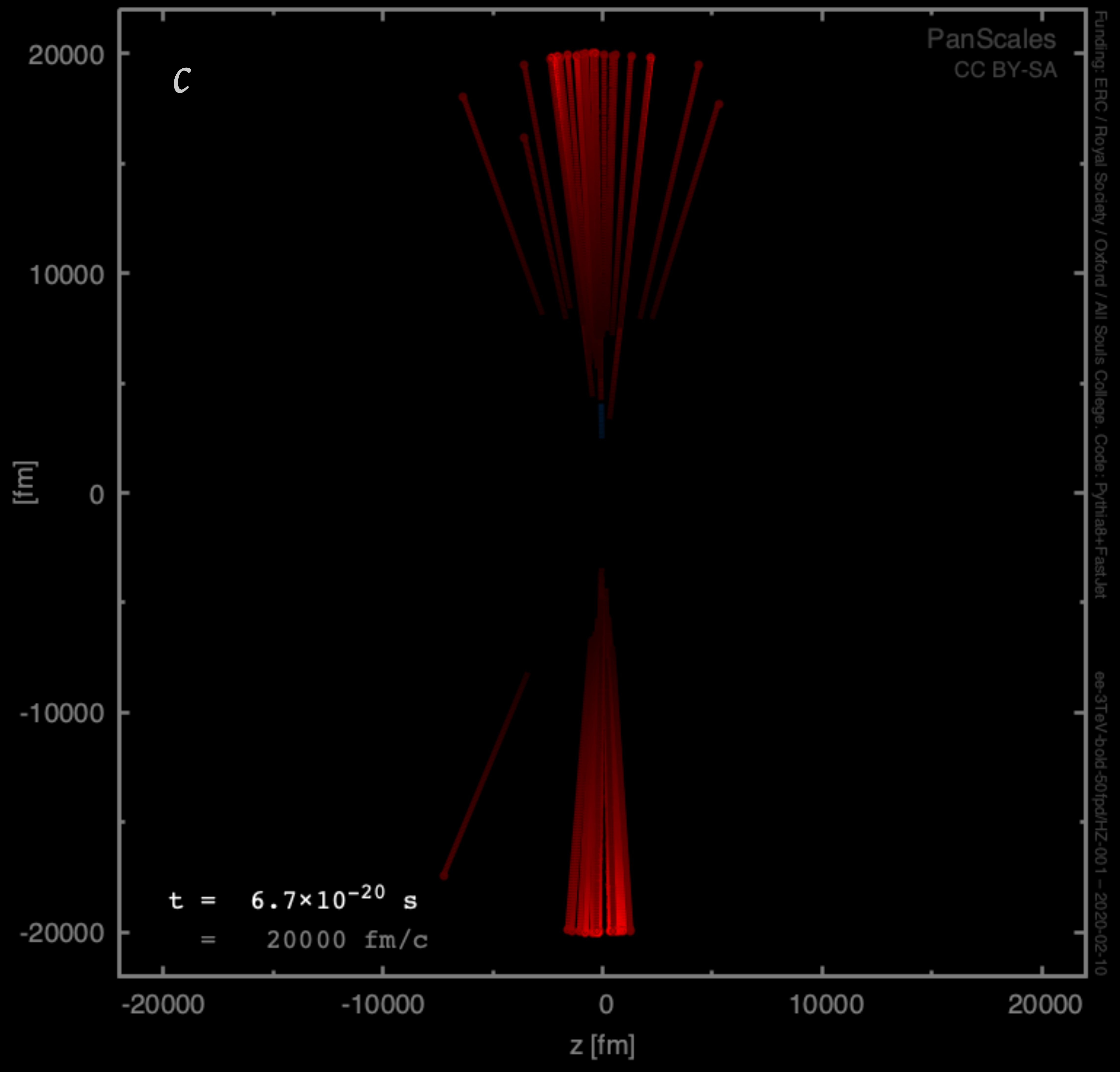
using full event information

how much information is hidden among the hundreds of particles produced in a collisions?

pure QCD event



event with Higgs & Z boson decays



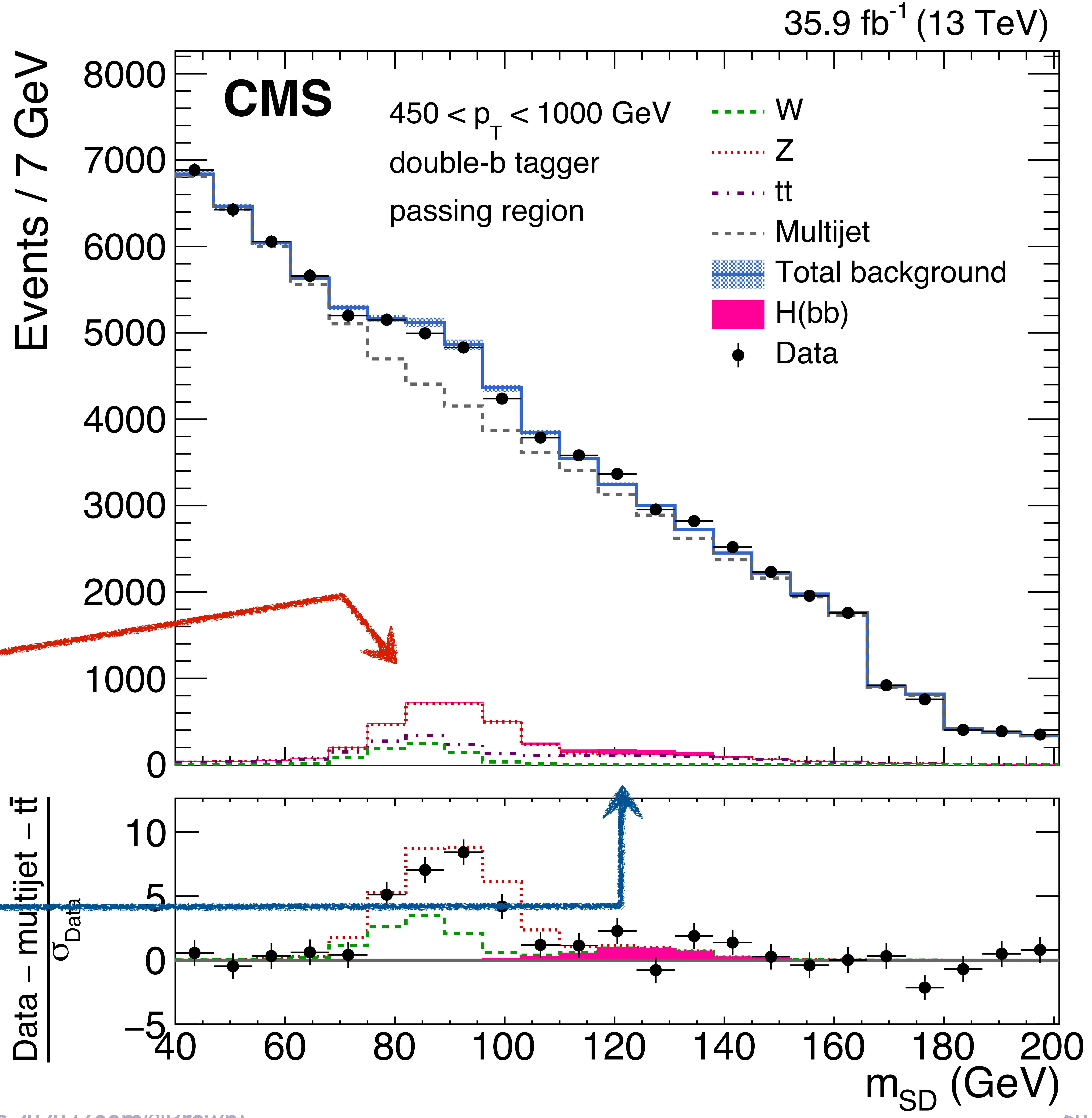
high p_T Higgs & [SD] jet mass

We wouldn't trust electromagnetism if we'd only tested at one length/ momentum scale.

New Higgs interactions need testing at both low and (here) **high momenta.**

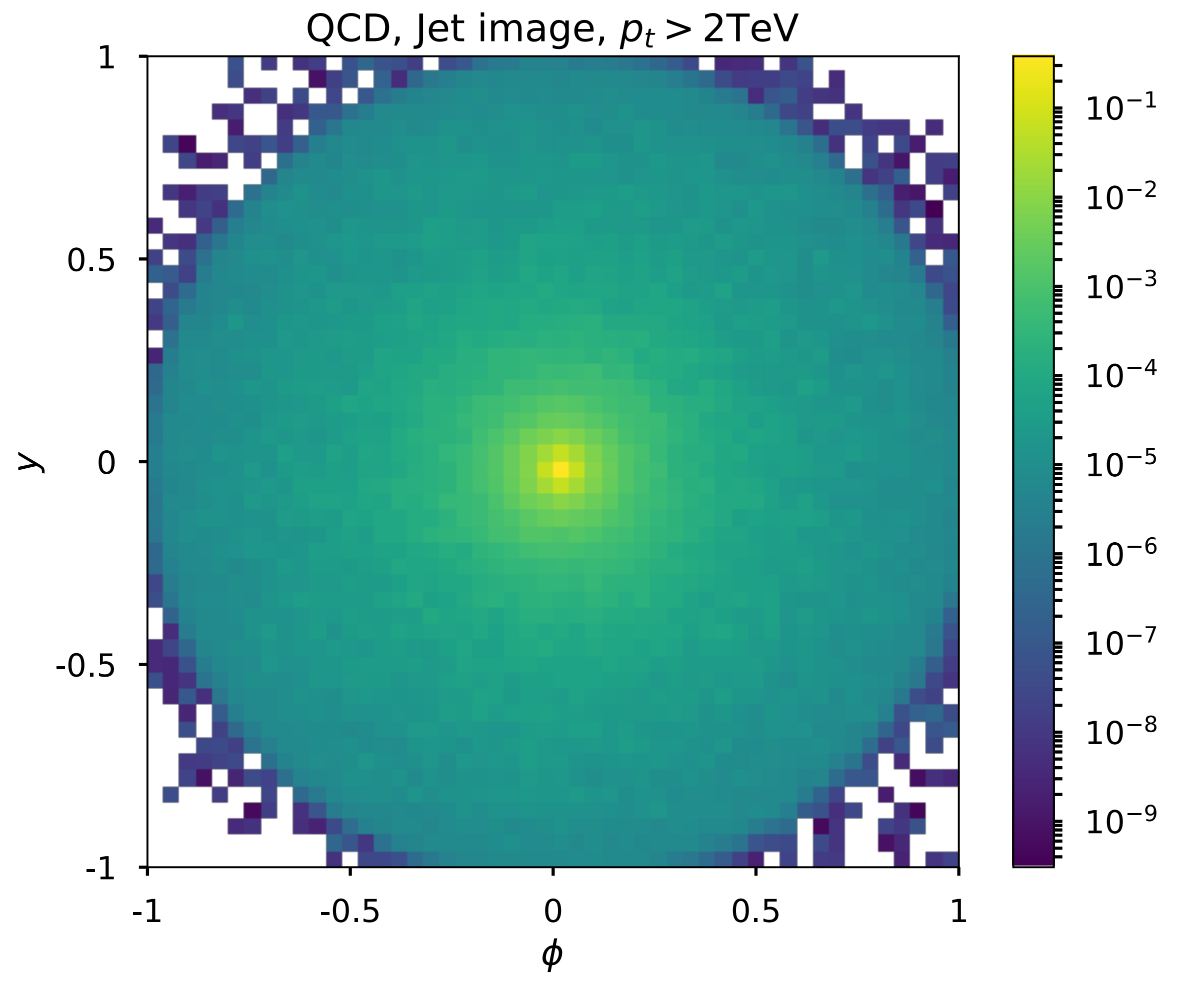
high-p_T Z → bb (5σ)

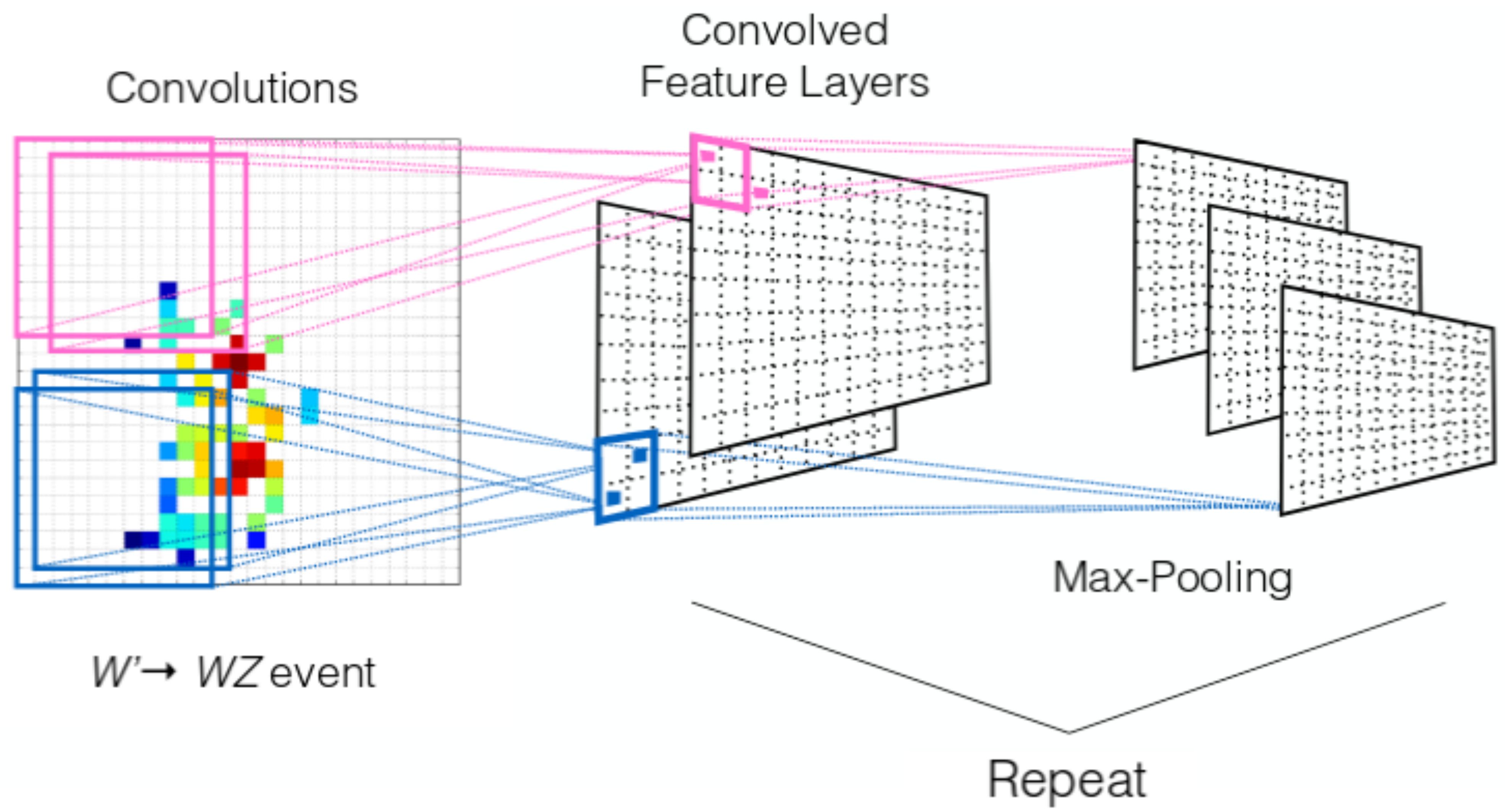
high-p_T H → bb (~ 1σ)



Convolutional neural networks and jet images

- Project a jet onto a fixed $n \times n$ pixel image in rapidity-azimuth, where each pixel intensity corresponds to the momentum of particles in that cell.
- Can be used as input for classification methods used in computer vision, such as deep convolutional neural networks.





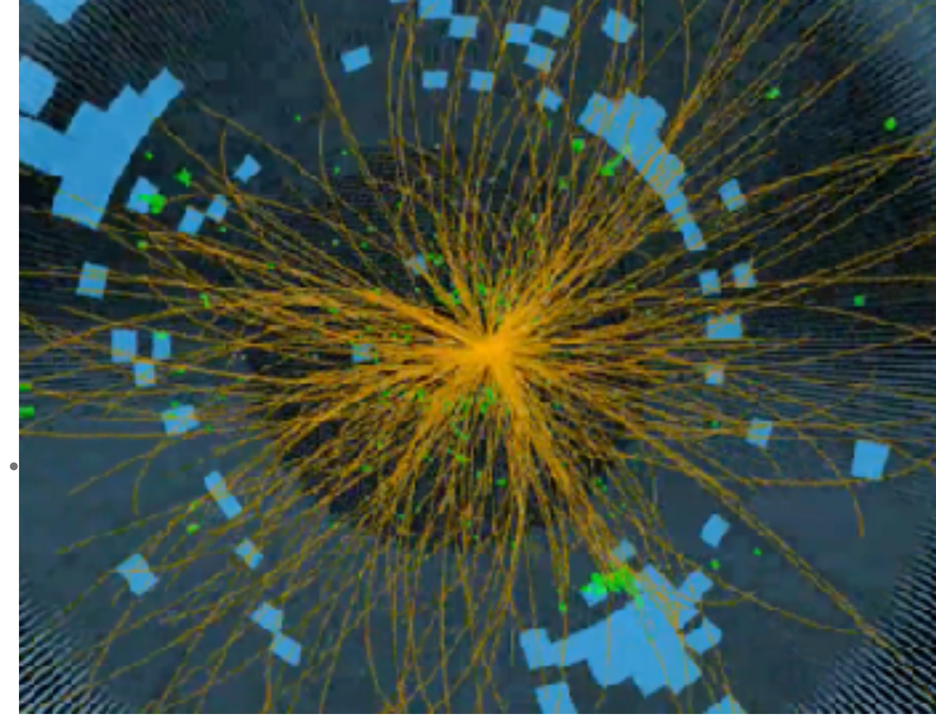
[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]

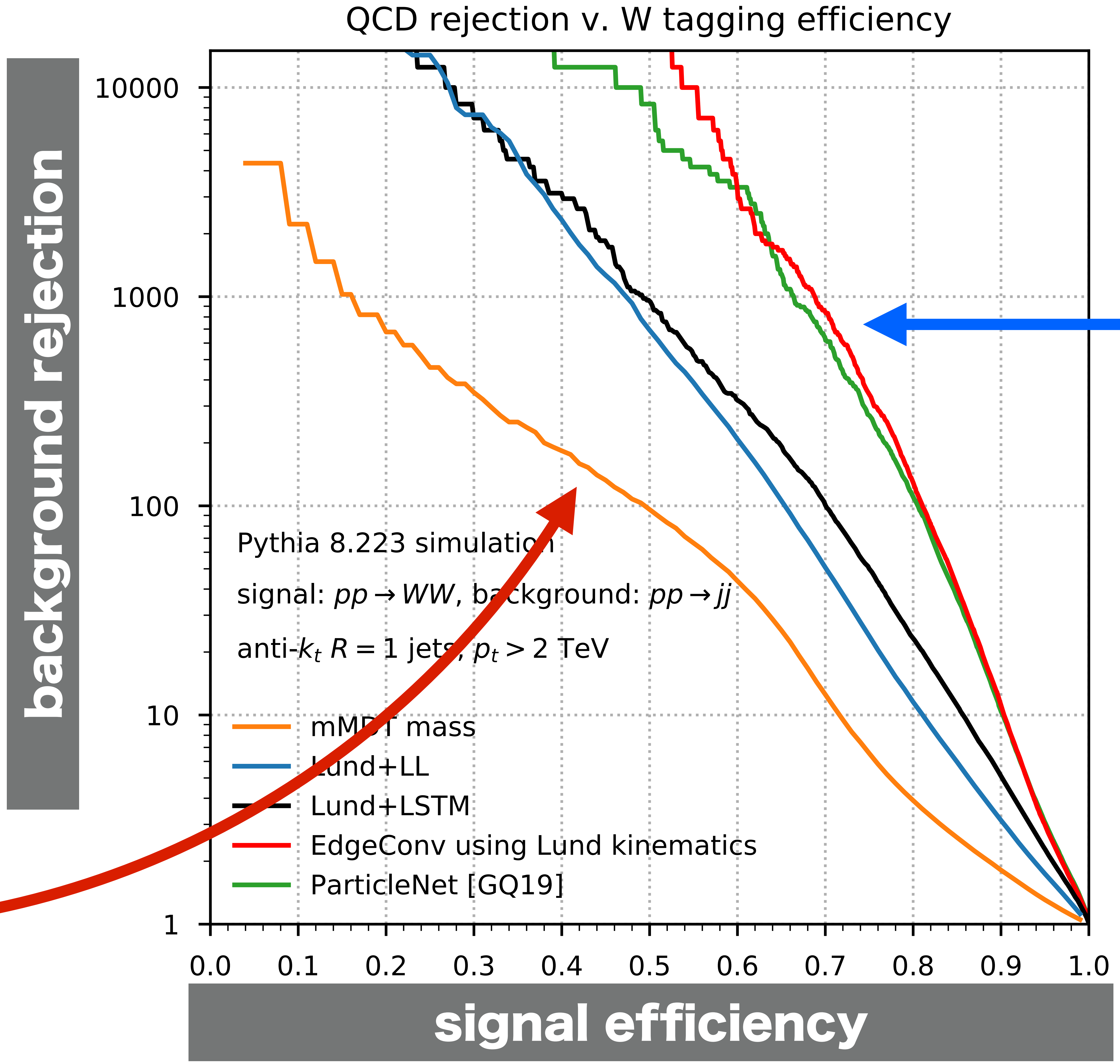
powerful

but black box

using full event information for H/etc. boson tagging



Dreyer 2020 (work in progress)



QCD rejection with use of full jet substructure (2019 tools)

100x better

QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants

First started to be exploited by Thaler & Van Tilburg with "N-subjettiness" (2010/11)

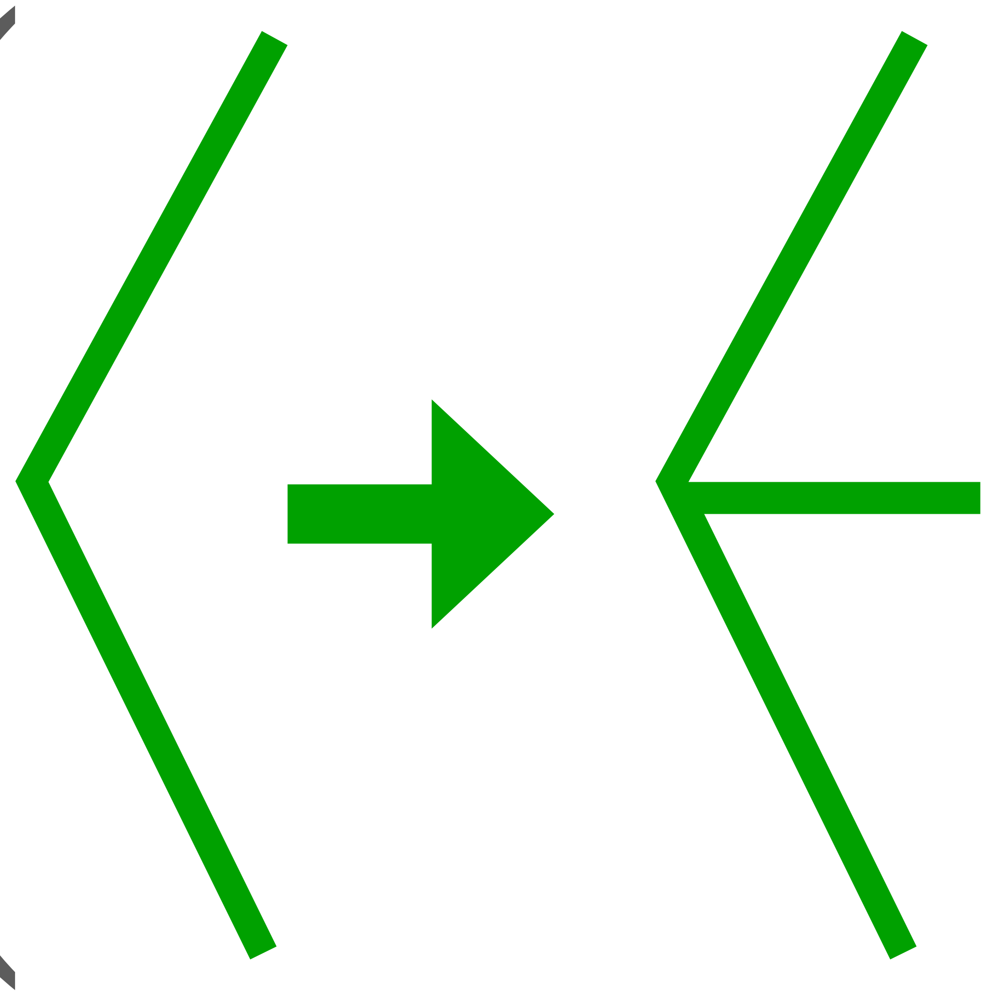
general purpose Monte Carlo event generators: THE BIG 3

Herwig 7 **Pythia 8** **Sherpa 2**

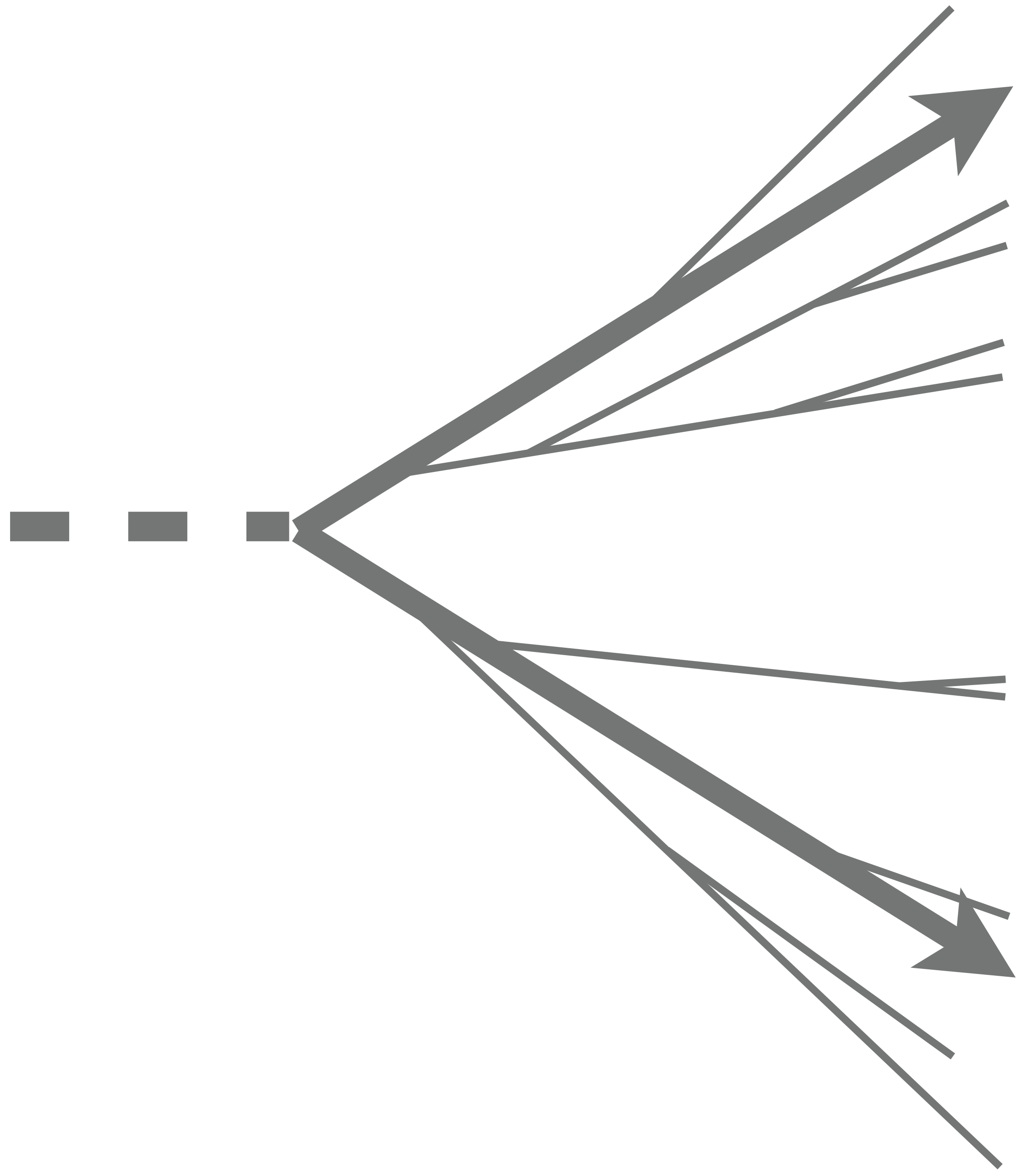
they do an amazing job of simulation vast swathes of data; collider physics would be unrecognisable without them

What is a parton shower? At its simplest…

$$\sum_{n=0}^{\infty}\prod_{i=1}^{n}\Bigg($$



$$\Bigg) =$$



iteration of 2→3 (or 1→2) splitting kernel

What questions can we ask about parton showers (PS)?

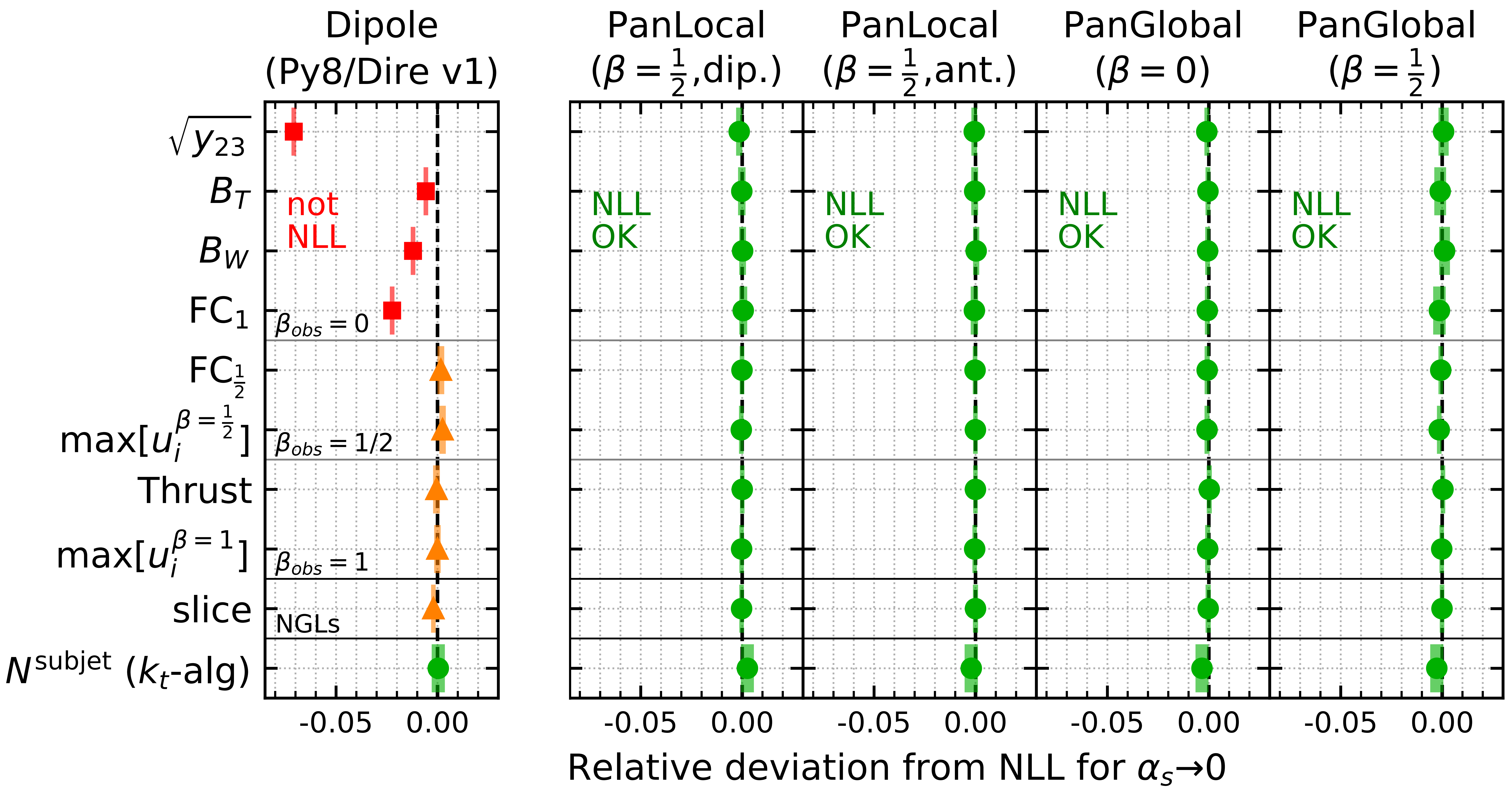
- in what sense is the distribution of final n-particle states be correctly described, for arbitrary n?
- can a (iterated 2→3) parton shower reproduce known logarithmic resummations, & to what accuracy?

With appropriate **classification of phasespace** (Lund diagrams), and analysis of **asymptotic limits of parton showers**, it becomes possible to answer these questions and design new showers with well-defined logarithmic accuracy (NLL)

Dasgupta, Dreyer, Hamilton, Monni & GPS 1805.09327, idem + Soyez 2002.11114

standard parton showers

new "PanScales" parton showers, designed specifically to achieve NLL accuracy



"PanScales" family reproduces squared matrix element for arbitrary n, in limit where each & every pair of particles is well separated in logarithm of angle, energy or transverse momentum

(modulo spin correlations, work ongoing)

first time comprehensive accuracy tests achieved for parton showers — sets baseline for future work & demonstrates that it is possible to achieve NLL accuracy from simple iterated 2→3 splitting

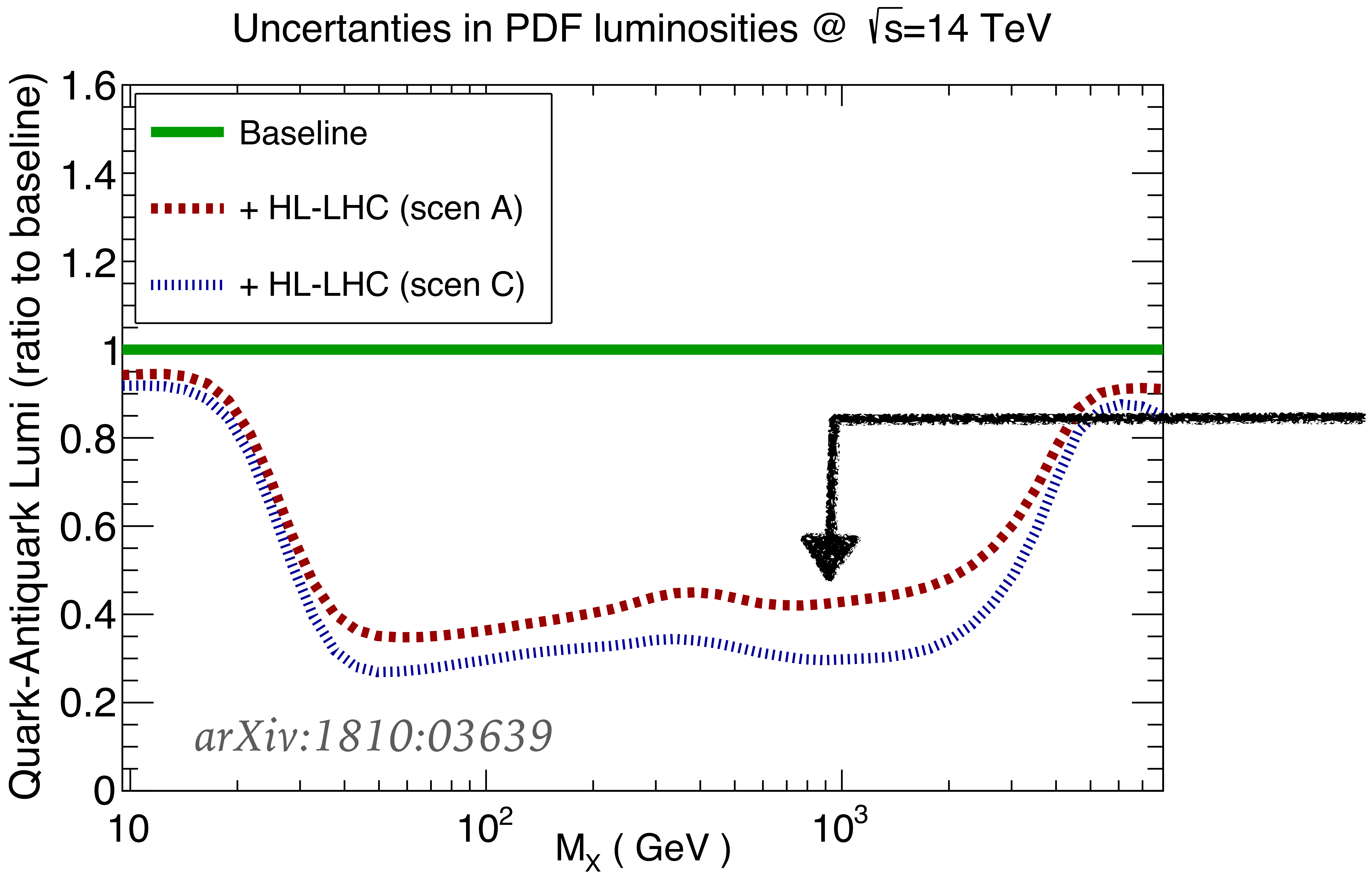
Conclusions

conclusions

- LHC has already far surpassed what was originally envisaged in terms of its potential for accurate measurements (e.g. Z production with $< 1\%$ accuracy)
- relative to current results, $20 - 80 \times$ more stats on its way, i.e. potential for $4 - 9 \times$ higher accuracy
- with perturbation theory as our only rigorous tool, progress in calculating amplitudes is essential to successful physics exploitation of this wealth of data
- amplitudes (and associated perturbative IRC safe cross sections) are not the only issue — parton showering, matching/merging, hadronisation all become increasingly important as one pushes the boundaries of accuracy and information-extraction in LHC events.

BACKUP

likely progress in PDFs



up to $\times 2$ reduction in uncertainty on partonic luminosities (e.g. # of quark-antiquark collisions) relative to today's PDFs