SEARCHES FOR DARK SECTORS AT CMS

JAVIER DUARTE

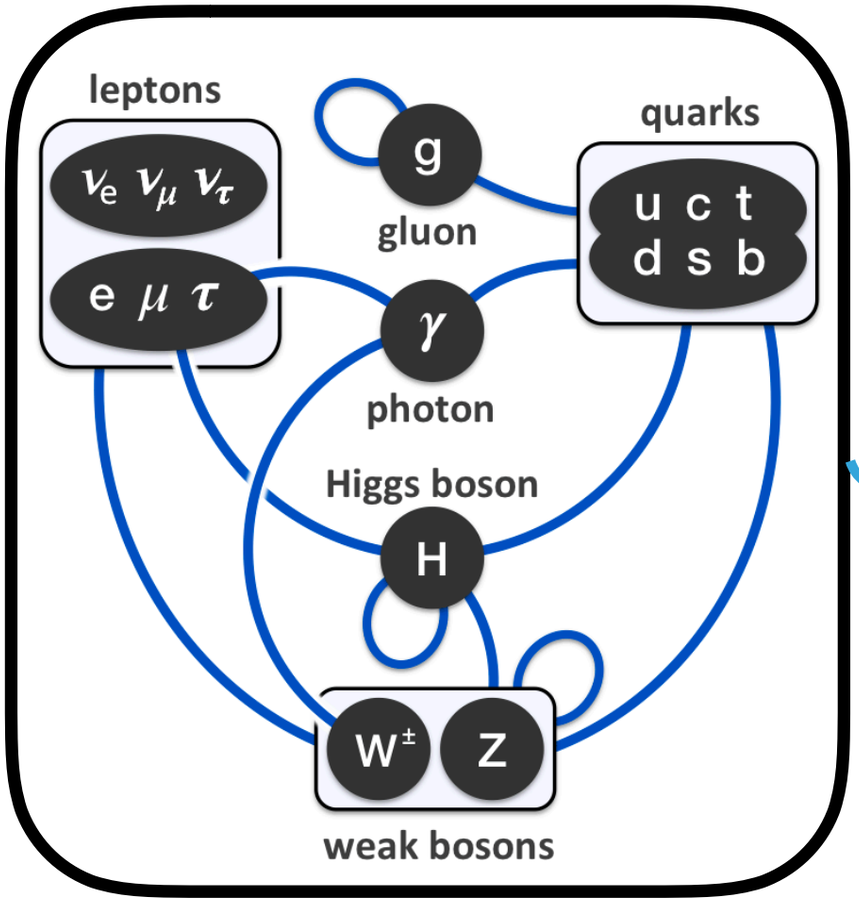
MAY 20, 2019

LHCP, PUEBLA, MEXICO

WHAT ARE DARK SECTORS?

Standard model

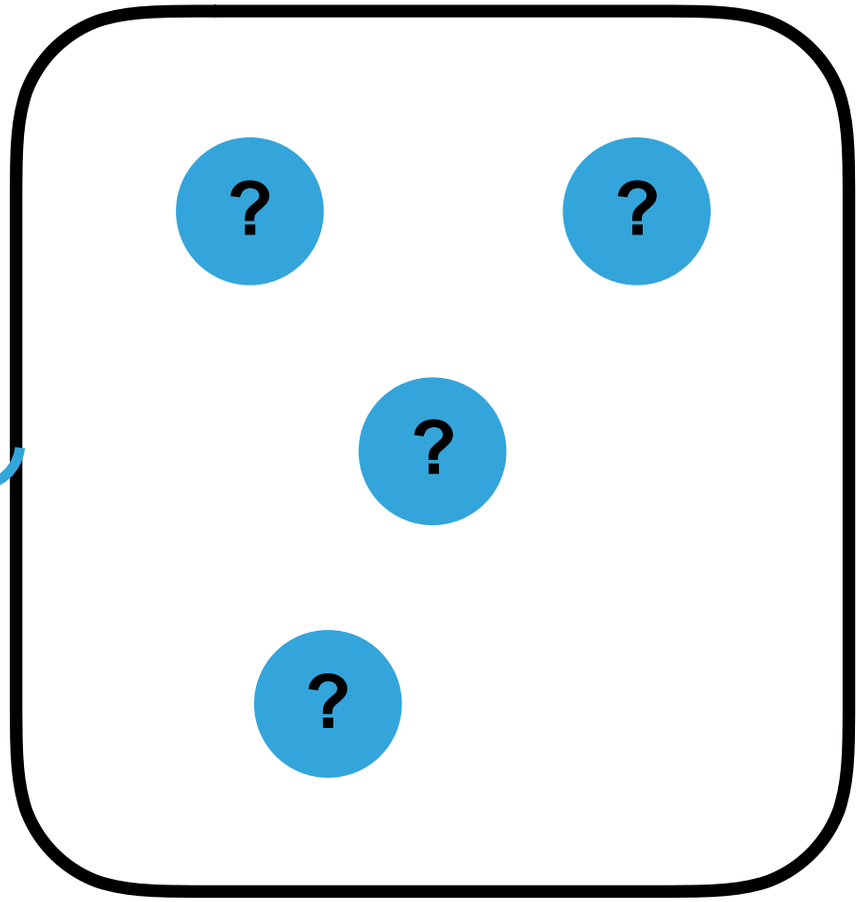
$SU(3) \times SU(2) \times U(1)_Y$



?

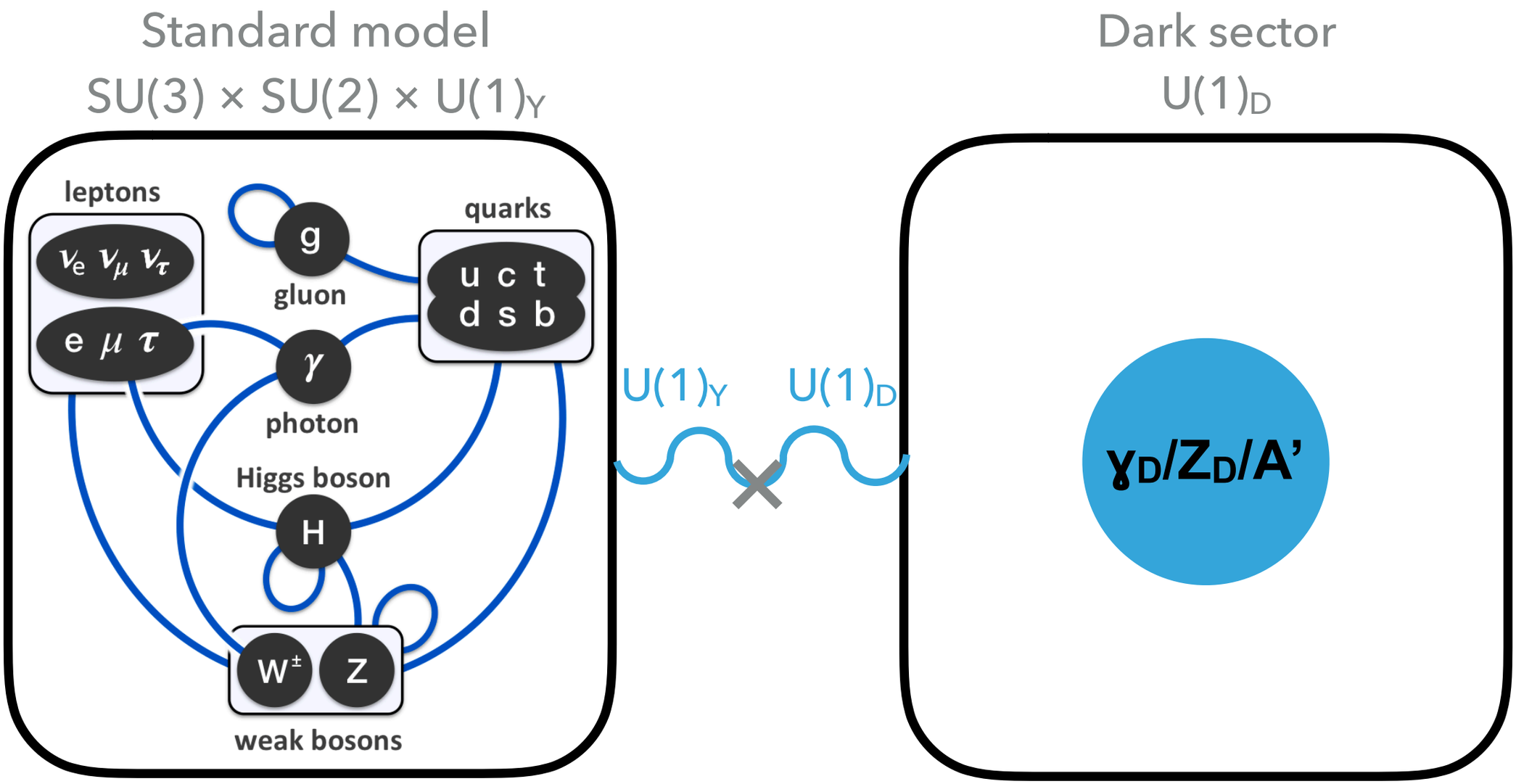
Dark sector

G_D



- New set of particles typically charged under some “dark” forces
- Weak coupling (mediator or mixing or loop-induced) allows interactions between the SM and the dark sector

MINIMAL DARK PHOTON



- Kinetic mixing: dark photon mixes with standard photon and induces coupling to fermions

$$\mathscr{L} \supset -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} \quad \Longrightarrow \quad \mathscr{L} \supset \epsilon e \bar{\phi} \gamma^{\mu} \phi A'_{\mu}$$

CMS SEARCHES FOR DARK SECTORS

Higgs portal

$Z(l^+l^-)H(\gamma\gamma_D)$ [EXO-19-007]
H(inv.) [arXiv:1809.05937]
$H \rightarrow \gamma_D\gamma_D + X \rightarrow 4\mu + X$ [arXiv:1812.00380]

A. Hall Thurs. PM

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Dark QCD mediator

emerging jets [JHEP 02 (2019) 179]
semi-visible jets

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Minimal dark photon

high mass dilepton [JHEP 06 (2018) 120]
low mass dimuon (data scouting)

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Simplified DM mediator

boosted dijet+jet [EXO-18-012]
boosted bb+jet [PRD 99, 012005 (2019)]
boosted dijet+γ [EXO-17-027]
dijet [EXO-17-026]
monojet [PRD 97, 092005 (2018)]
mono Higgs [EXO-18-011]
...

D. Yu Tues. AM

1. DARK PHOTONS IN ZH DECAYS

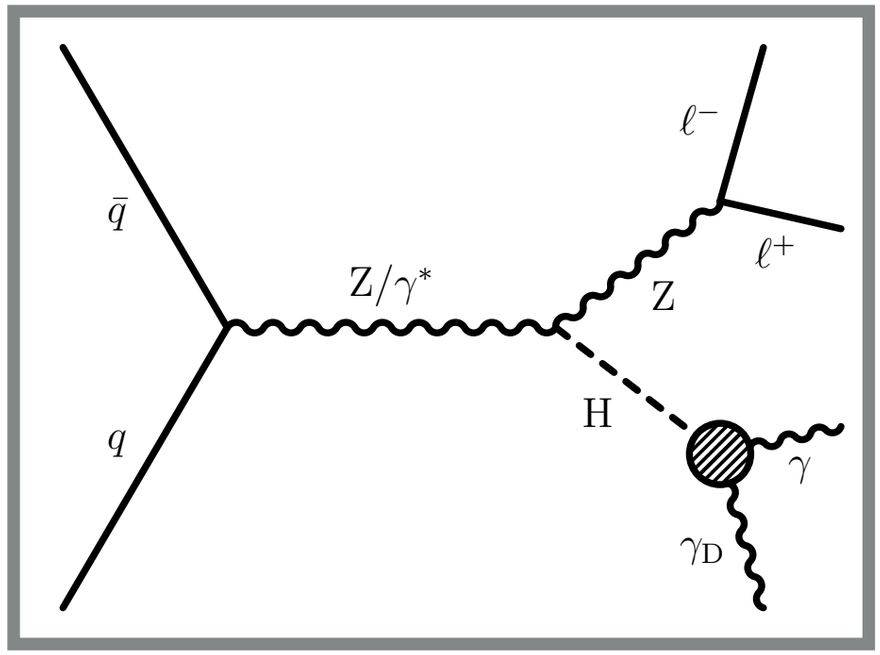
2. DARK QCD WITH EMERGING JETS

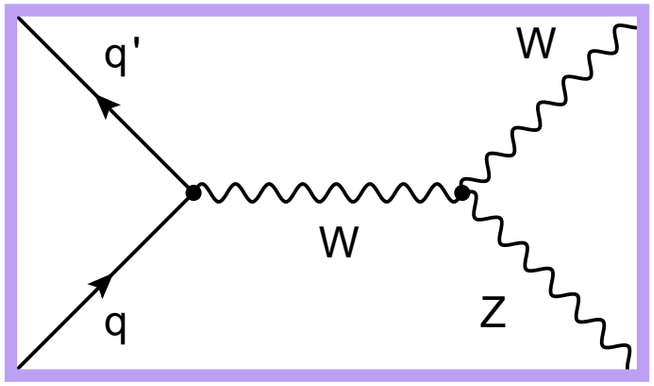
3. OUTLOOK

HIGGS DECAY TO PHOTON + DARK PHOTON

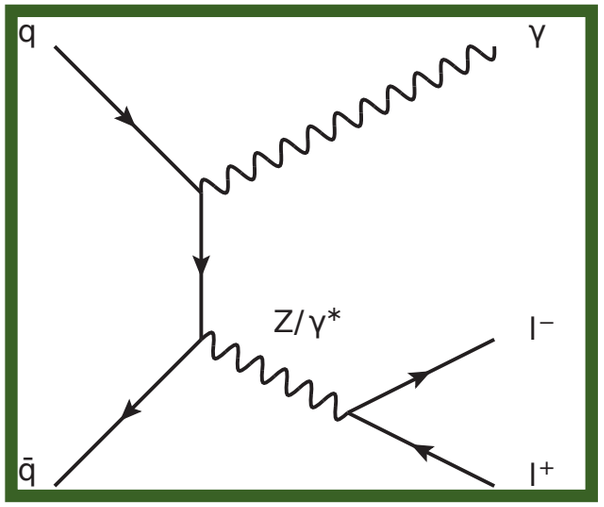
EXO-19-007

- $H \rightarrow \gamma\gamma_D$ induced at loop level (no kinetic mixing) [arXiv:1603.01377]
- ZH production mode with $Z \rightarrow l^+l^-$
  - Signature: $Z(l^+l^-) + \gamma + p_T^{miss}$
- Main backgrounds:
  - Nonresonant: top, WW
  - Resonant (3l): WZ
  - Resonant (2l + γ): WZ, ZZ
  - Resonant (no MET): $Z\gamma$, Z+jets
  - Other: VVV





WZ

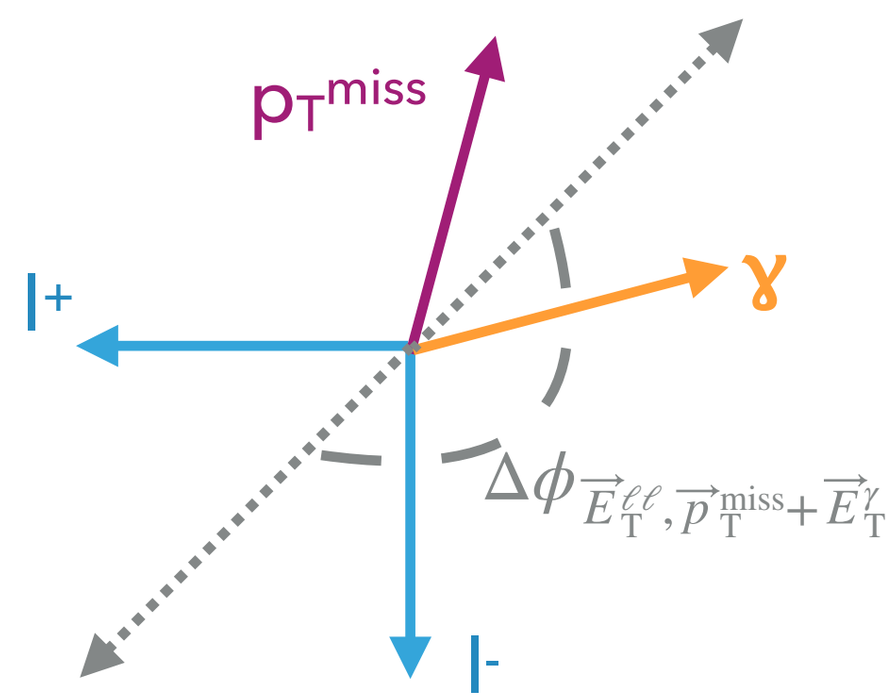


$Z\gamma$

EVENT SELECTION

- Selection to reduce Zγ and Z+jets to < 5% of total background

Variable	Selection	Reject
Leptons	2 leptons, $p_T > 25/20$ GeV	WZ, ZZ, VVV
Photons	$\geq$1 photon, $E_T^\gamma > 25$ GeV	All but Zγ
$\lvert m_{\ell\ell} - m_Z \rvert$	< 15 GeV	WW, top-quark
Anti b tagging	Applied medium working point	Top-quark, VVV
Jet counting	≤ 2	Top-quark, VVV
$\Delta\phi_{\vec{\ell\ell},\vec{p}_T^{\,miss}+\vec{E}_T^\gamma}$	>2.5 radians	Zγ
$\lvert p_T^{\vec{p}_T^{\,miss}+\vec{E}_T^\gamma} - p_T^{\ell\ell} \rvert / p_T^{\ell\ell}$	<0.4	Zγ
$\Delta\phi_{jet,p_T^{miss}}$	>0.5	Zγ
$p_T^{\ell\ell}$	> 60 GeV	Zγ
$m_{\ell\ell\gamma}$	> 100 GeV	Zγ
p_T^{miss}	> 110 GeV	Zγ
m_T	< 350 GeV	WW, top-quark



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EXO-19-007

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- Key analysis variables: m_T and $|\eta^\gamma|$

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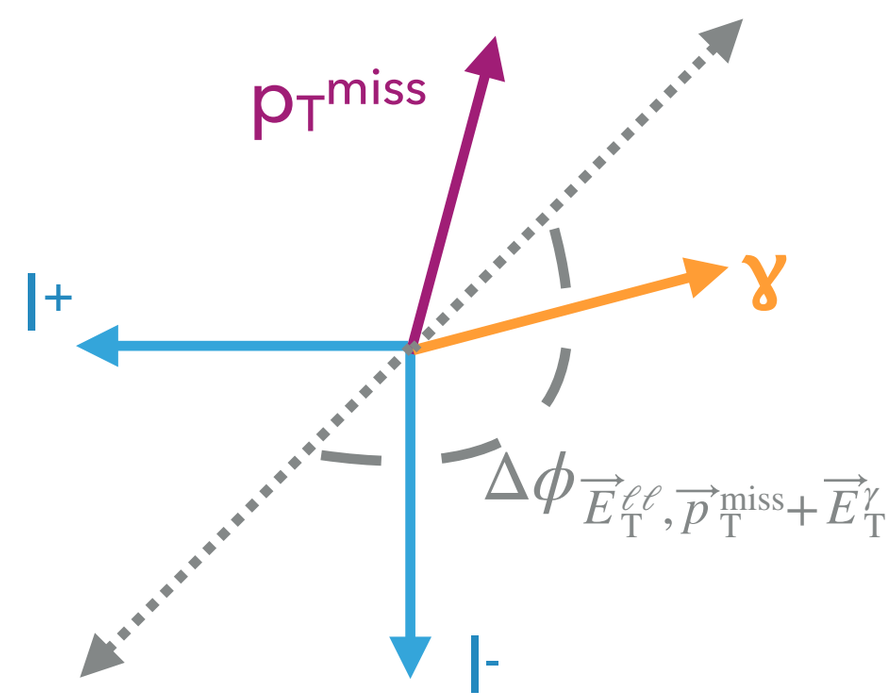
$$m_T = \sqrt{2p_T^{miss}E_T^\gamma[1 - \cos(\Delta\phi_{\vec{p}_T^{\,miss},\vec{E}_T^\gamma})]}$$



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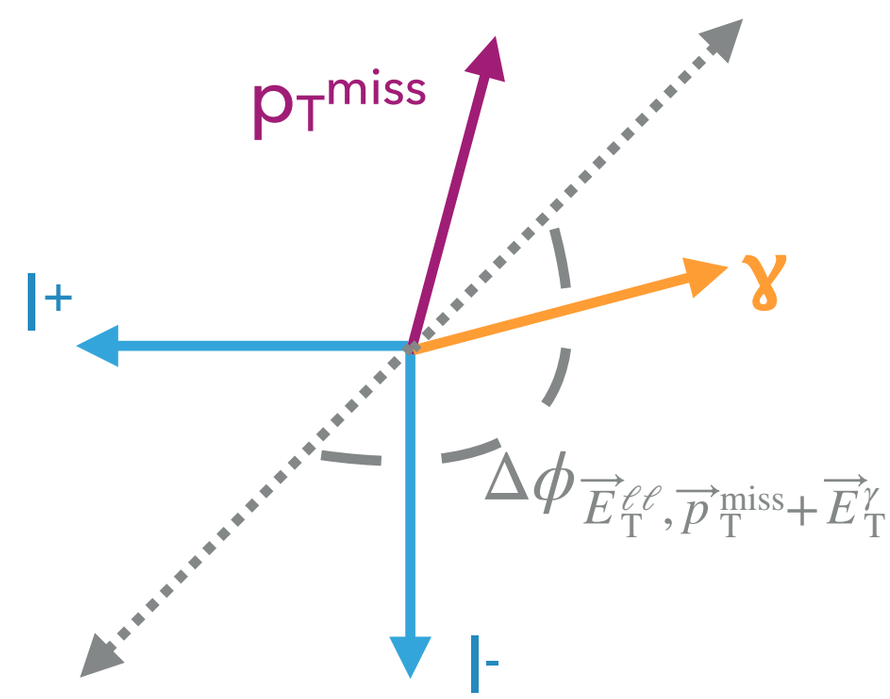
- Control regions isolate WZ, ZZ, and top/WW backgrounds for data-driven estimate



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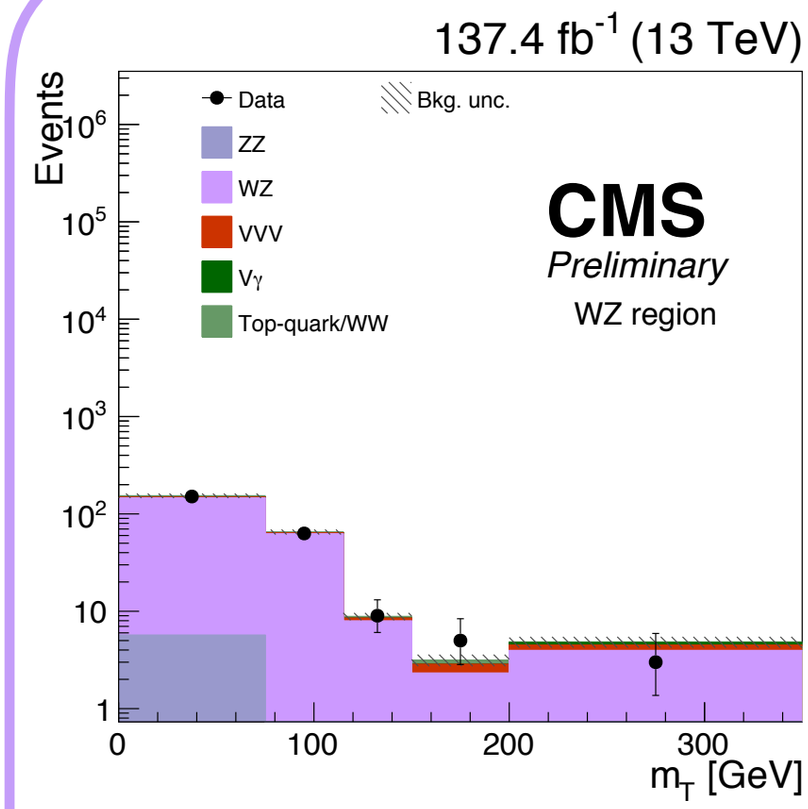
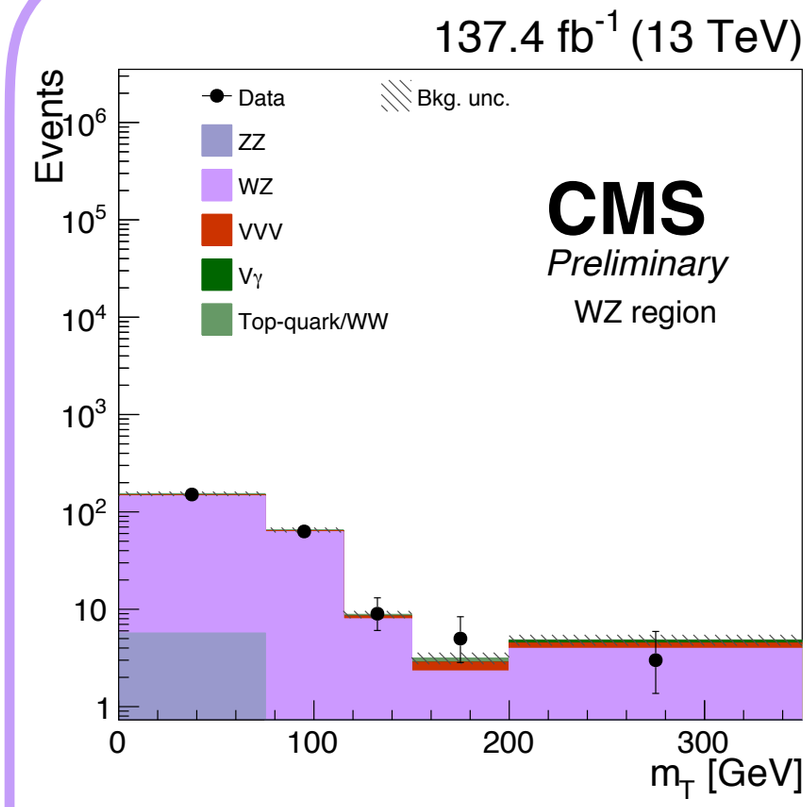


- WZ region: lepton from W instead of photon satisfies selection criteria

CONTROL REGIONS

EXO-19-007



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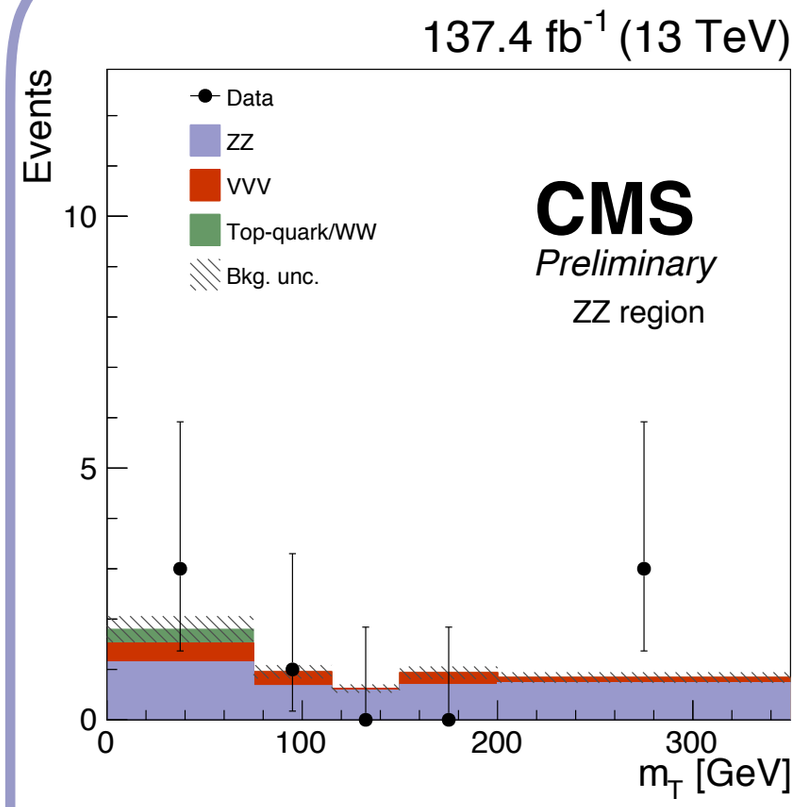
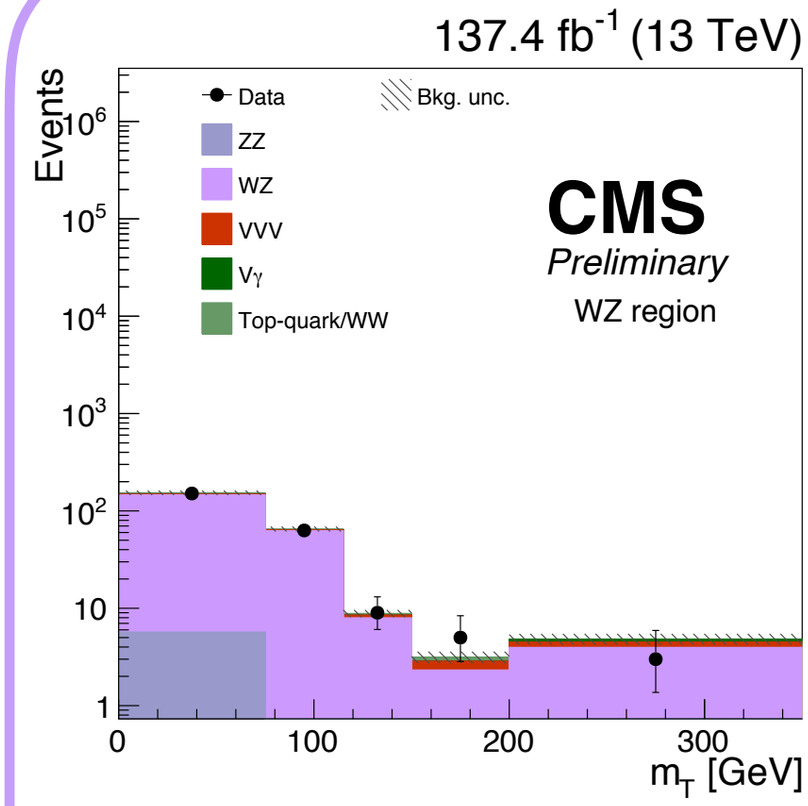


- ZZ region: dilepton from Z instead of photon satisfies selection criteria

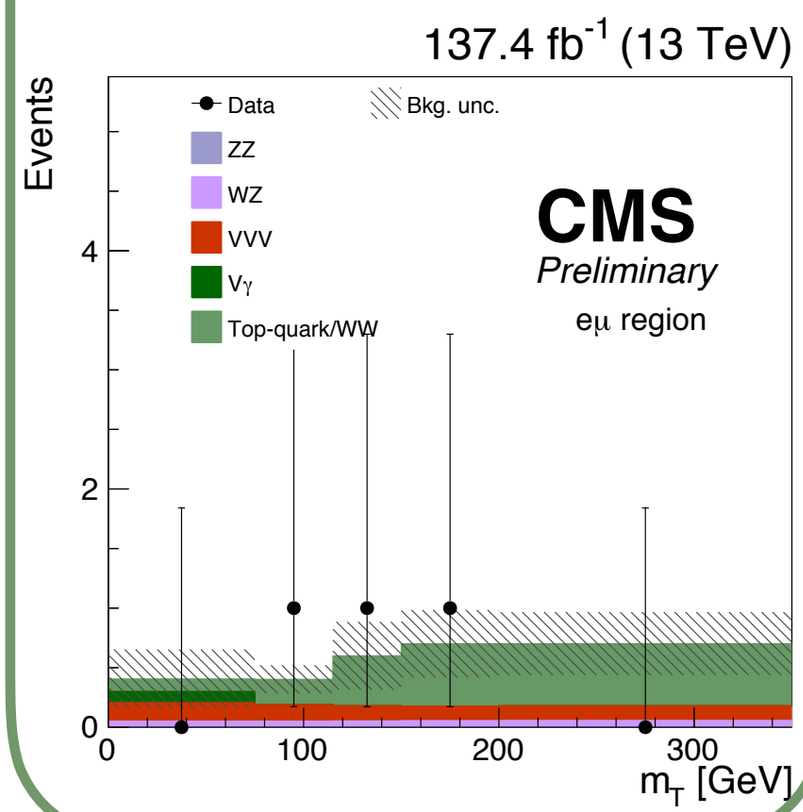
CONTROL REGIONS

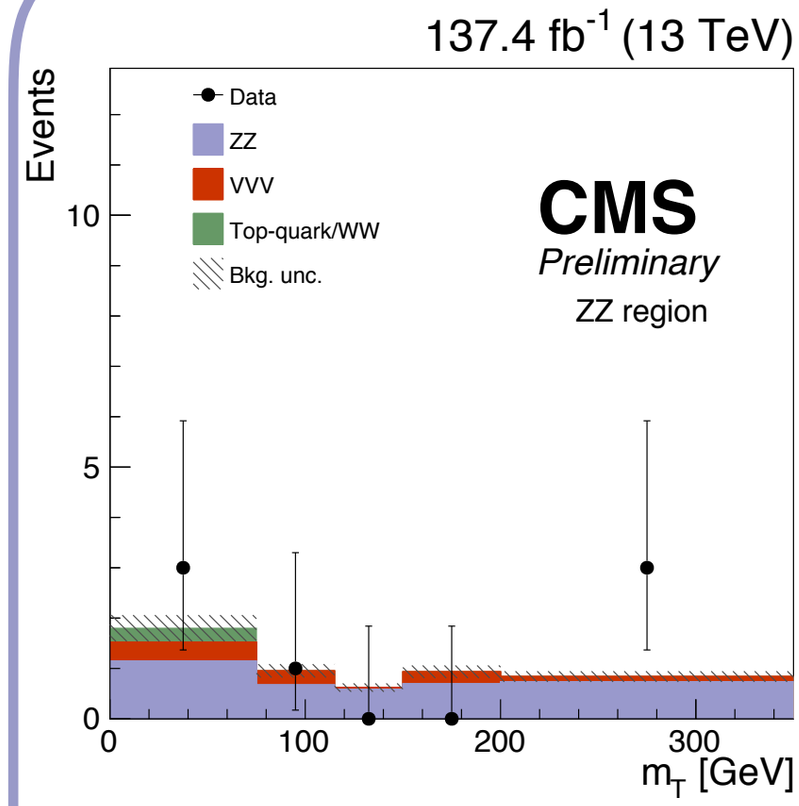
EXO-19-007



- WZ region: lepton from W instead of photon satisfies selection criteria

- eμ region: opposite flavor instead of same flavor dilepton





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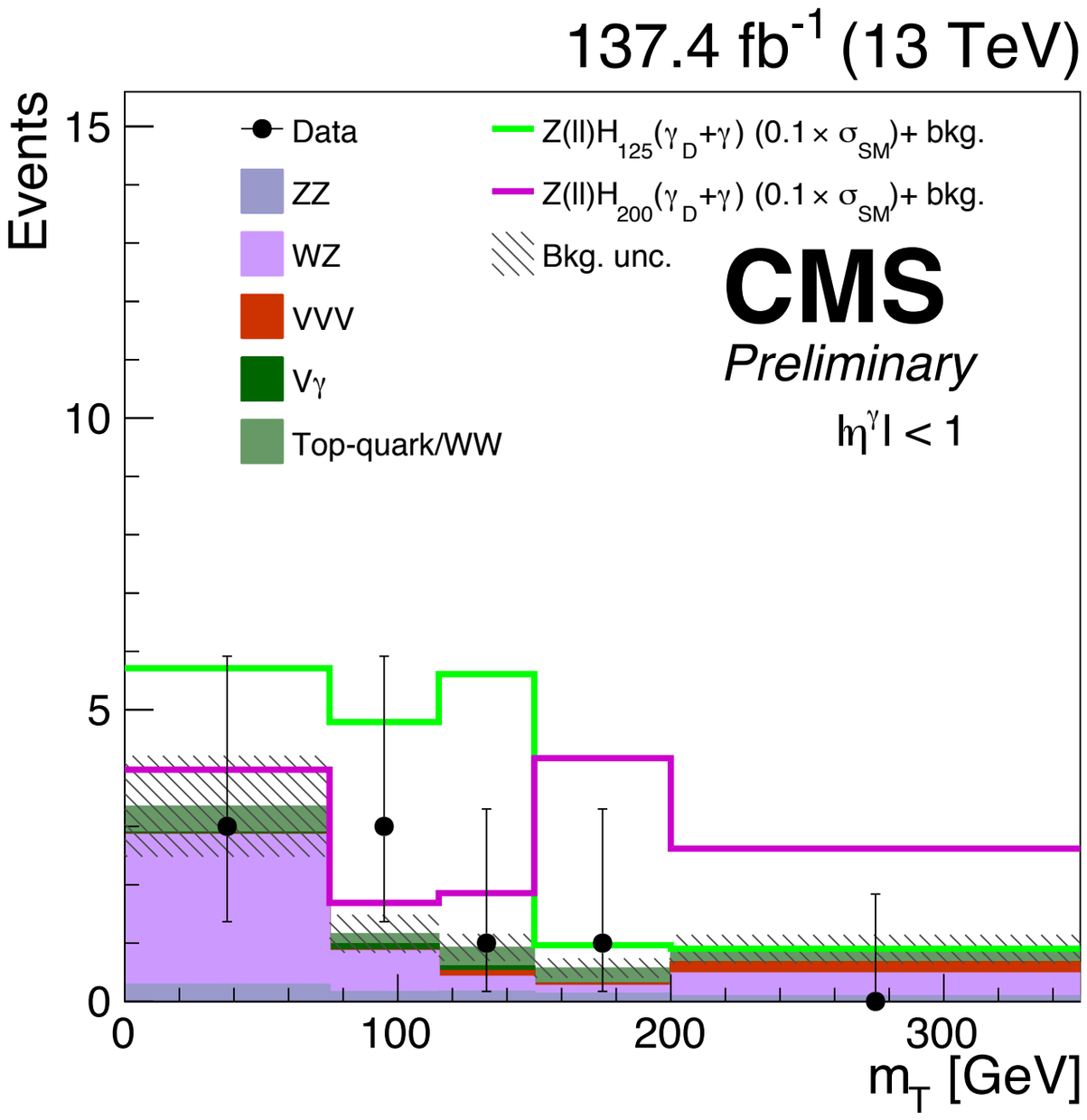
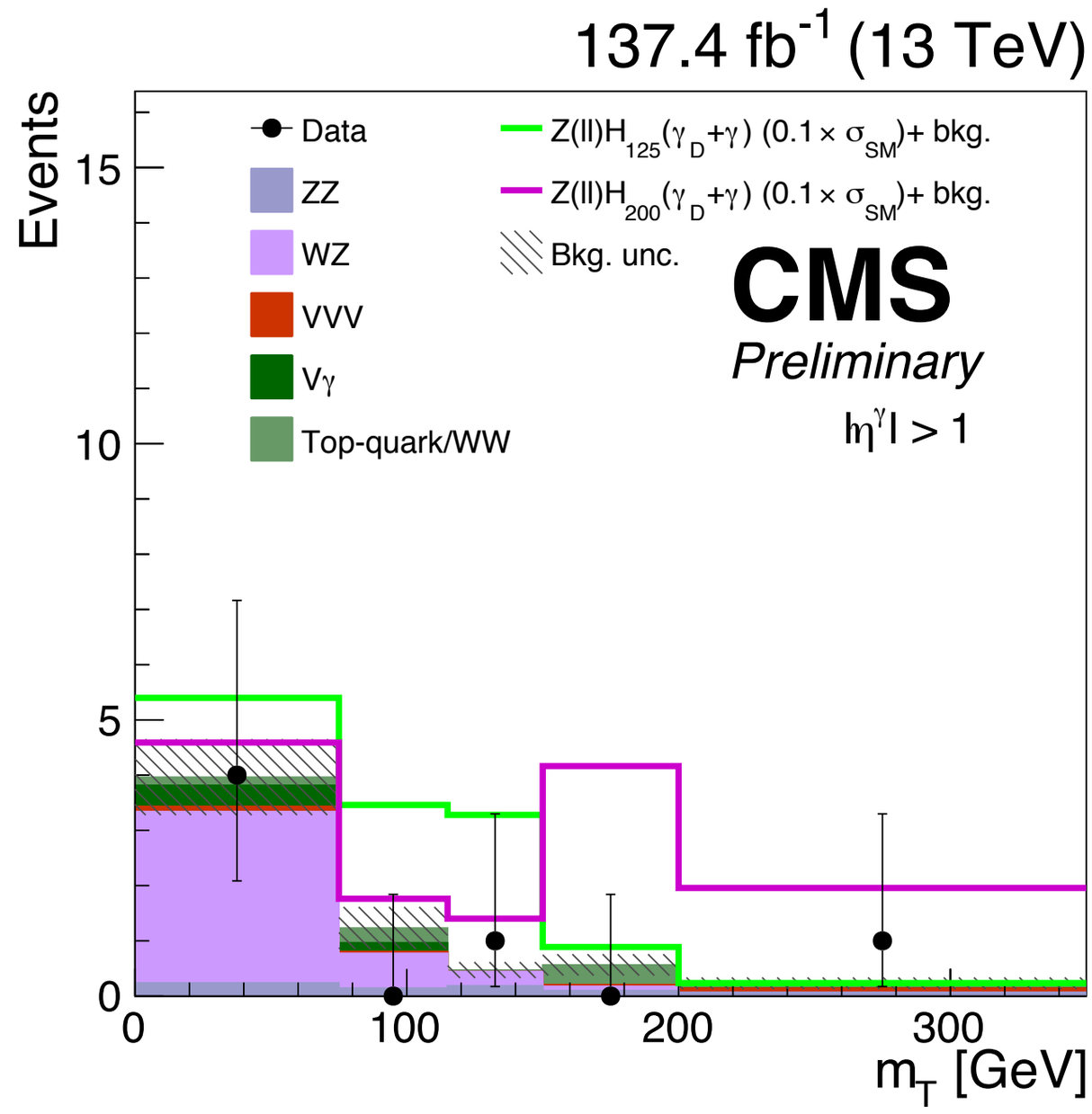
SIGNAL REGIONS

EXO-19-007

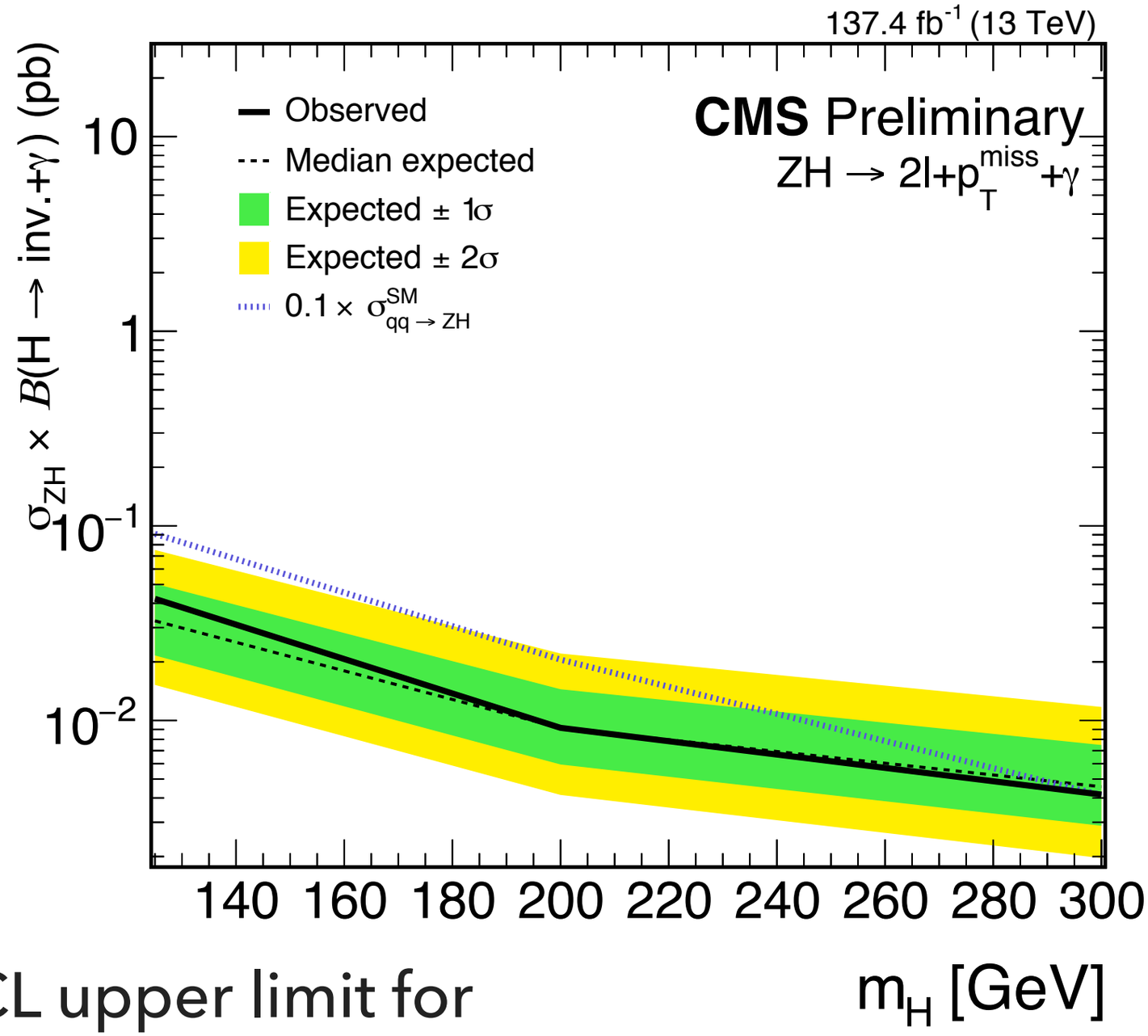
- Signal (m_H = 125 and 200 GeV) with B(H → inv. +γ) = 10%
- No excess observed





RESULTS

Process	Yields
Data	14
Nonresonant bkg.	2.4 ± 1.1
WZ	8.1 ± 2.0
ZZ	1.5 ± 0.3
$Z\gamma$	0.7 ± 0.7
Other bkg.	0.6 ± 0.3
Total bkg.	13.3 ± 3.8
ZH_{125} (BR=10%)	17.9 ± 1.2 (1.42 ± 0.09 %)
ZH_{200} (BR=10%)	12.3 ± 0.8 (4.32 ± 0.28 %)
ZH_{300} (BR=10%)	3.9 ± 0.2 (6.80 ± 0.34 %)



- Observed (expected) 95% CL upper limit for 125 GeV Higgs B(H → inv. +γ) < 4.6% (3.6%)
- First upper limits on final states with undetected dark photons using Higgs boson decays at the LHC!

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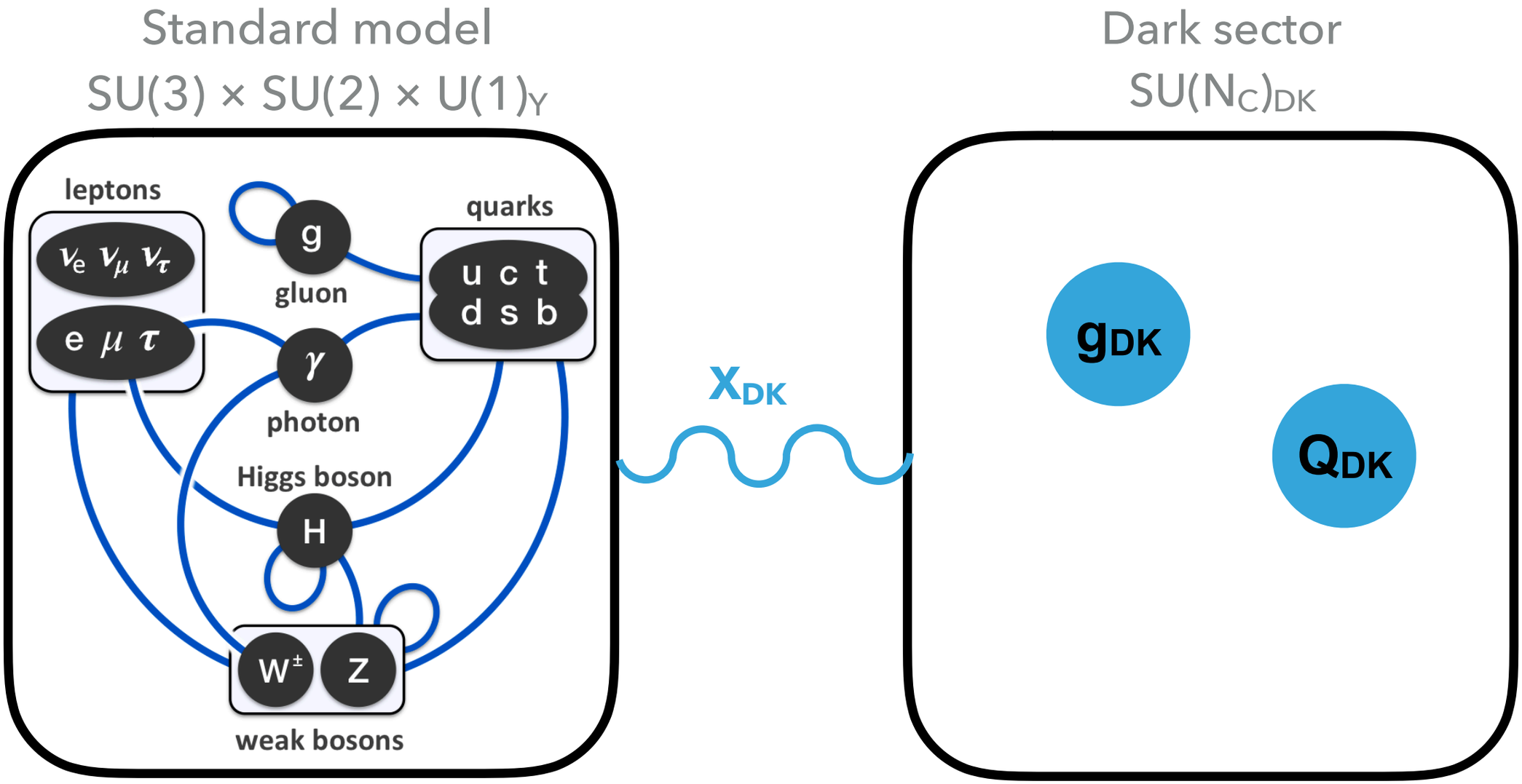
3. OUTLOOK

DARK QCD

JHEP 05 (2015) 059

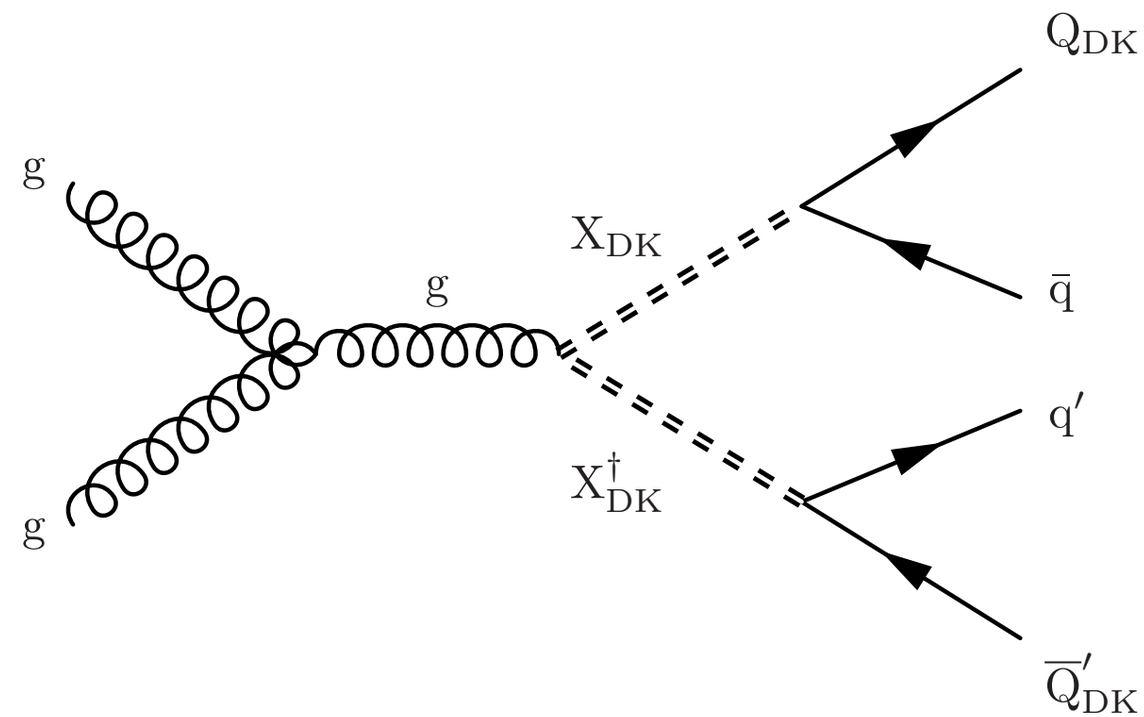


- Q_{DK} fermions charged under dark QCD $SU(N_C)_{DK}$
- X_{DK} mediator charged under both QCD and dark QCD

EMERGING JETS

JHEP 05 (2015) 059

- X_{DK} pair produced in gluon fusion or quark-antiquark annihilation
  - Decays to Q_{DK} q



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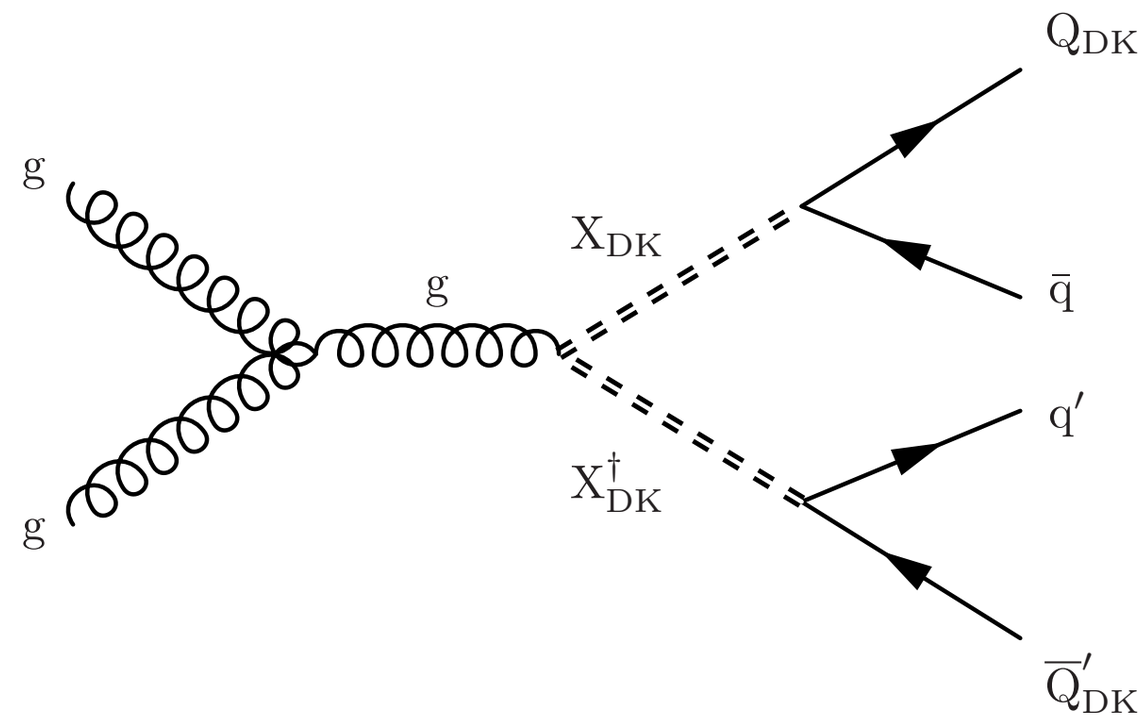
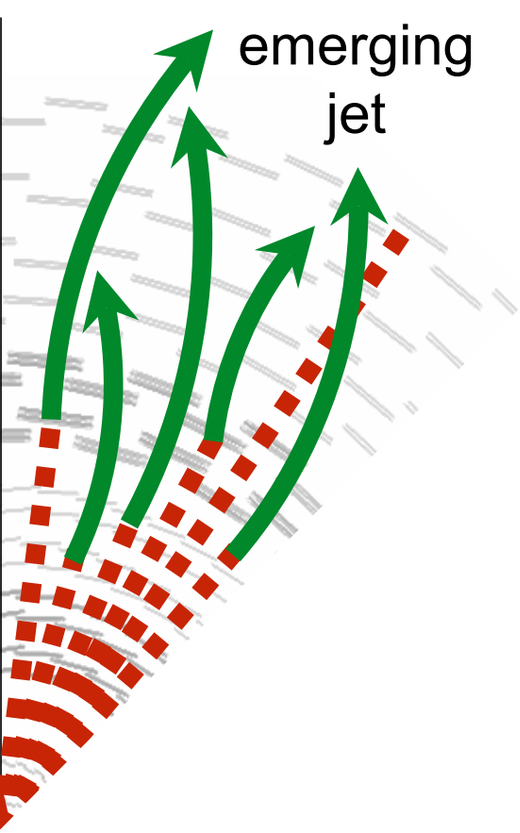




- Dark mesons and dark baryons form which decay to SM hadrons after non-negligible lifetime
  - Lightest dark pion lifetime (probe 1–10^3 mm)

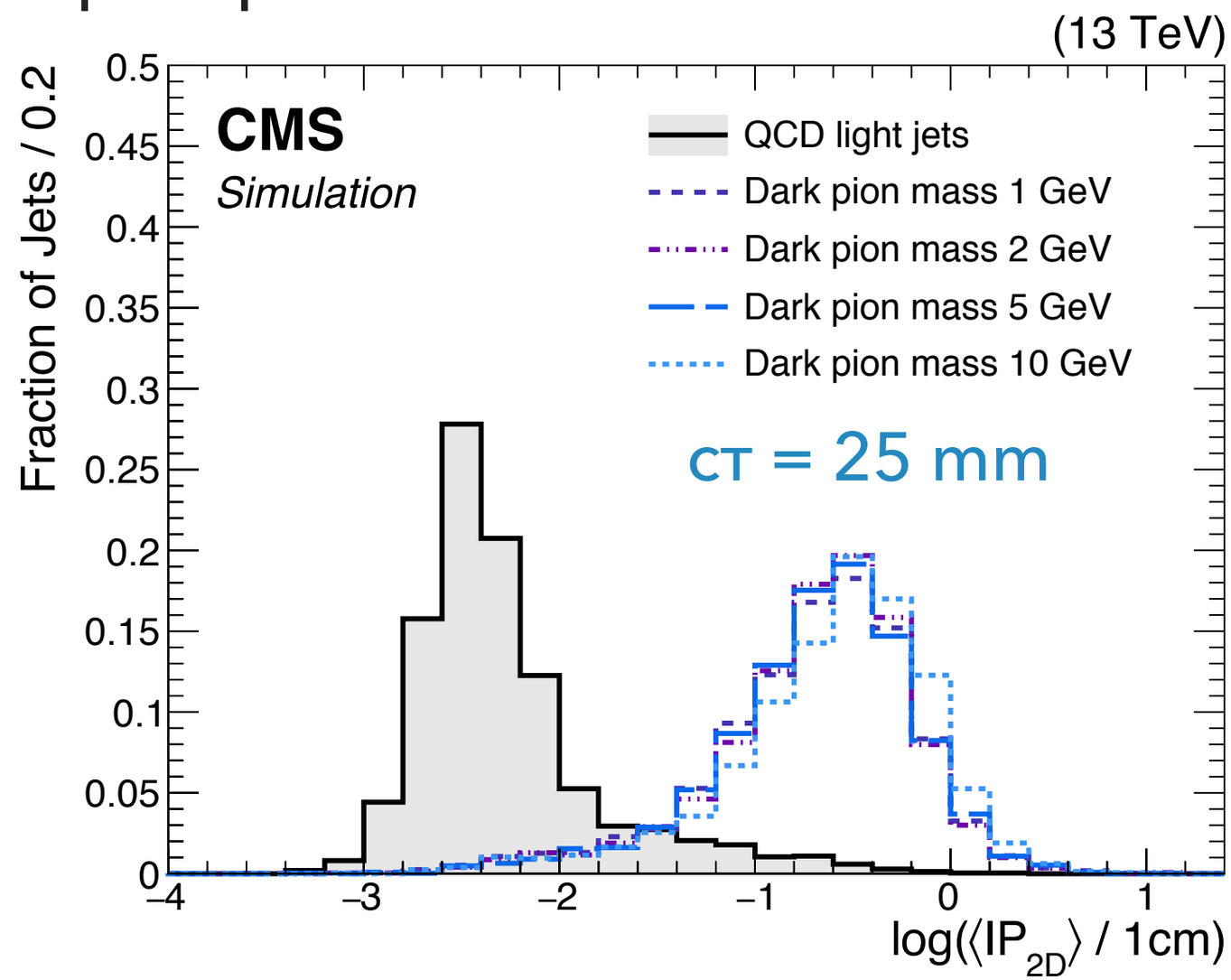
$$c\tau \approx 80\,\mathrm{mm}\left(\frac{1}{\kappa^4}\right)\left(\frac{2\,\mathrm{GeV}}{f_{\pi_{\mathrm{DK}}}}\right)^2\left(\frac{100\,\mathrm{MeV}}{m_{\mathrm{down}}}\right)^2\left(\frac{2\,\mathrm{GeV}}{m_{\pi_{\mathrm{DK}}}}\right)\left(\frac{m_{X_{\mathrm{DK}}}}{1\,\mathrm{TeV}}\right)^4$$

  - Emerging jets!

ANALYSIS STRATEGY

JHEP 05 (2015) 059

- **Tag** emerging jets using track impact parameter variables

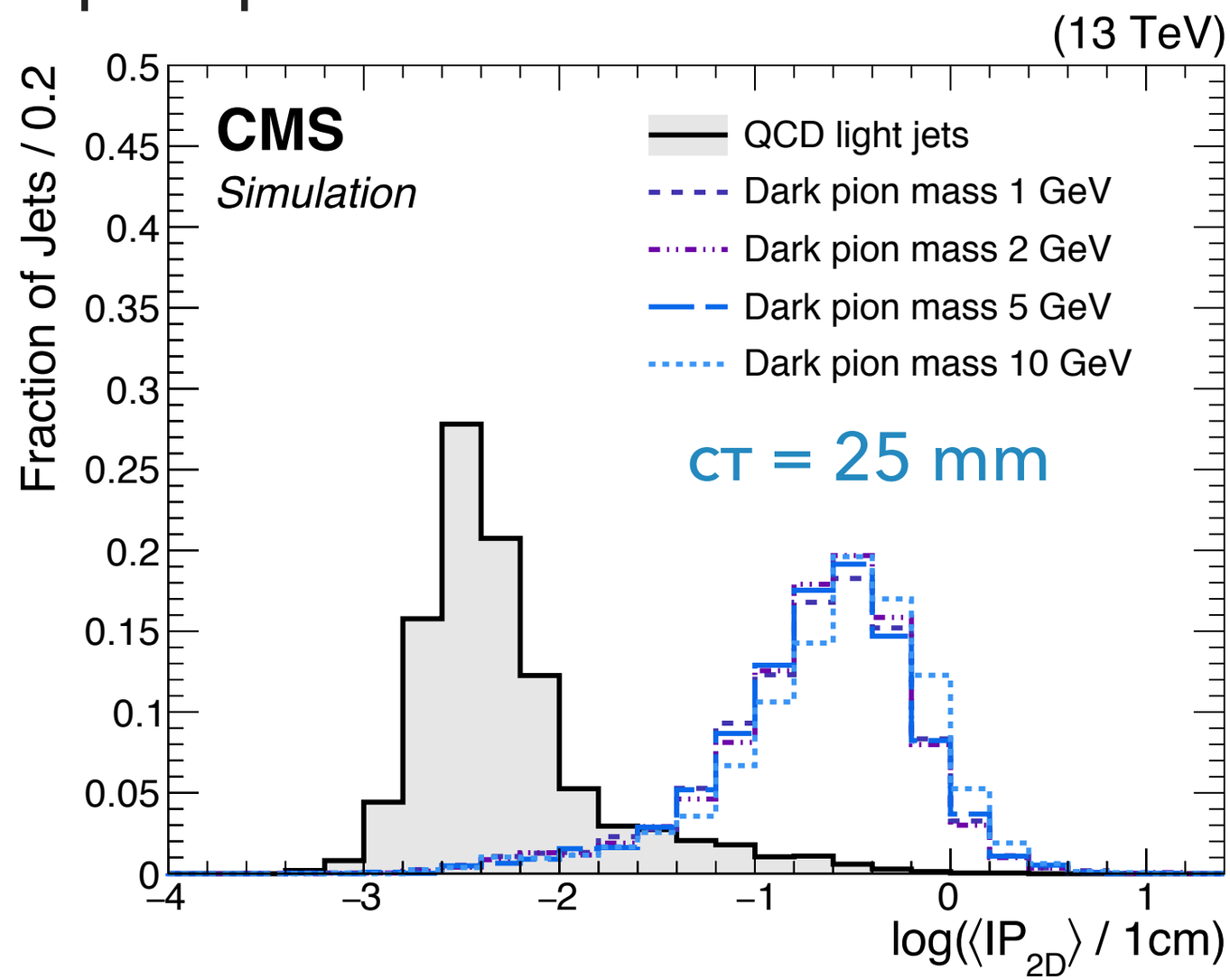


ANALYSIS STRATEGY

JHEP 05 (2015) 059

- **Tag** emerging jets using track impact parameter variables

- Require 4 jets with
  - 2 tagged emerging jets or
  - 1 tagged and $p_T^{miss} > 200$ GeV for large $c\tau$
  - trigger on $H_T = \sum p_T(j_{1,2,3,4})$



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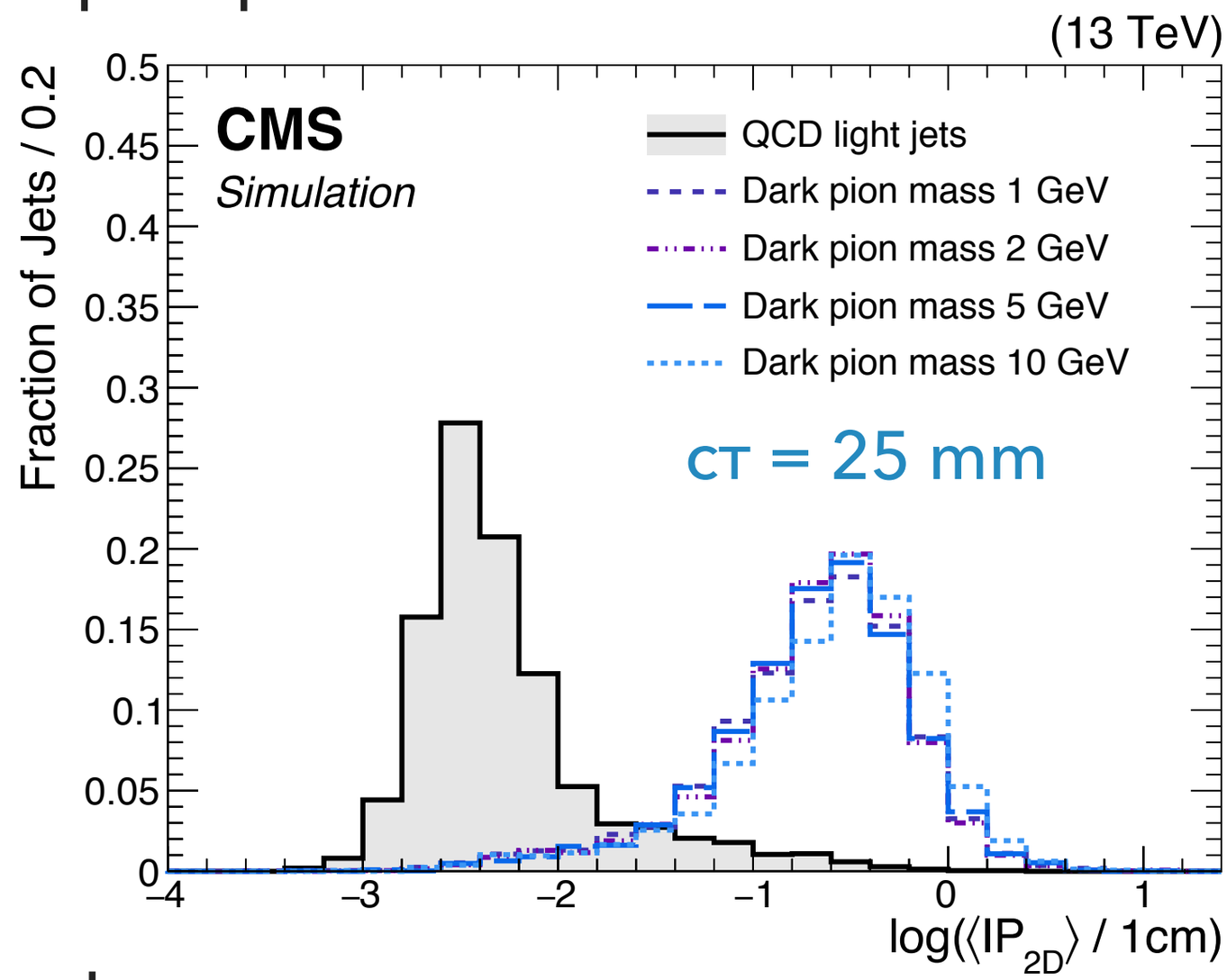

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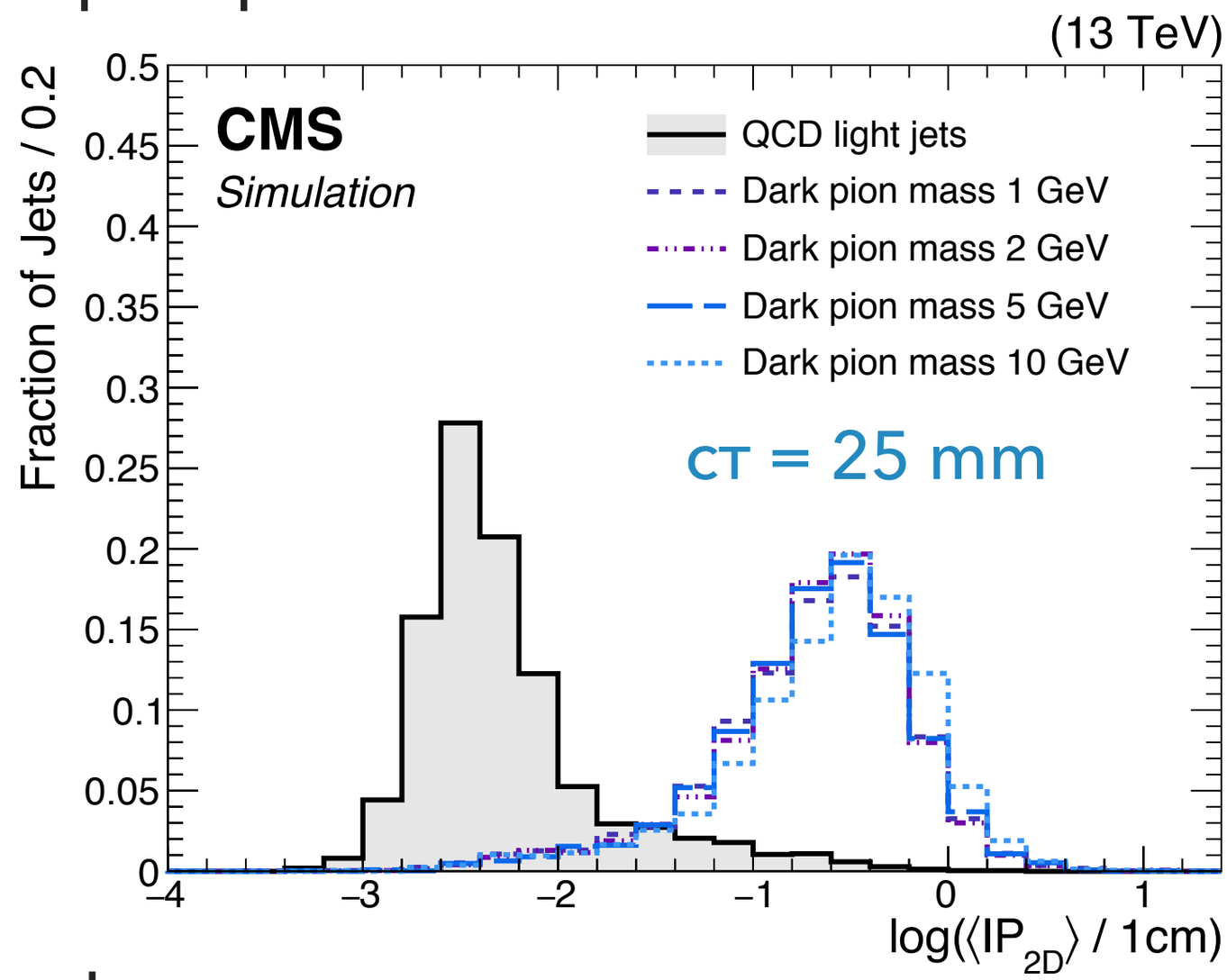

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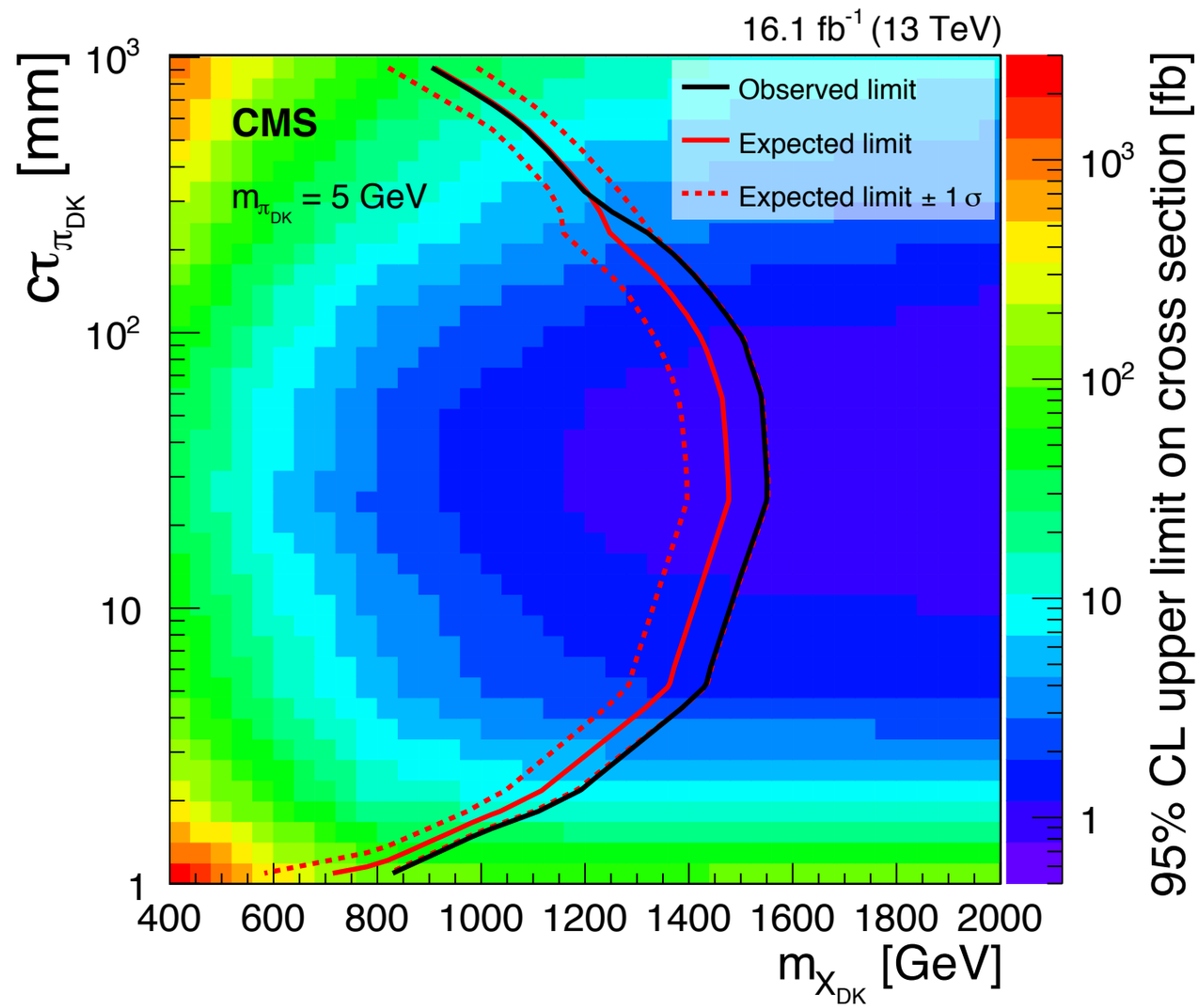
- Categorize with tagging WPs and kinematic selection → **7 signal regions**
- Background estimation:
  misid. rate (from **γ** CR) × QCD CR yield = SR yield

RESULTS

- Observed data agree with background predictions (within uncertainties)
- Limits do not depend strongly on $m_{\pi_{DK}}$
- Exclude $m_{X_{DK}}$ between 400 and 1250 GeV for $c\tau_{\pi_{DK}}$ between 5 and 225 mm



Set number	Expected	Observed	Signal	Model parameters $m_{X_{DK}}$ [GeV]	$m_{\pi_{DK}}$ [GeV]	$c\tau_{\pi_{DK}}$ [mm]
1	$168 \pm 15 \pm 5$	131	36.7 ± 4.0	600	5	1
2	$31.8 \pm 5.0 \pm 1.4$	47	$(14.6 \pm 2.6) \times 10^2$	400	1	60
3	$19.4 \pm 7.0 \pm 5.5$	20	15.6 ± 1.6	1250	1	150
4	$22.5 \pm 2.5 \pm 1.5$	16	15.1 ± 2.0	1000	1	2
5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0	1000	2	150
6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5	1000	10	300
7	$4.40 \pm 0.84 \pm 0.28$	2	5.61 ± 0.64	1250	5	225

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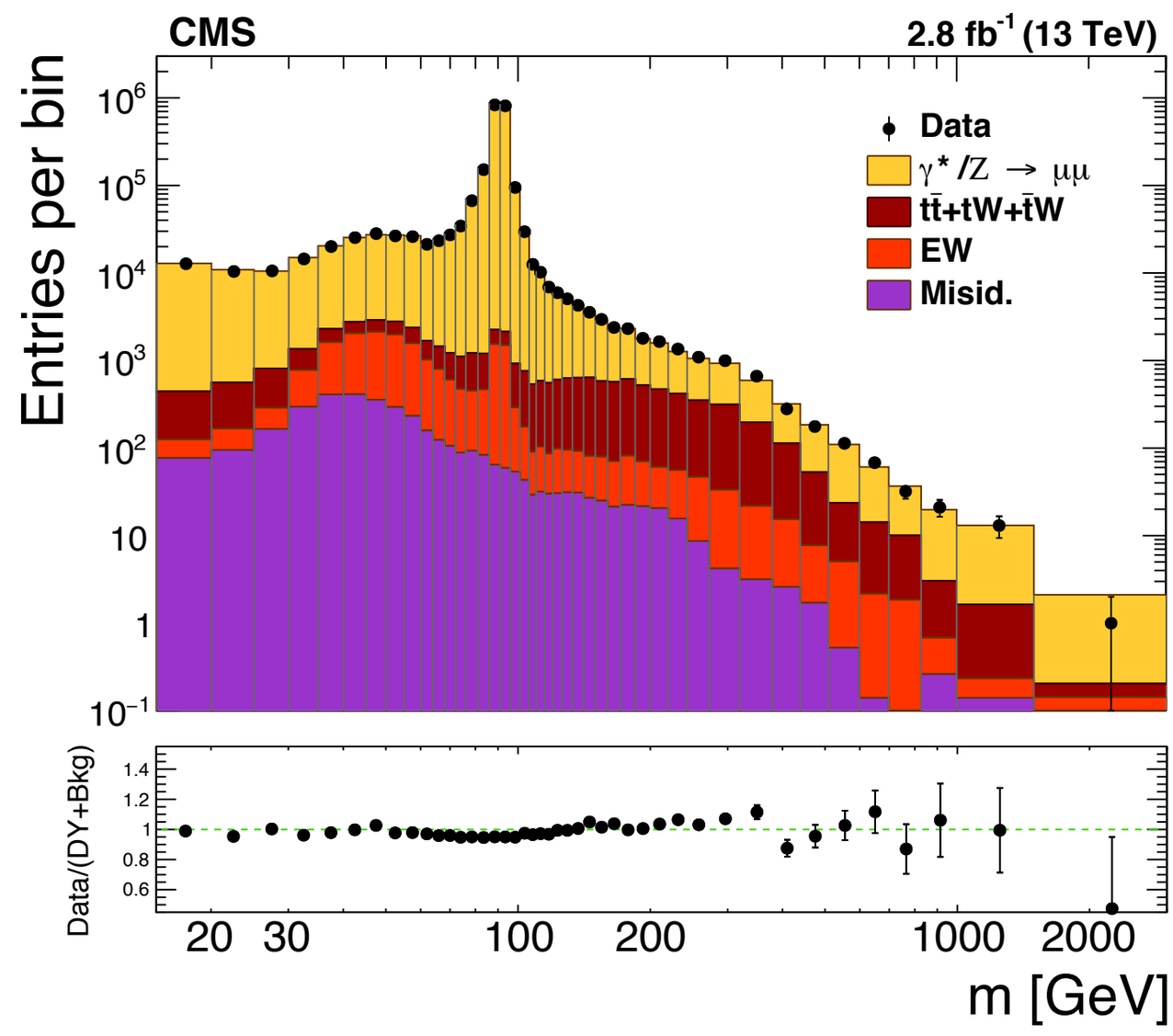
STANDARD DIMUON TRIGGERS

arXiv:1812.10529

- Standard dilepton triggers have thresholds of 10-20 GeV on lepton p_T
- Difficult to trigger at lower dilepton mass offline $m_{\mu\mu} < 40$ GeV



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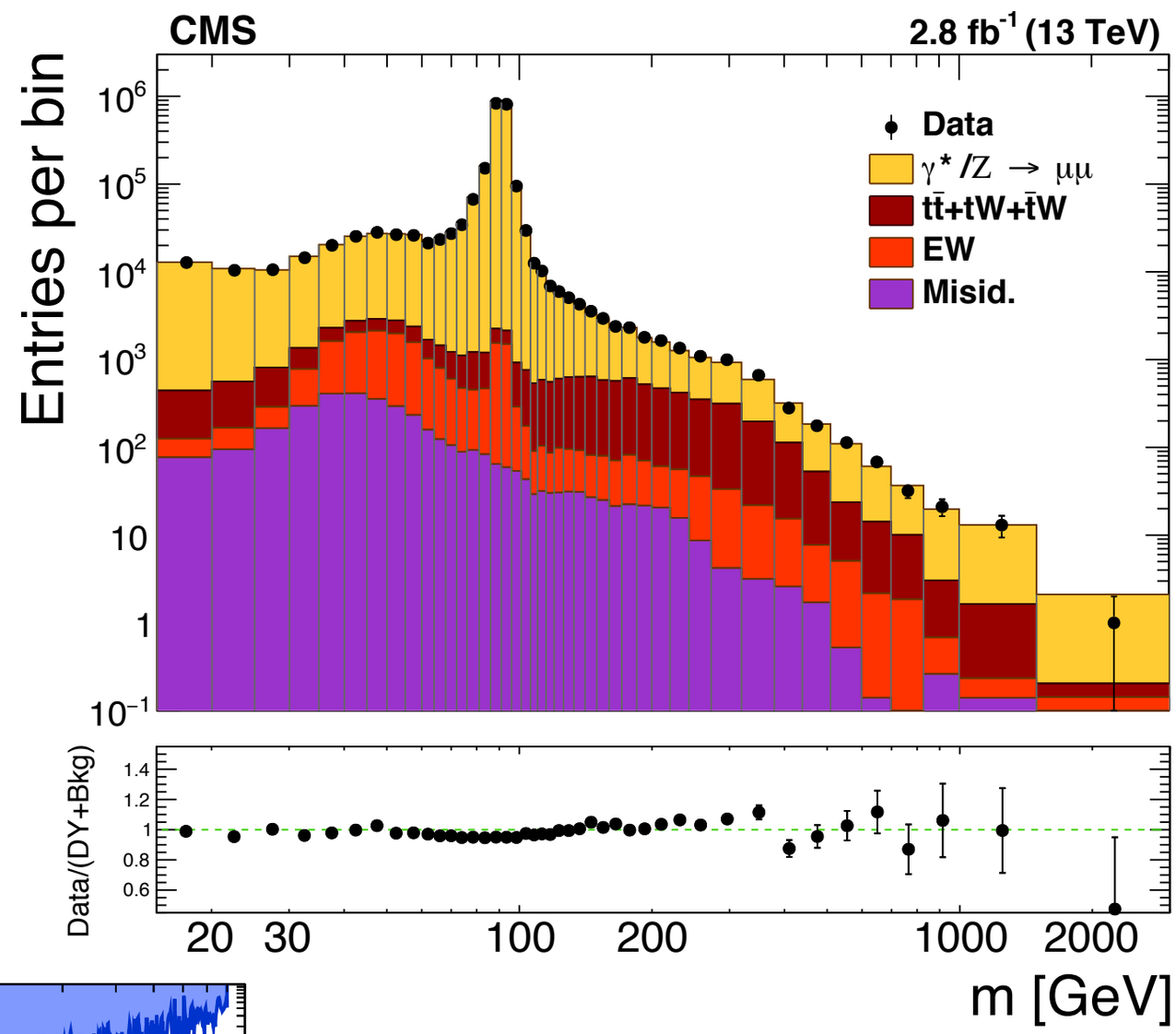

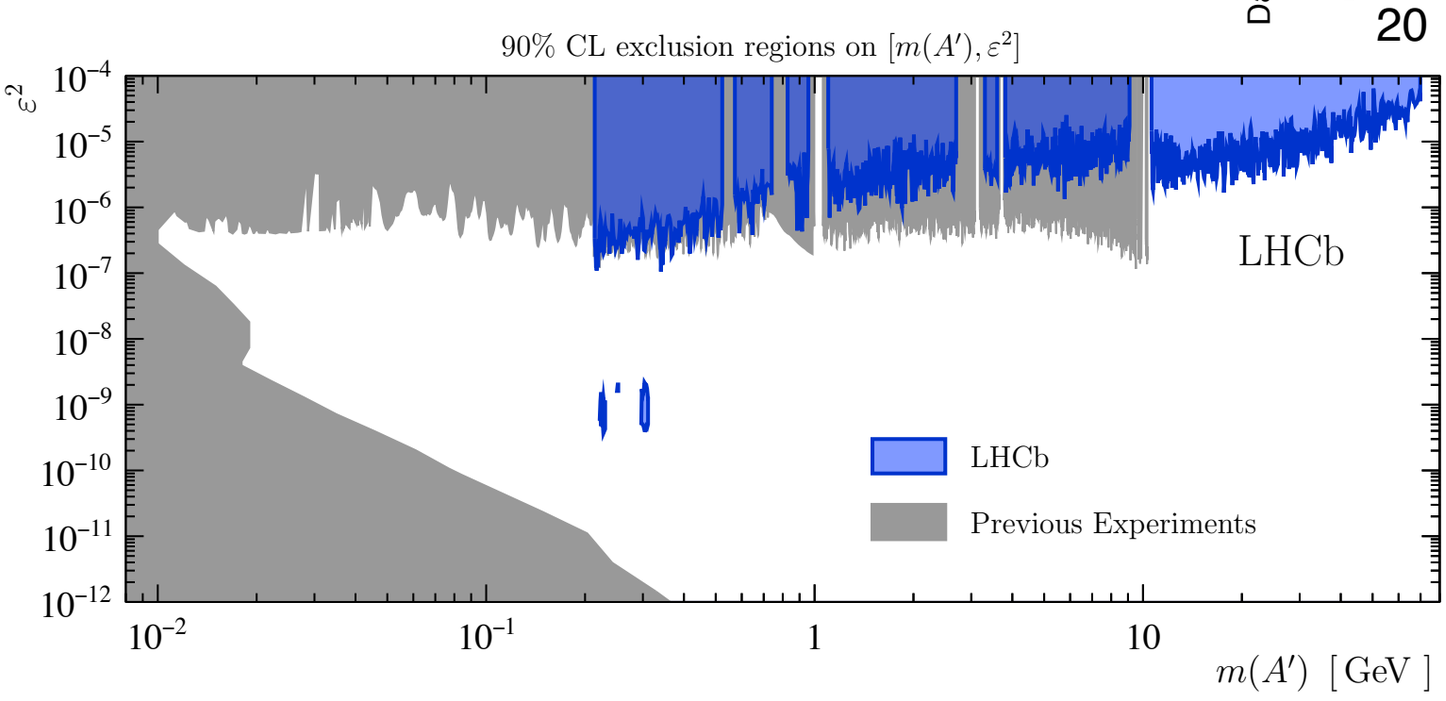

- LHCb best sensitivity for $m_{\mu\mu} > 10$ GeV [PRL 120, 061801]

MUON DATA SCOUTING

DP-2018-039

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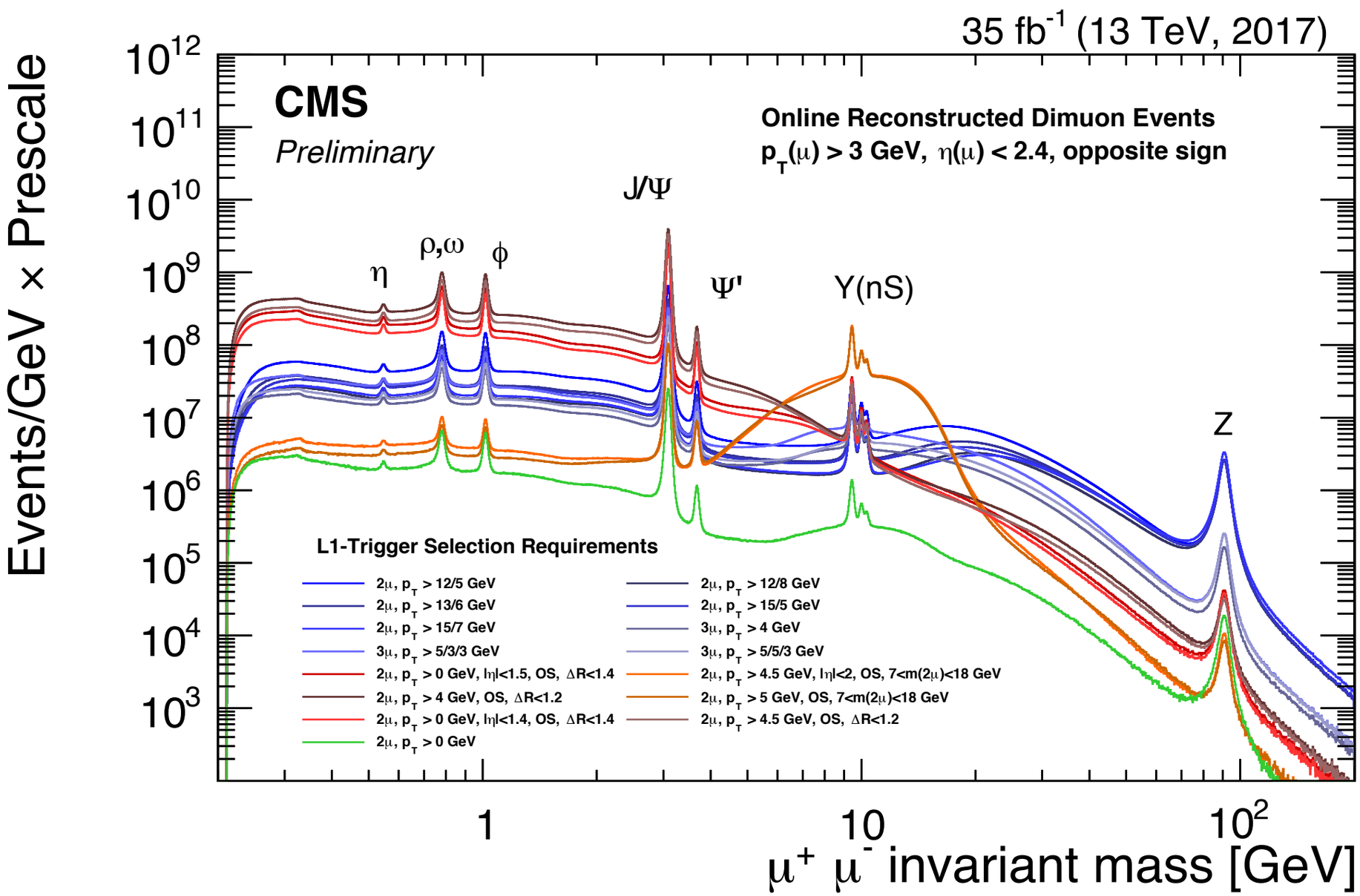
- Potential to improve CMS sensitivity to low-mass dimuon resonances
- Challenges: lower resolution, custom calibration, muon ID, larger background



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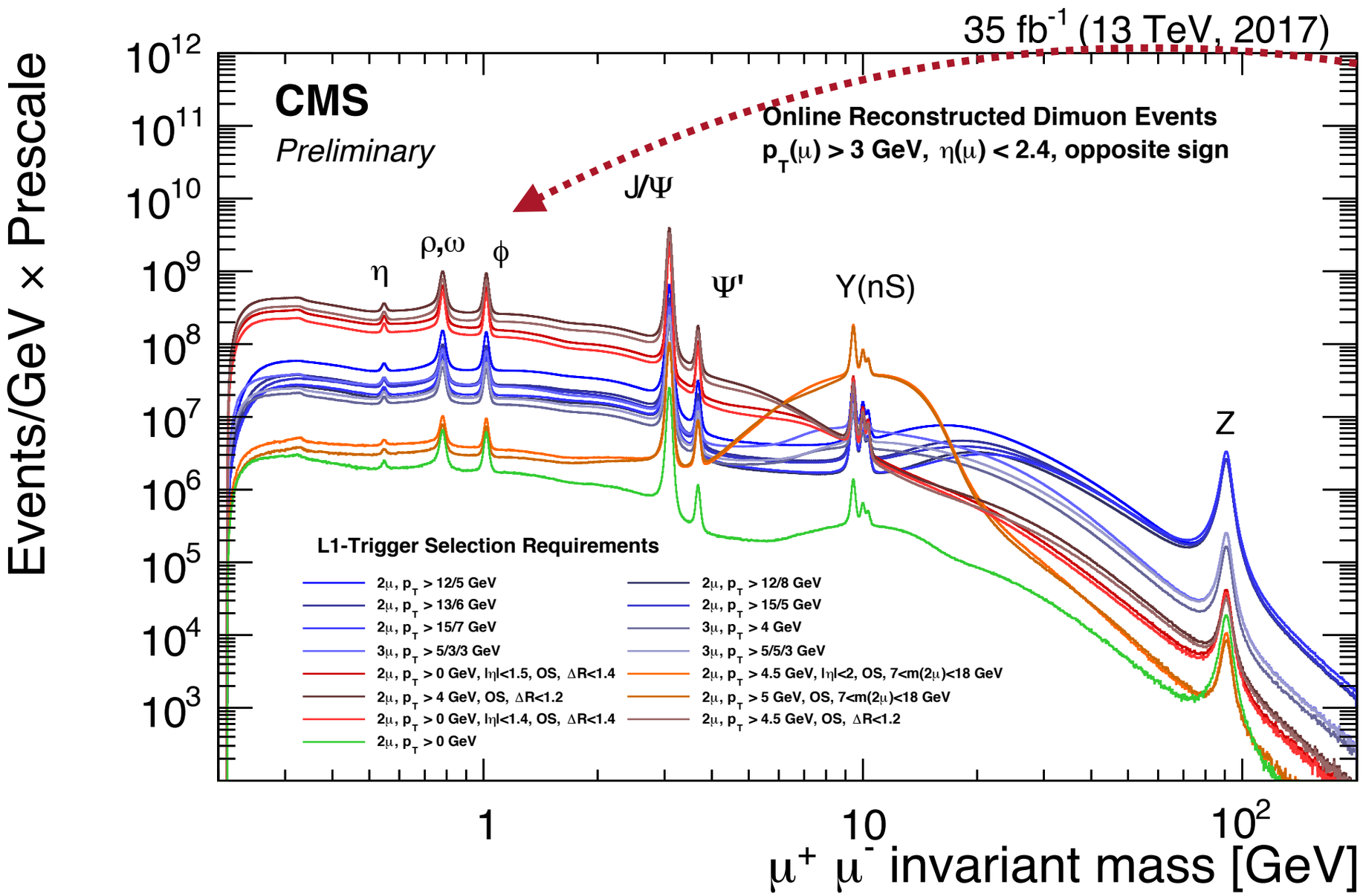

Online $m_{\mu\mu}$ < 10 GeV:
L1:
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p_T^{μ} > 4 GeV or
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MUON DATA SCOUTING

DP-2018-039

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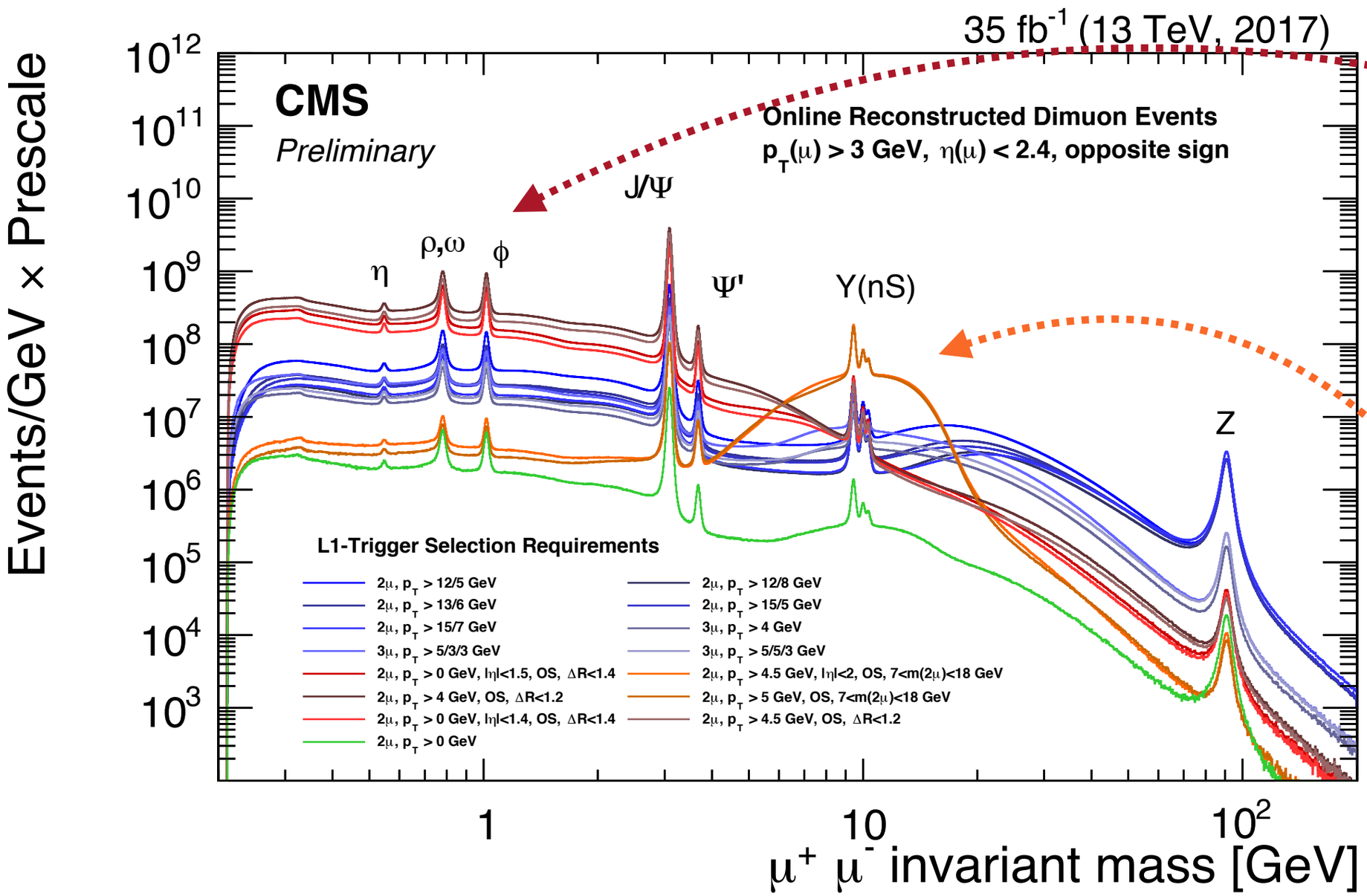

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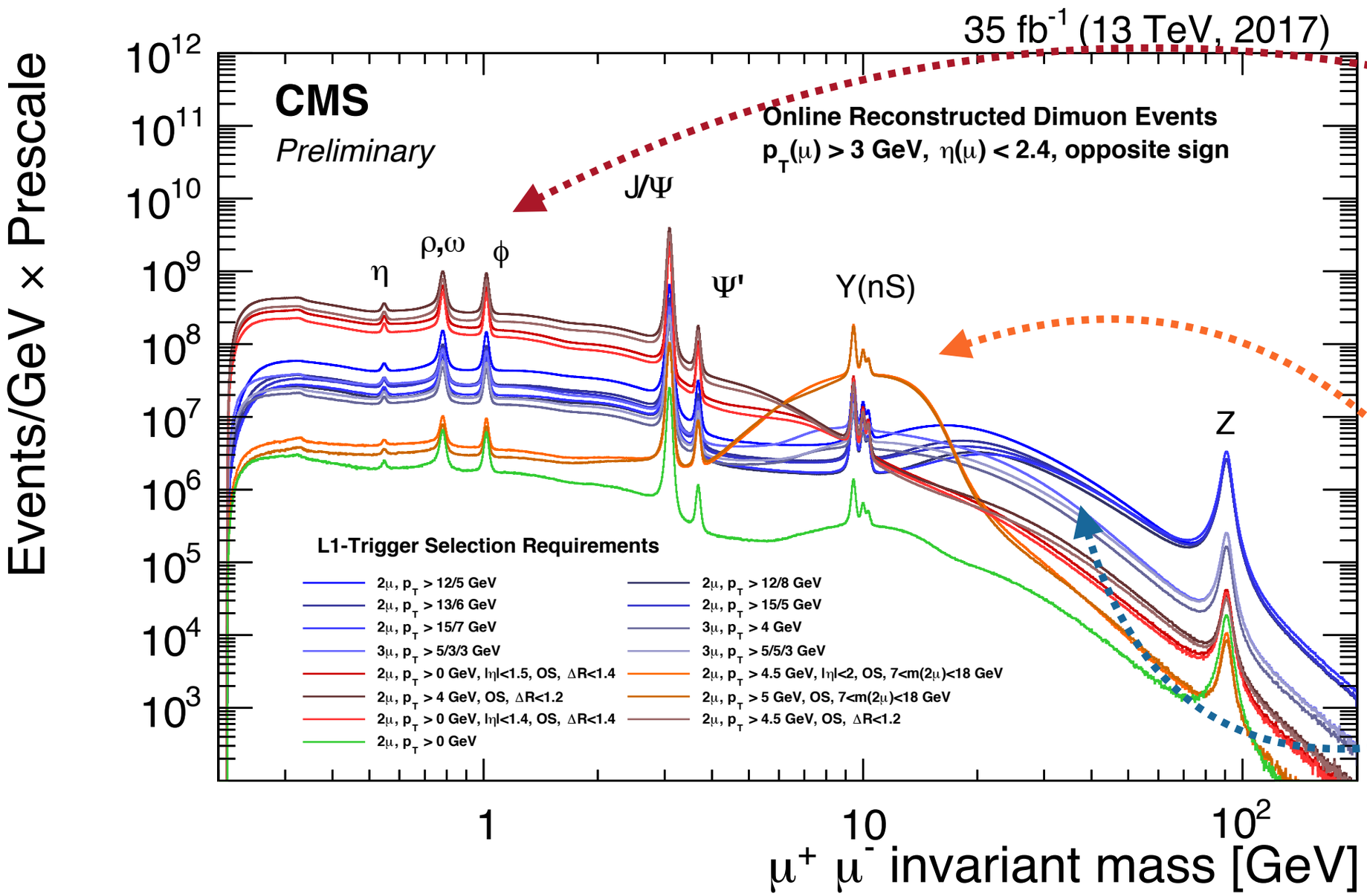

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$p_T^{\mu} > 15/7$ GeV

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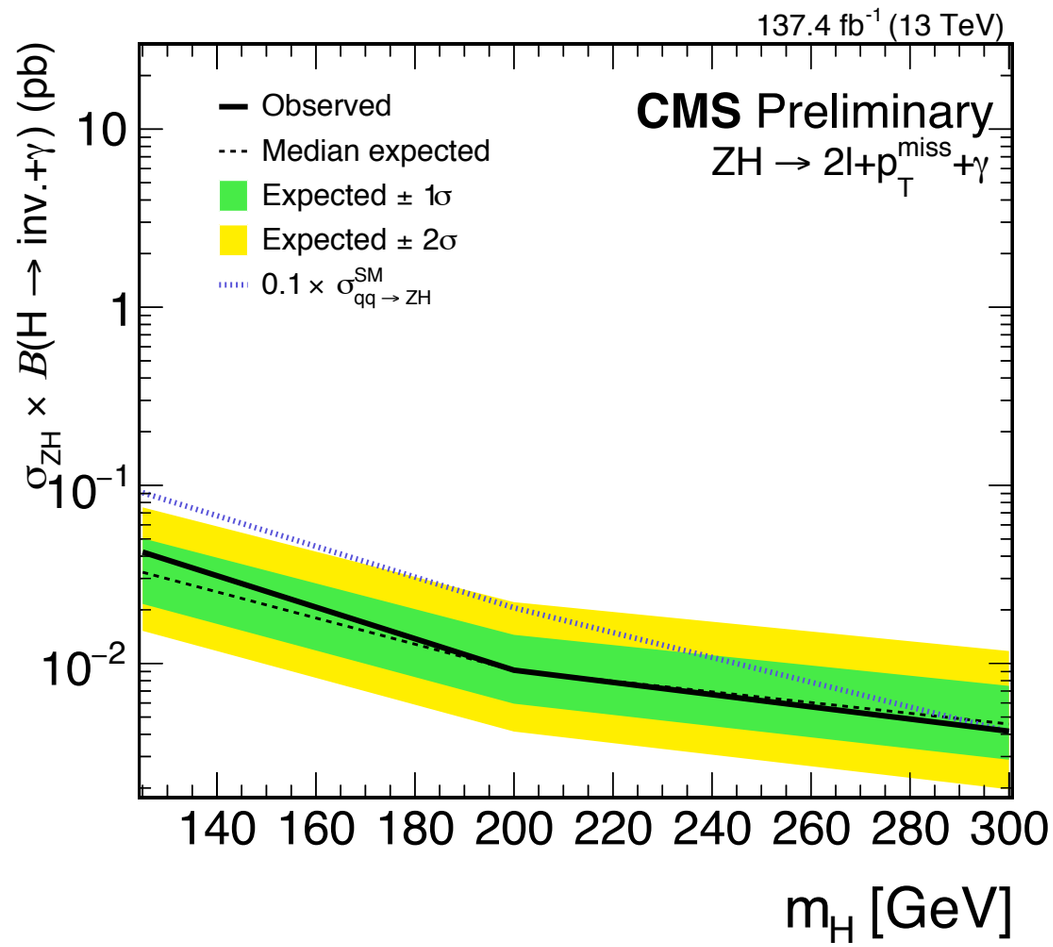

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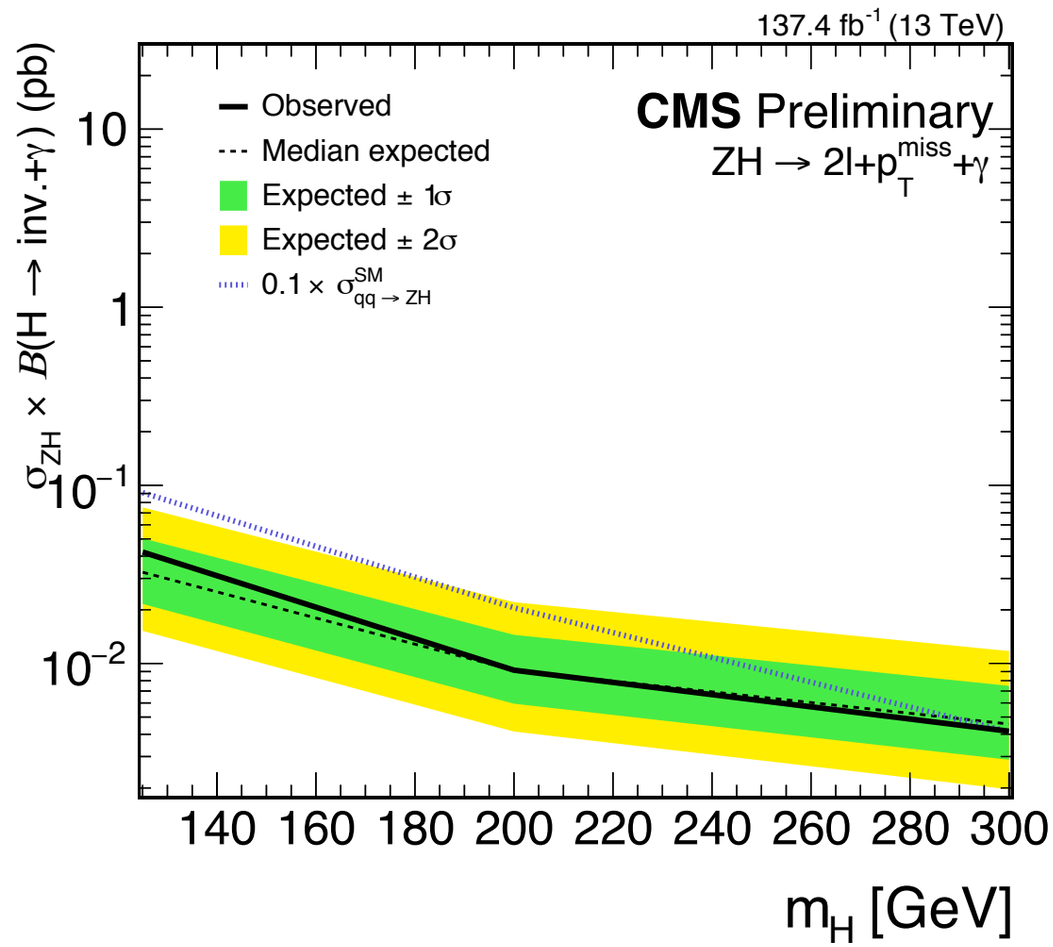

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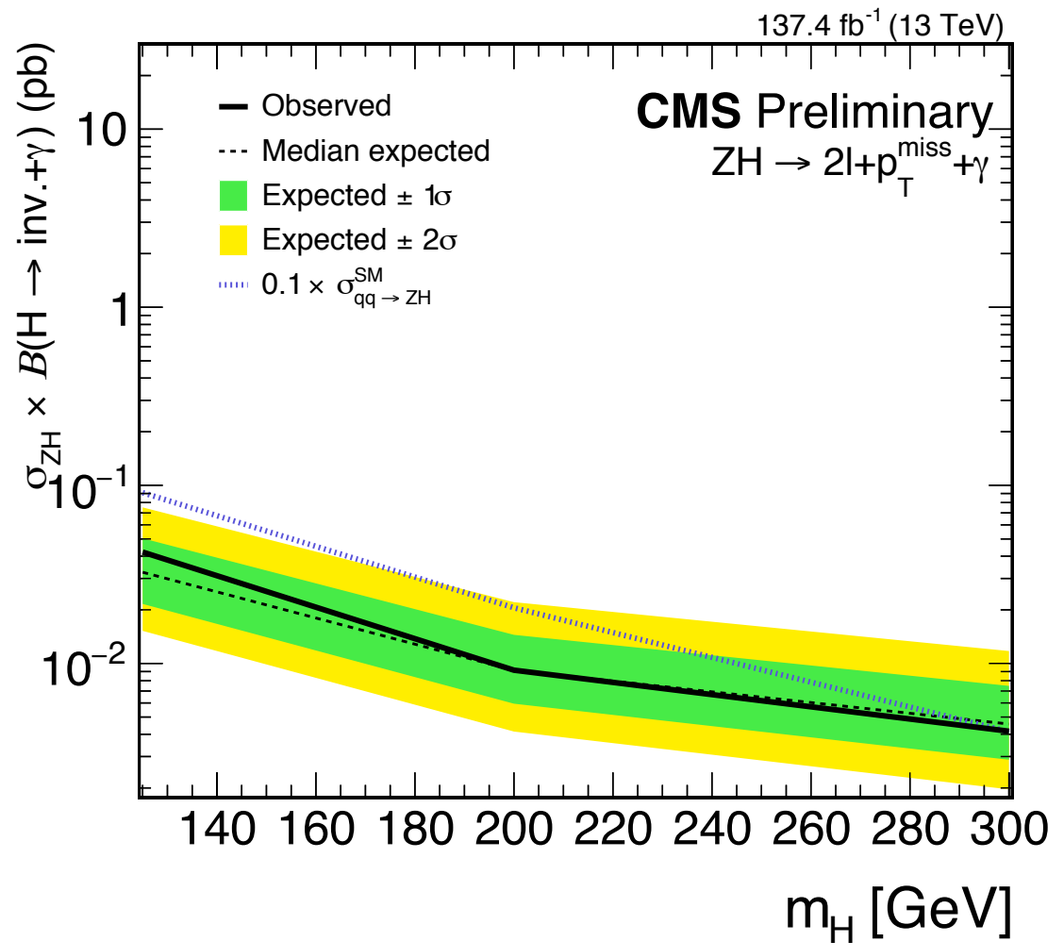


- Dark QCD: unique *emerging jet* signature excludes dark sector with mediator masses between 400 and 1250 GeV and dark pion lifetimes between 5 and 225 mm
- Minimal dark photon: low-mass dimuon search with data scouting forthcoming!

REFERENCES

- EXO-19-007: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-19-007/index.html
- EXO-18-001: JHEP 02 (2019) 179
- DP-2018-039: http://cds.cern.ch/record/2644377
- EXO-19-001: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-19-001/index.html
- EXO-16-047: JHEP 06 (2018) 120
- SMP-17-001: arXiv:1812.10529
- HIG-18-003: arXiv:1812.00380
- HIG-17-023: accepted by PLB

BACKUP

JAVIER DUARTE

MAY 20, 2019

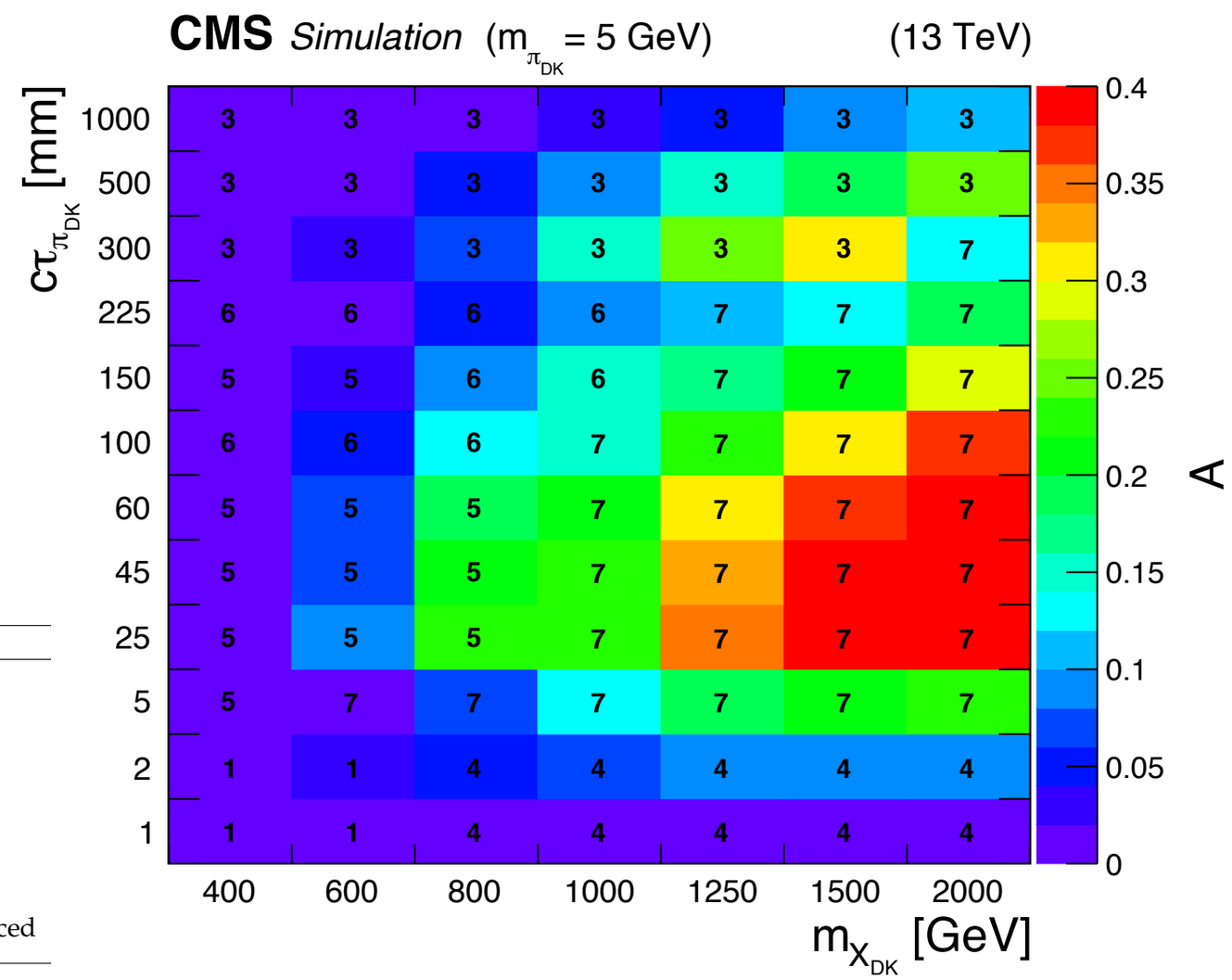
LHCP, PUEBLA, MEXICO

RESULTS

- Best signal region sensitivity

Criteria group	PU_{dz} (<) [cm]	D_N (<)	$\langle IP_{2D} \rangle$ (>) [cm]	α_{3D} (<)
EMJ-1	2.5	4	0.05	0.25
EMJ-2	4.0	4	0.10	0.25
EMJ-3	4.0	20	0.25	0.25
EMJ-4	2.5	4	0.10	0.25
EMJ-5	2.5	20	0.05	0.25
EMJ-6	2.5	10	0.05	0.25
EMJ-7	2.5	4	0.05	0.40
EMJ-8	4.0	20	0.10	0.50

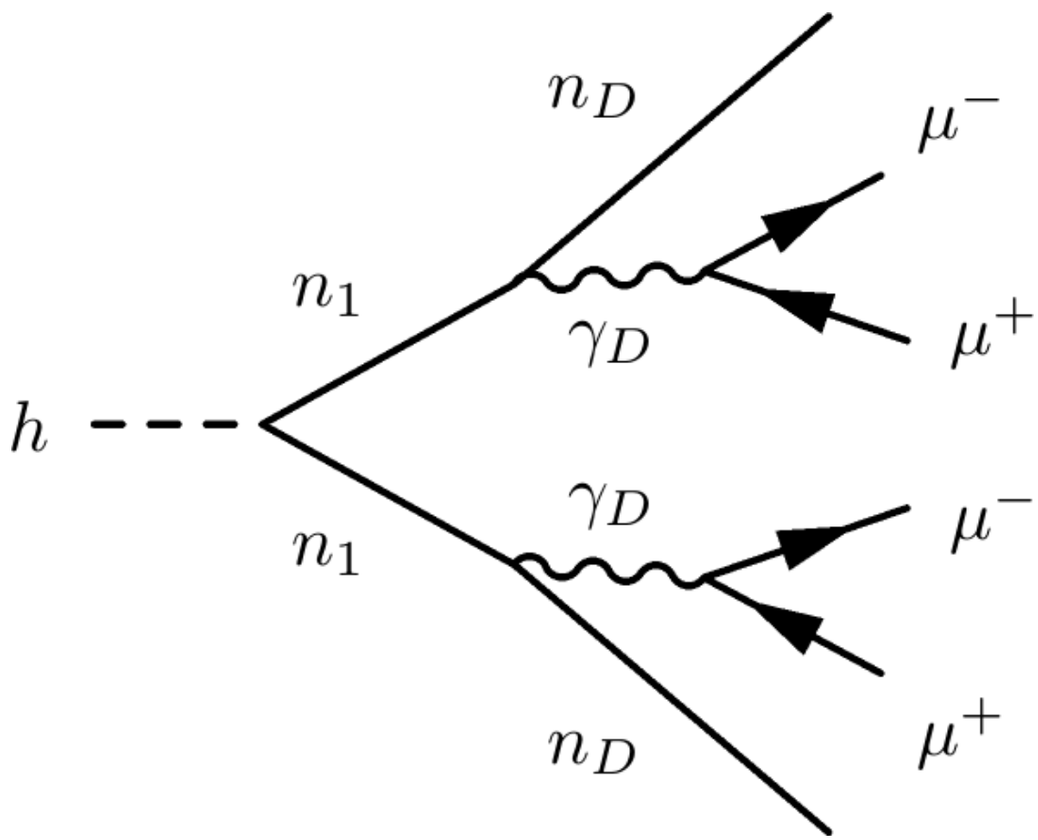
Set number	H_T	$p_{T,1}$	$p_{T,2}$	$p_{T,3}$	$p_{T,4}$	p_T^{miss}	$n_{EMJ}(\geq)$	EMJ group	no. models
1	900	225	100	100	100	0	2	1	12
2	900	225	100	100	100	0	2	2	2
3	900	225	100	100	100	200	1	3	96
4	1100	275	250	150	150	0	2	1	49
5	1000	250	150	100	100	0	2	4	41
6	1000	250	150	100	100	0	2	5	33
7	1200	300	250	200	150	0	2	6	103
8	900	225	100	100	100	0	2	7	SM QCD-enhanced
9	900	225	100	100	100	200	1	8	

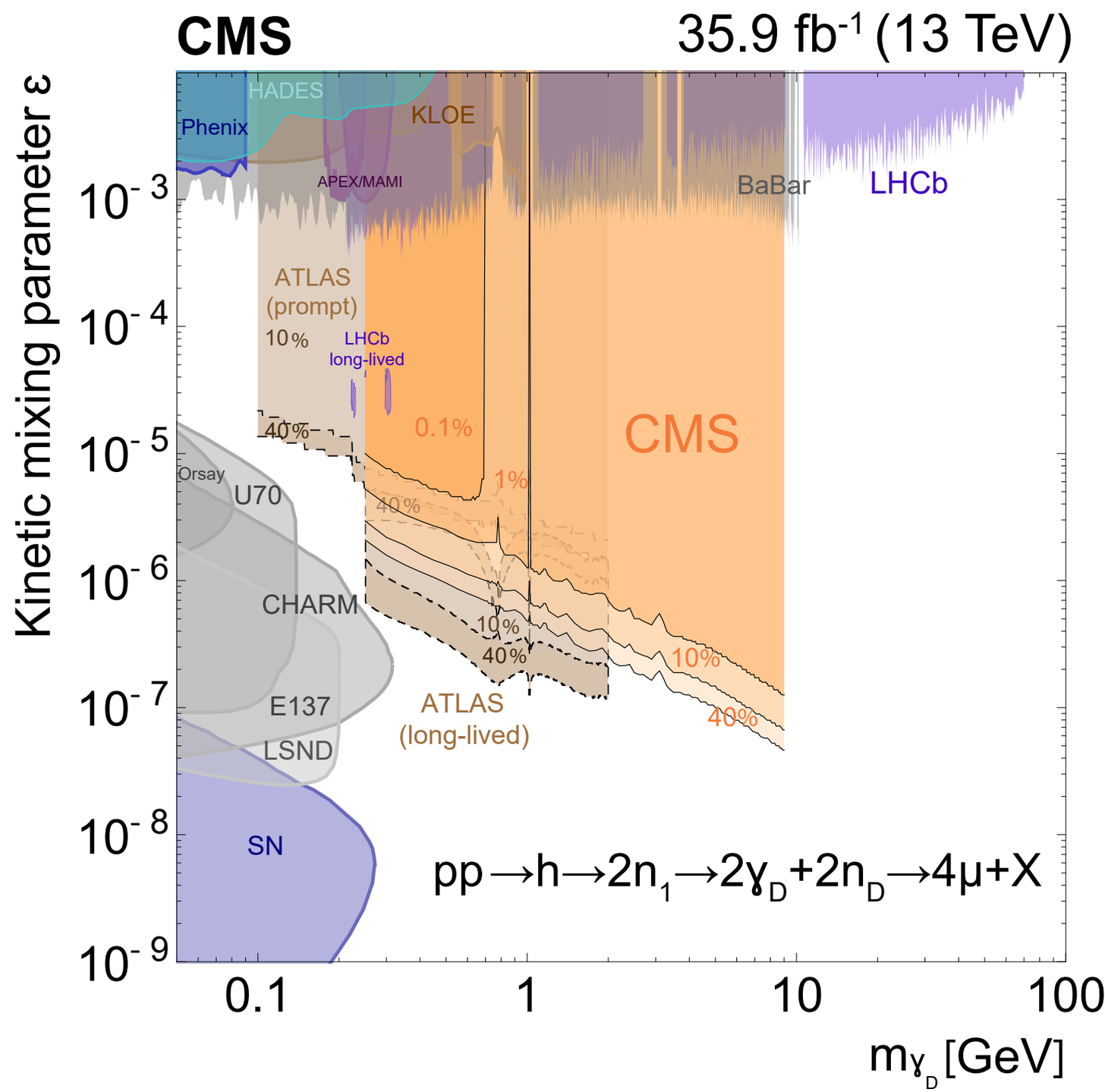


Set number	Expected	Observed	Signal	Model parameters $m_{X_{DK}}$ [GeV]	$m_{\pi_{DK}}$ [GeV]	$c\tau_{\pi_{DK}}$ [mm]
1	$168 \pm 15 \pm 5$	131	36.7 ± 4.0	600	5	1
2	$31.8 \pm 5.0 \pm 1.4$	47	$(14.6 \pm 2.6) \times 10^2$	400	1	60
3	$19.4 \pm 7.0 \pm 5.5$	20	15.6 ± 1.6	1250	1	150
4	$22.5 \pm 2.5 \pm 1.5$	16	15.1 ± 2.0	1000	1	2
5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0	1000	2	150
6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5	1000	10	300
7	$4.40 \pm 0.84 \pm 0.28$	2	5.61 ± 0.64	1250	5	225

DARK SUSY

arXiv:1812.00380

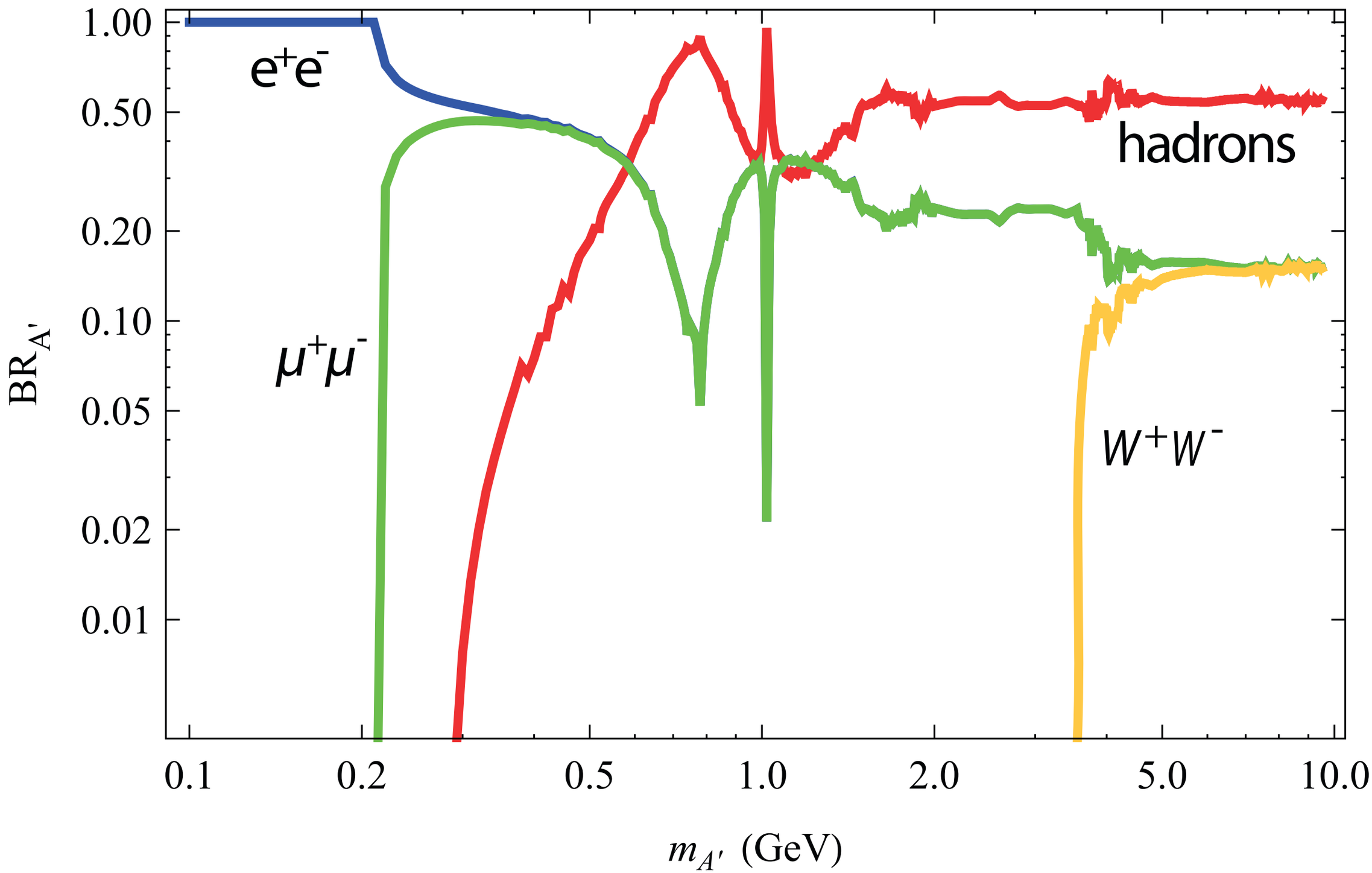




- Dark SUSY cascade decay

DARK PHOTON DECAYS

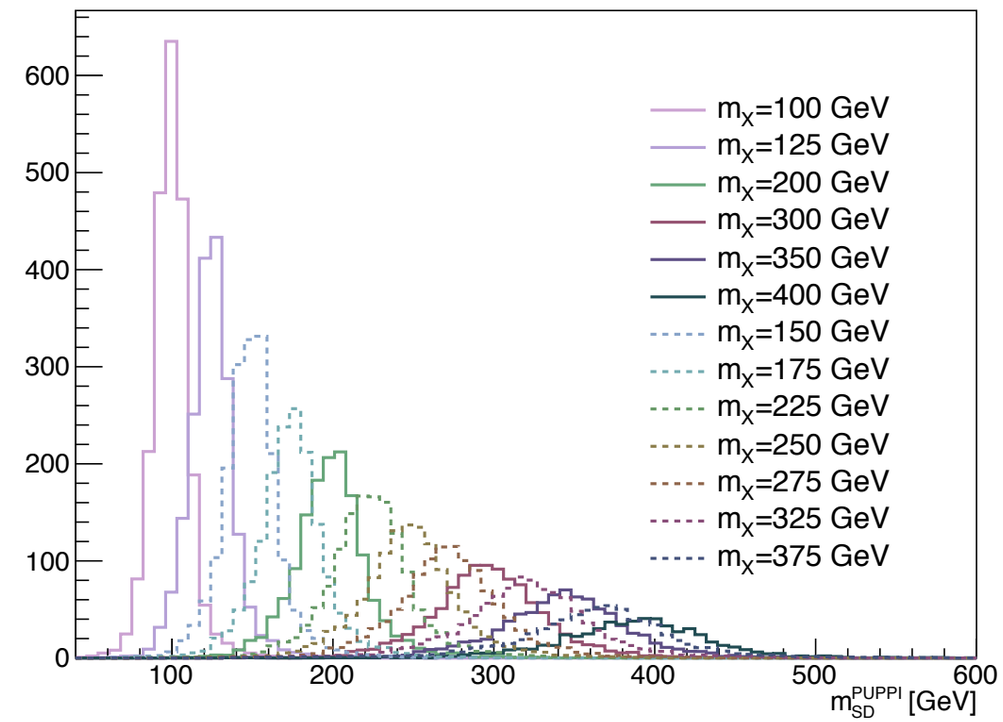
10.1393/ncr/i2015-10117-9



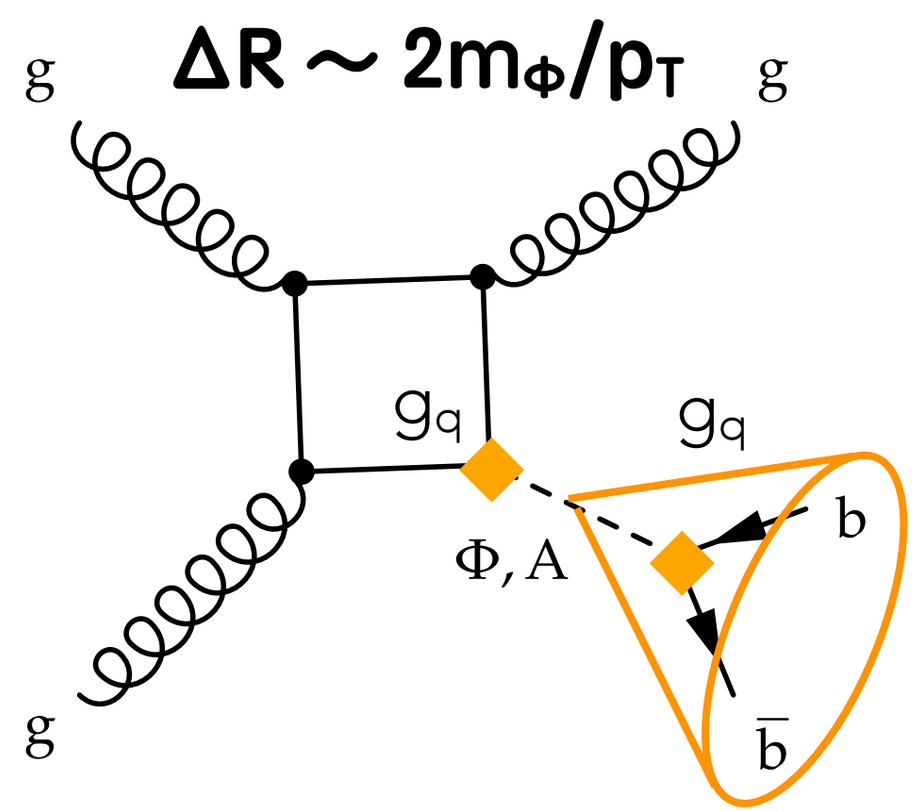
SEARCHING FOR Φ(BB)

Phys. Rev. D 99, 012005 (2019)

- **Generalize** H(bb) search for spin-0 **dark mediators** Φ/A(bb) from 50 to 350 GeV



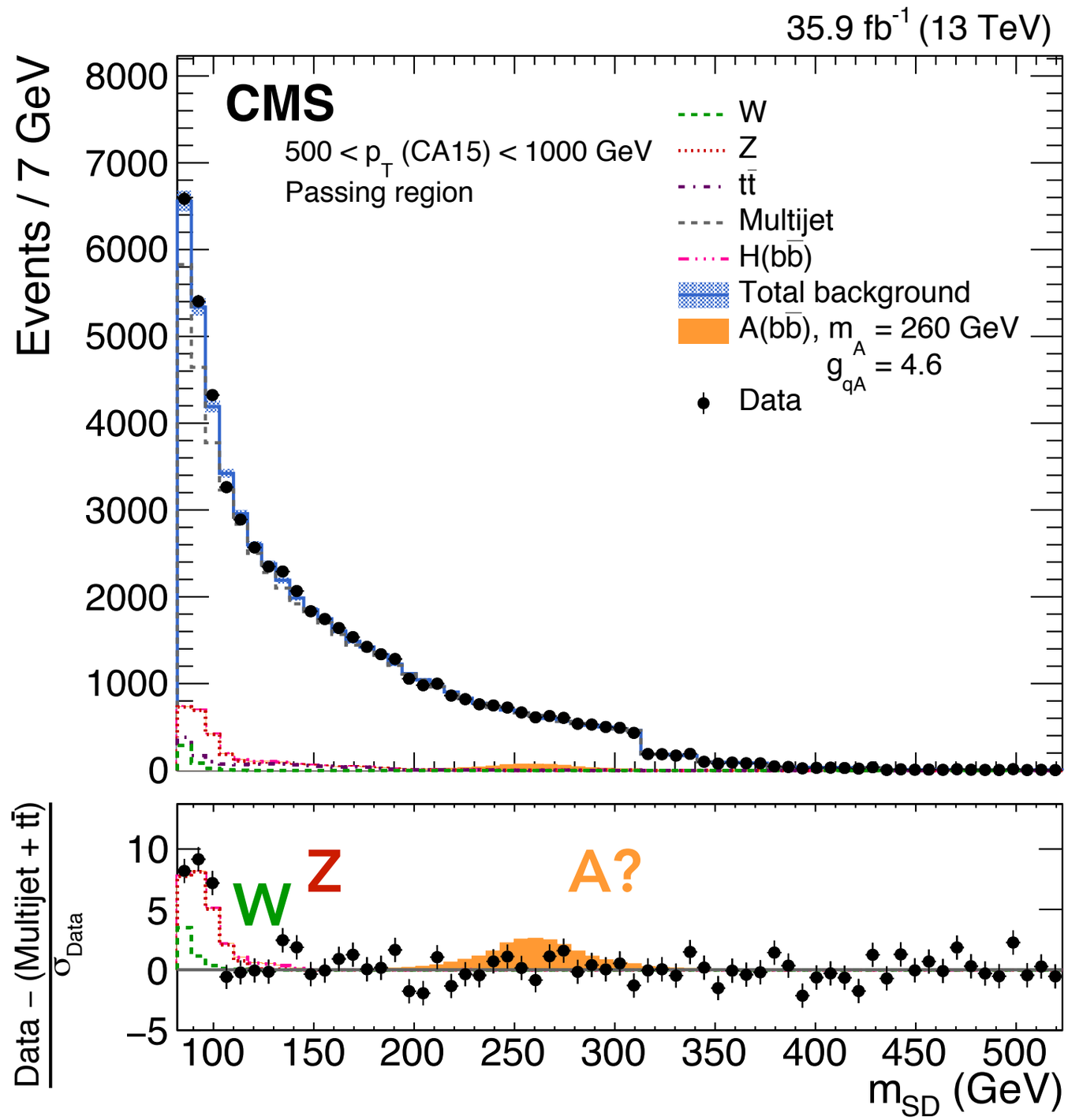
- Larger masses require using a **larger jet** cone, **re-optimizing** substructure cuts, and **re-training** the double-b tagger



SEARCHING FOR Φ(BB)

Phys. Rev. D 99, 012005 (2019)

- **Pseudoscalar** A(bb) hypothesis at 260 GeV
- Sensitive to **O(1) couplings** between **mediator** and **SM**



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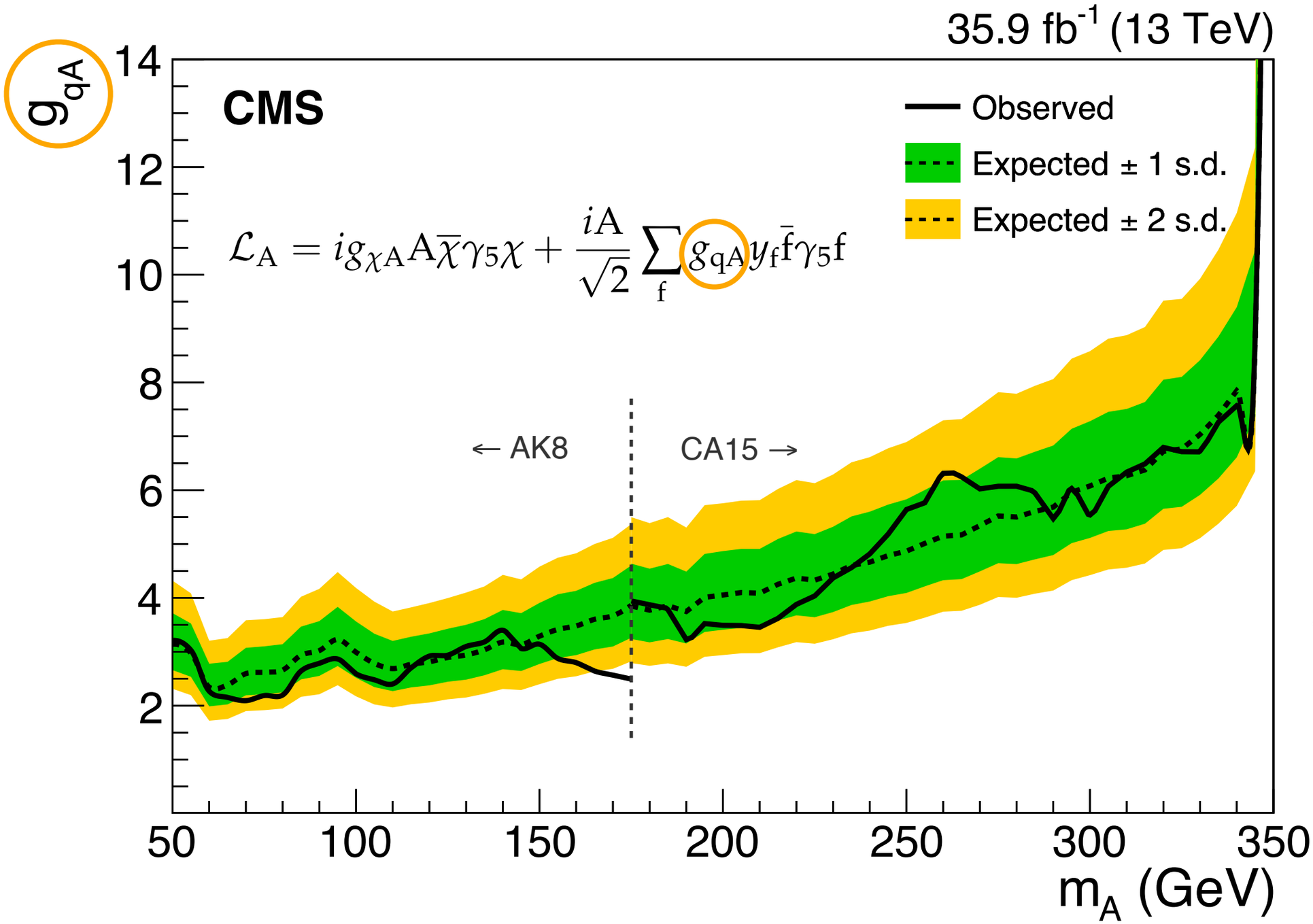

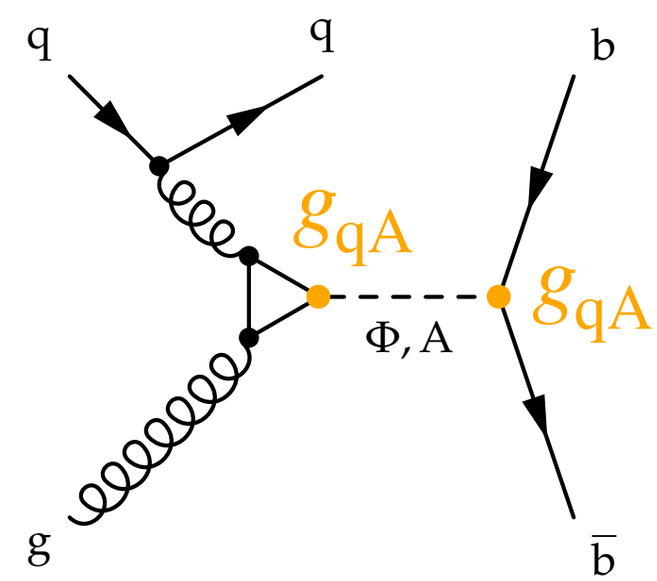

THE LARGE HADRON COLLIDER

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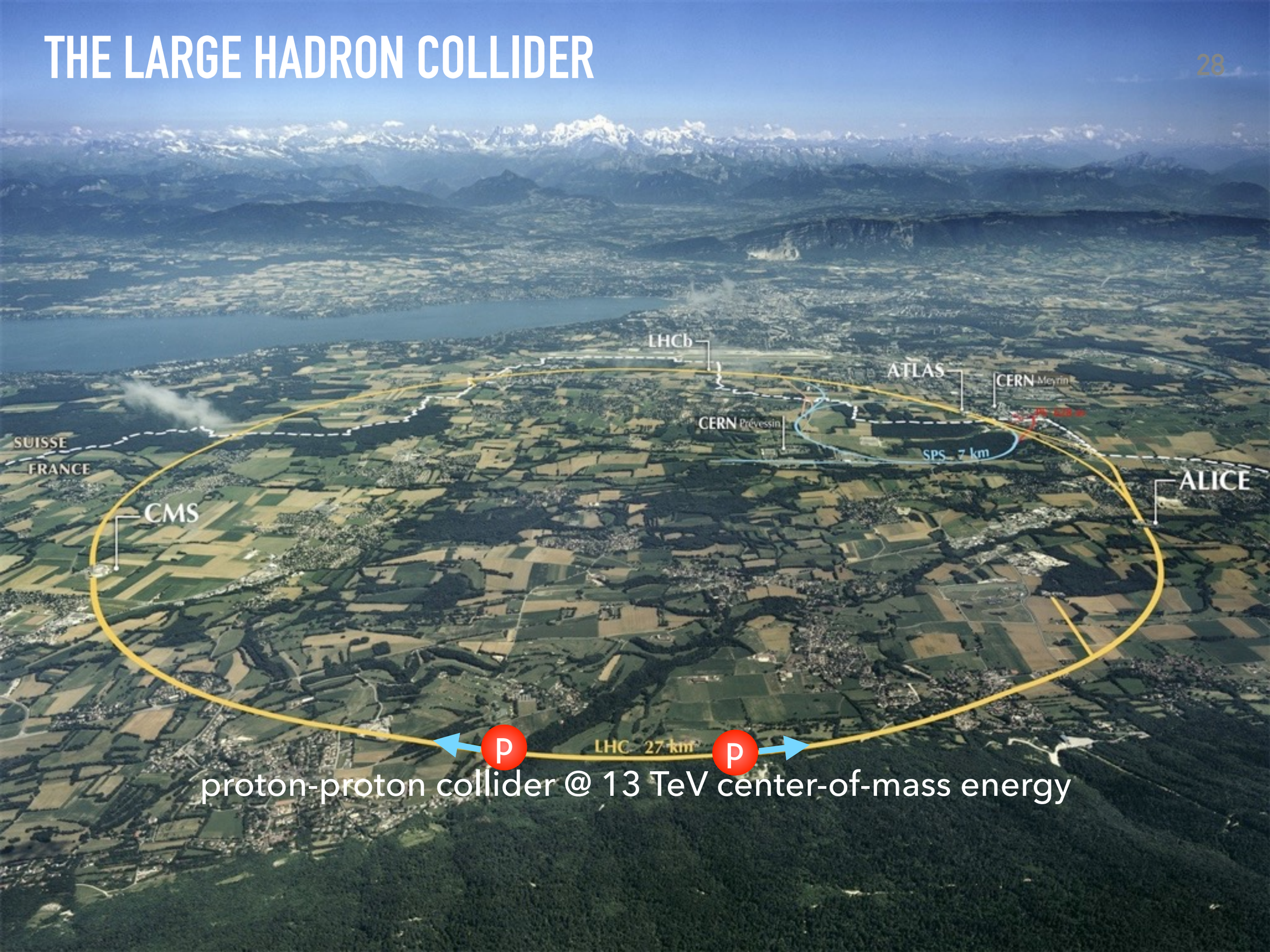

proton-proton collider @ 13 TeV center-of-mass energy

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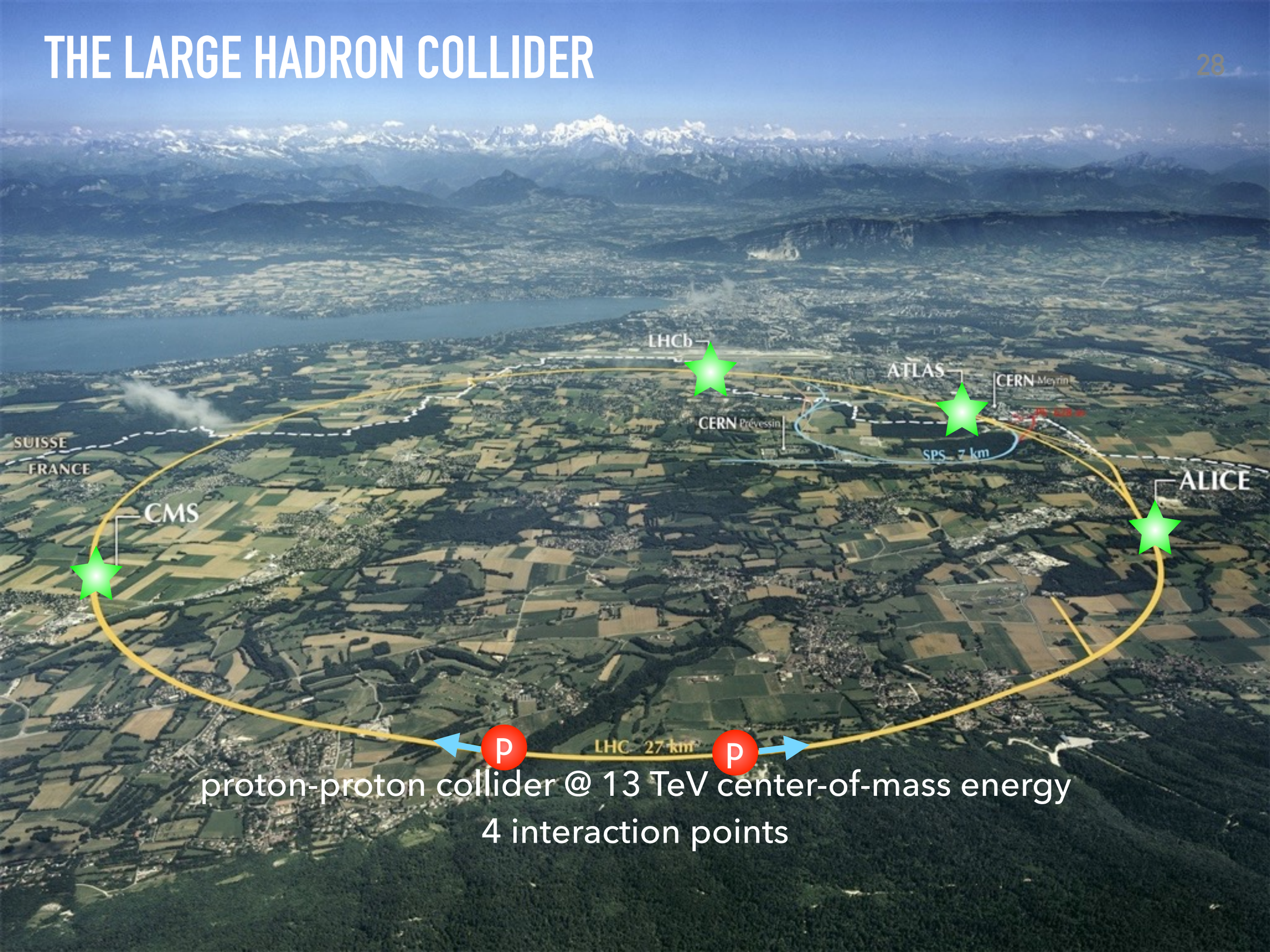

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4 interaction points

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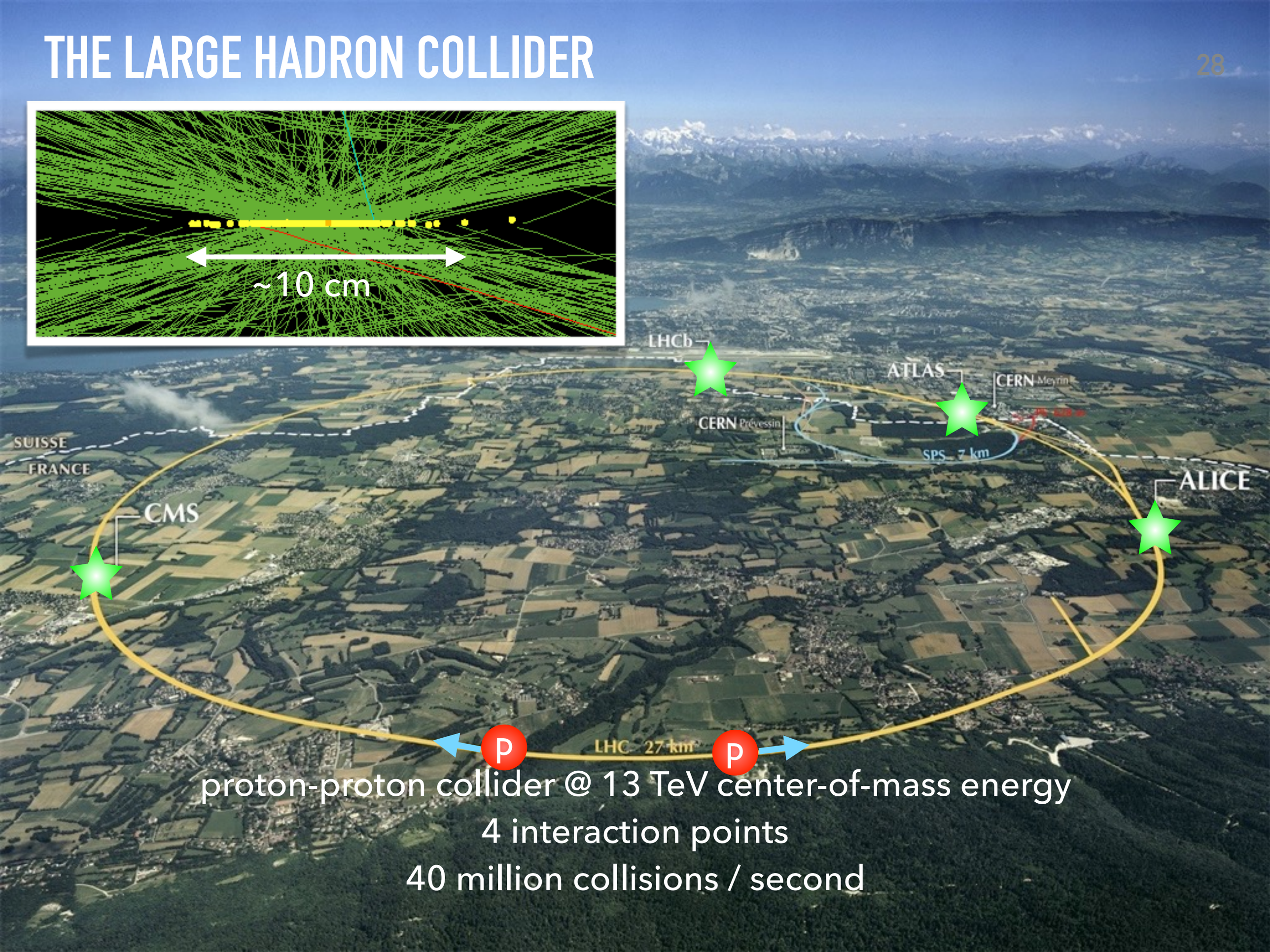

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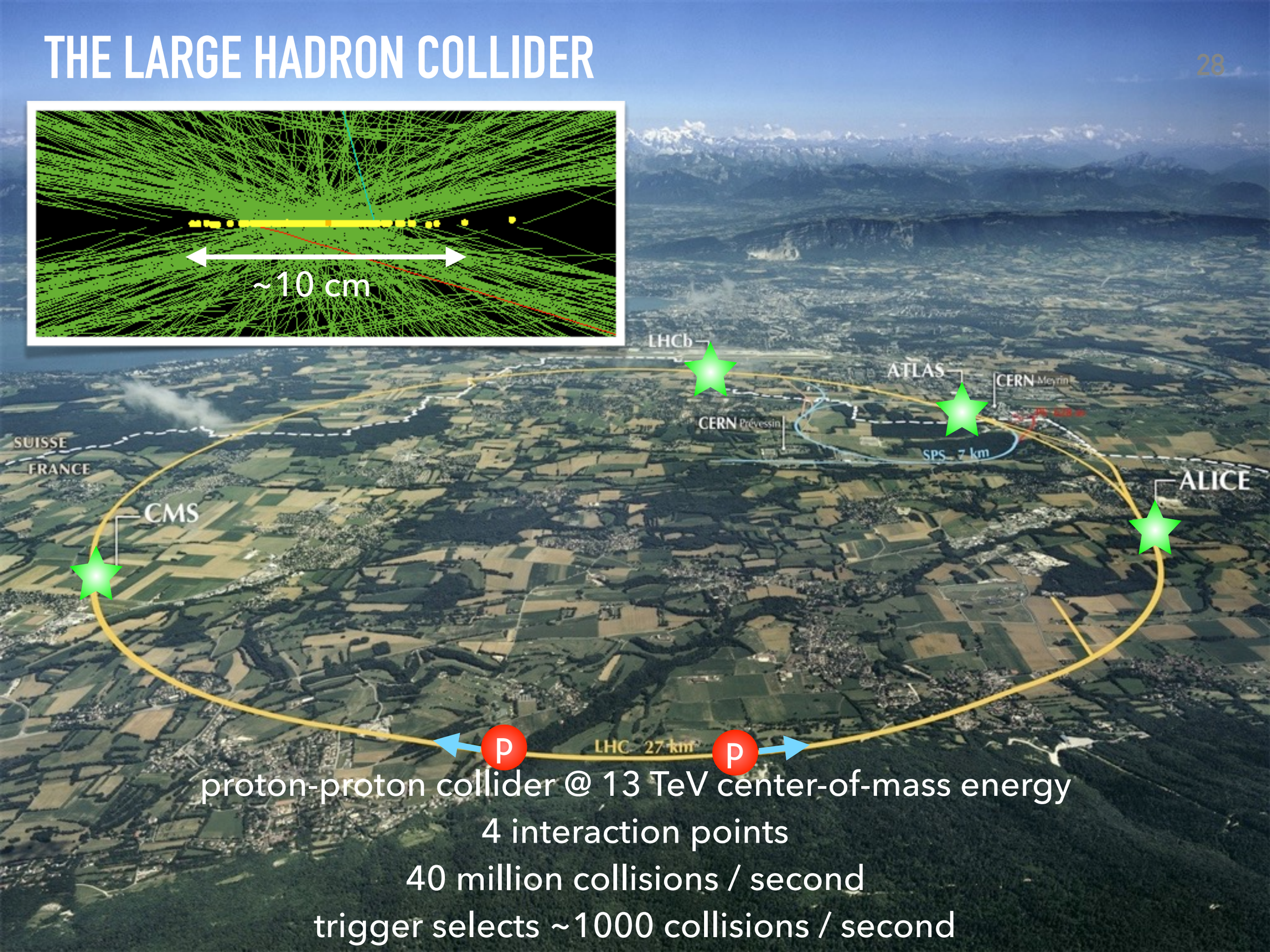

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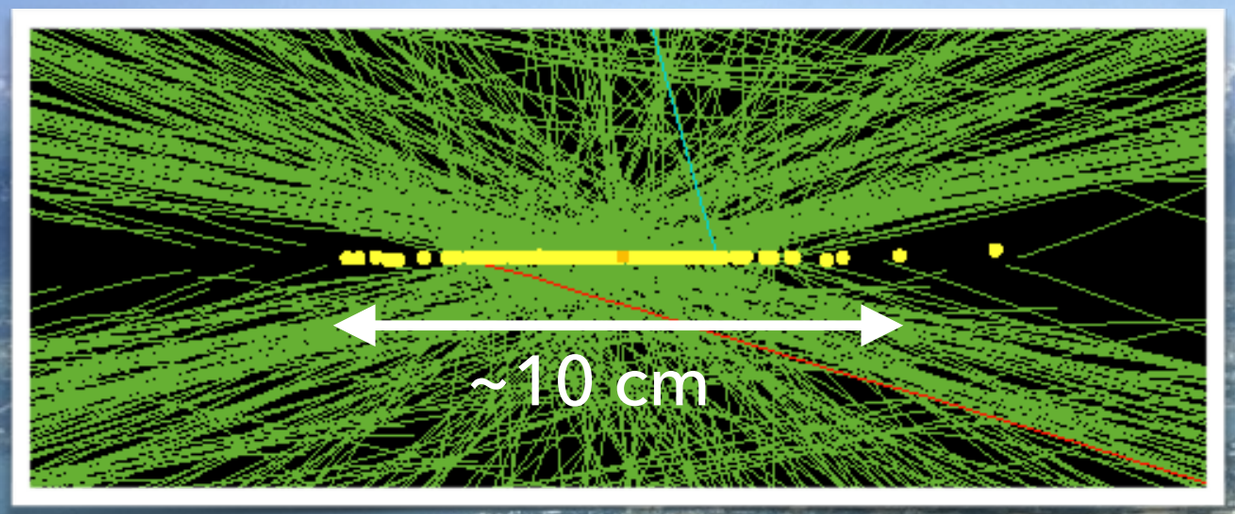

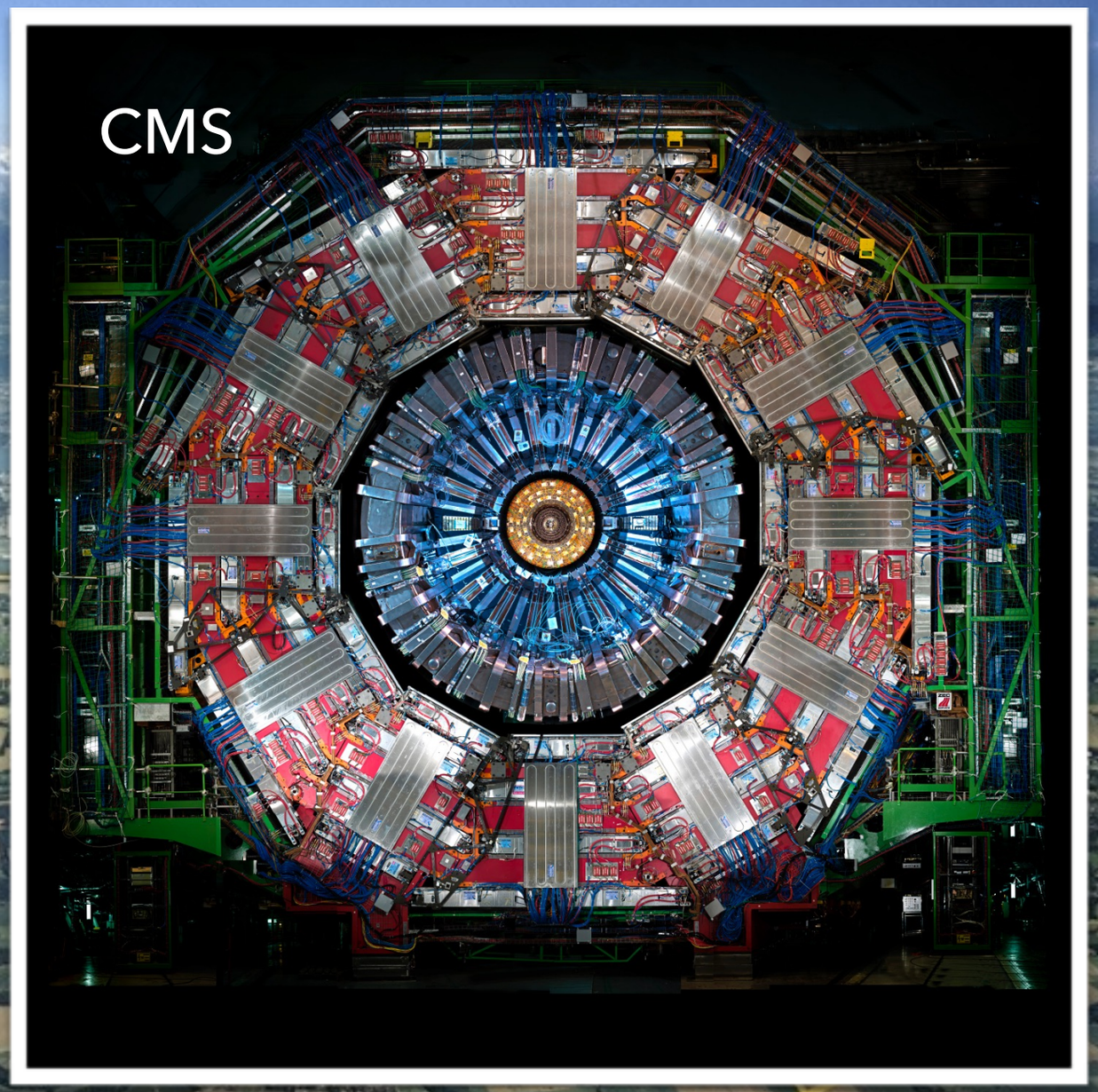

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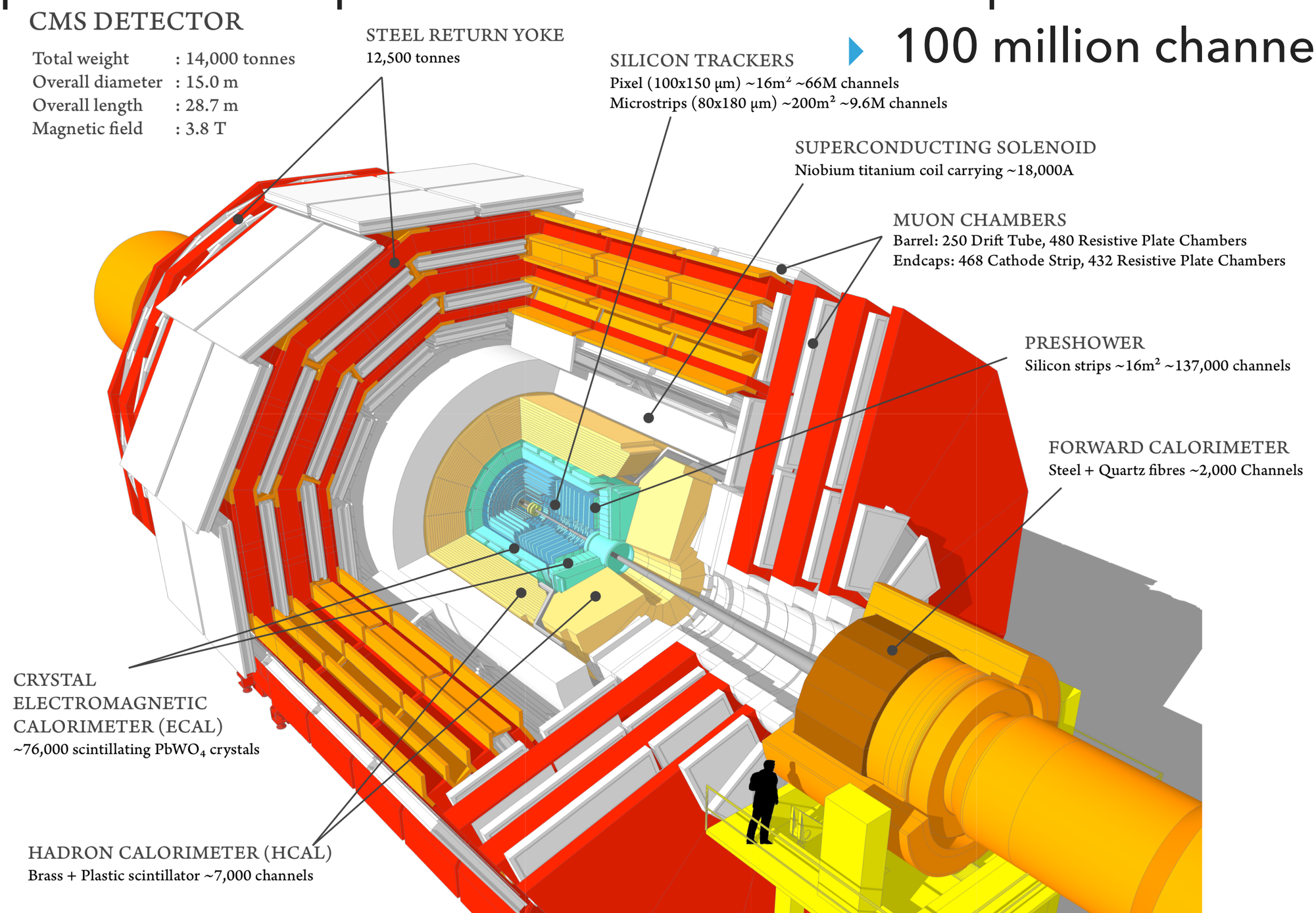
COMPACT MUON SOLENOID

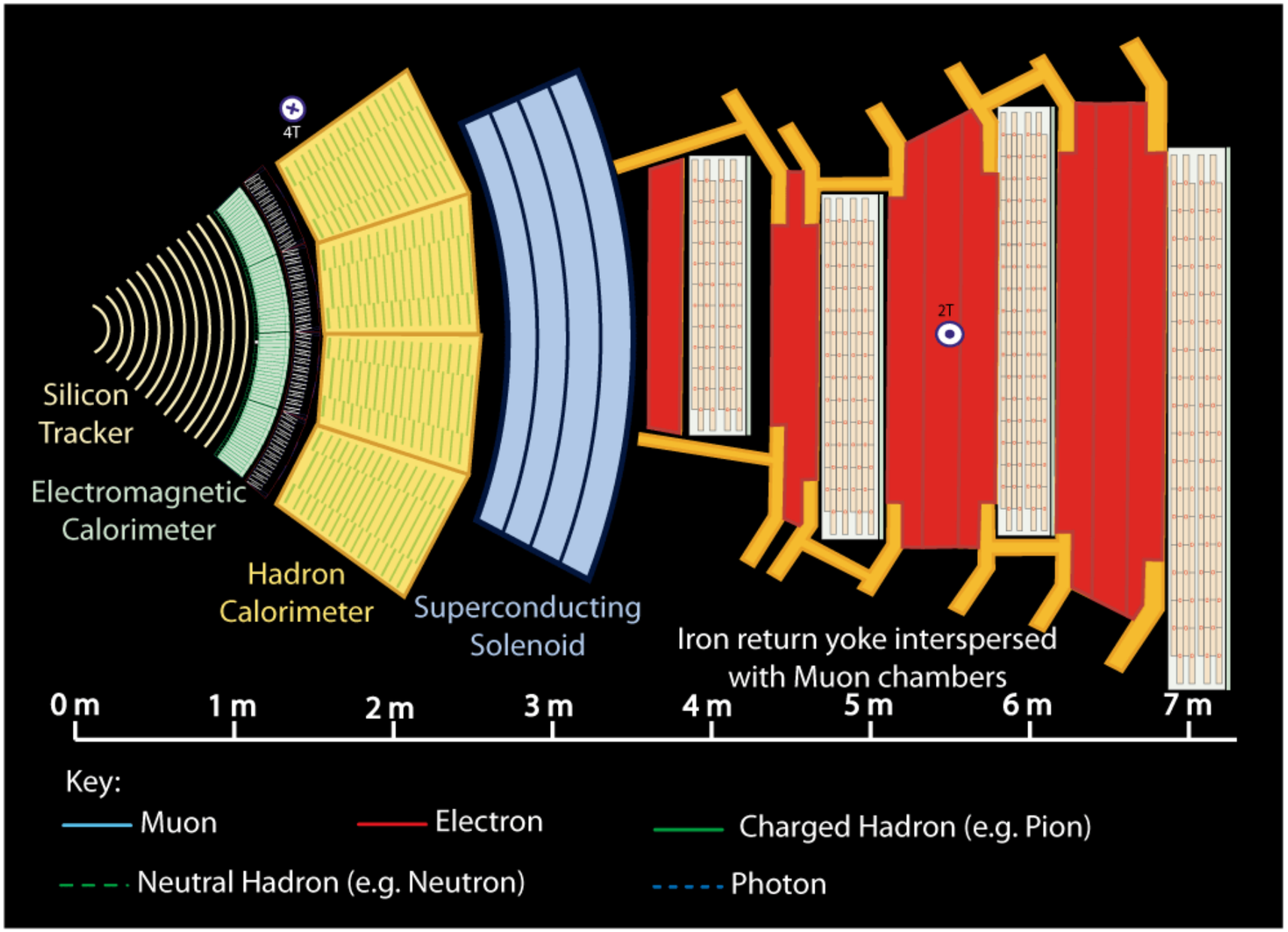
- Specialized components to measure different particles
  - 100 million channels



HOW CMS SEES QUARKS AND GLUONS

- Quarks and gluons interact via the strong force and are never seen in isolation

  → become *jets* of hadrons (bound states)



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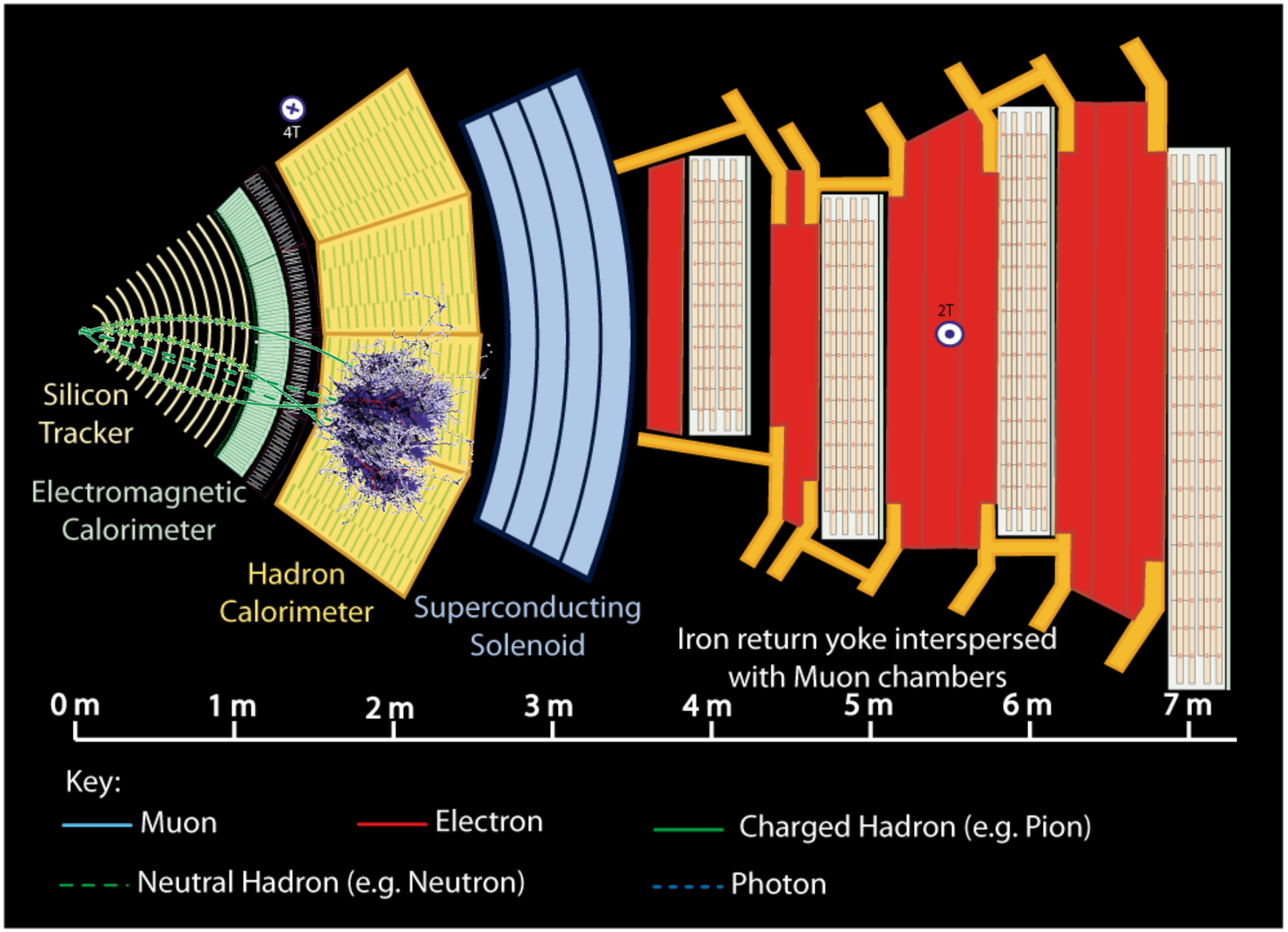

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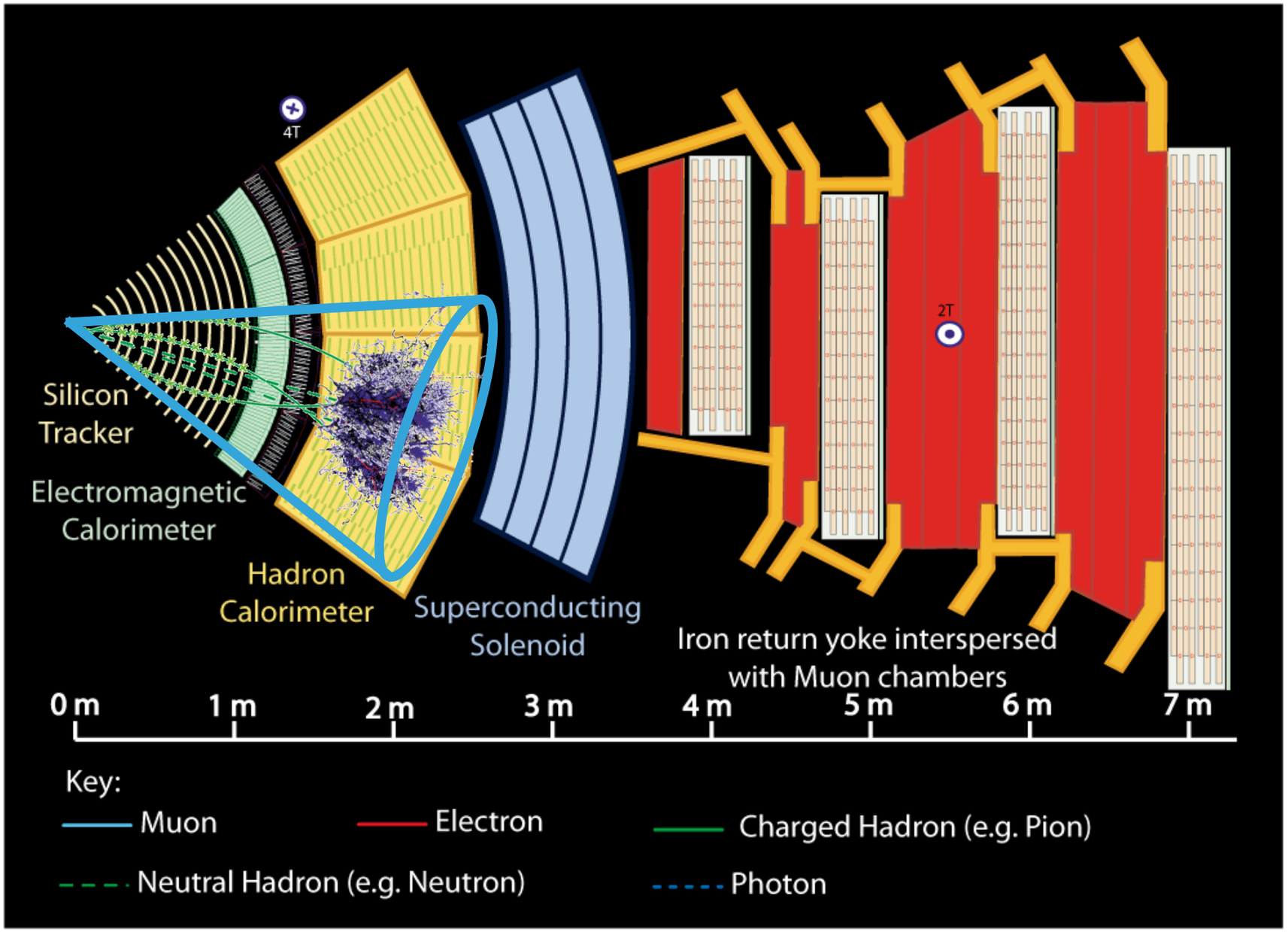
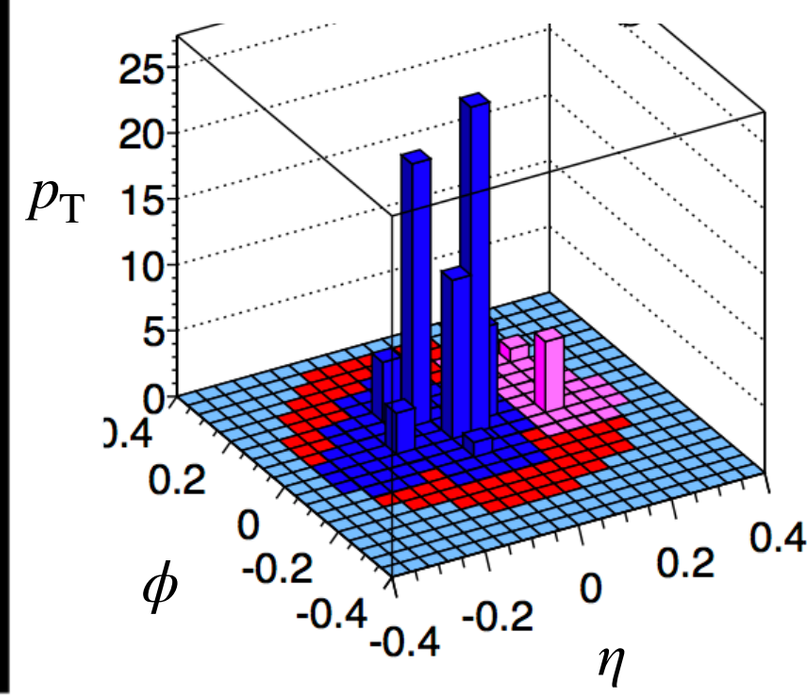
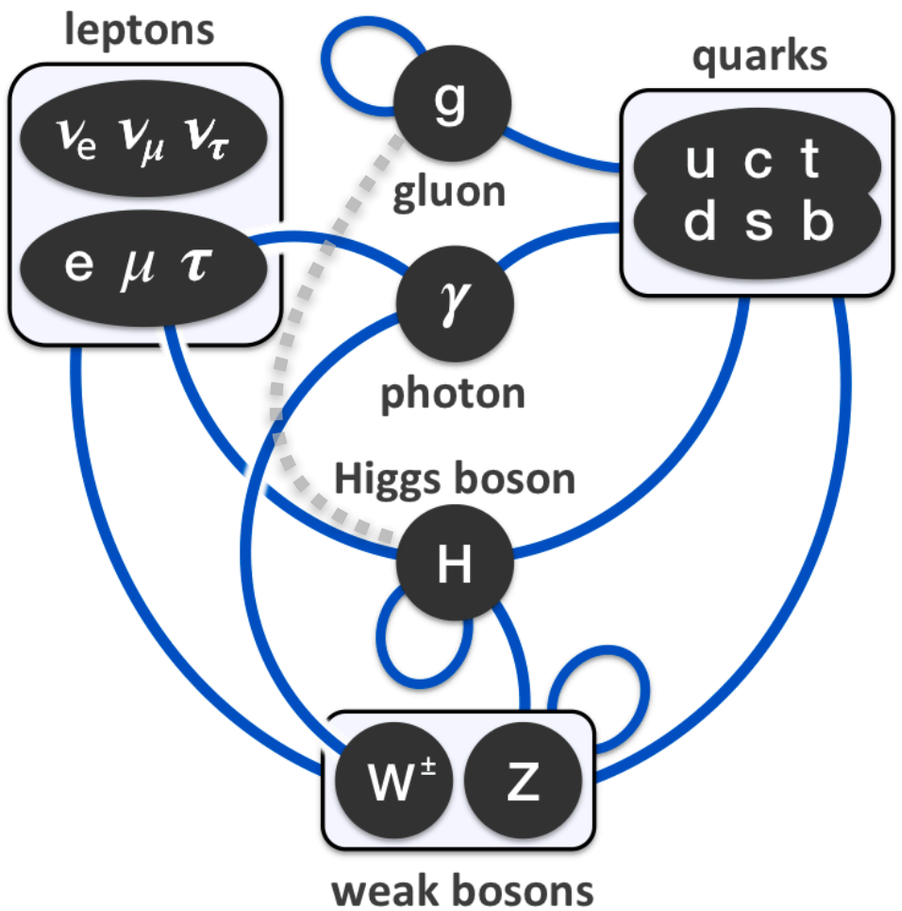
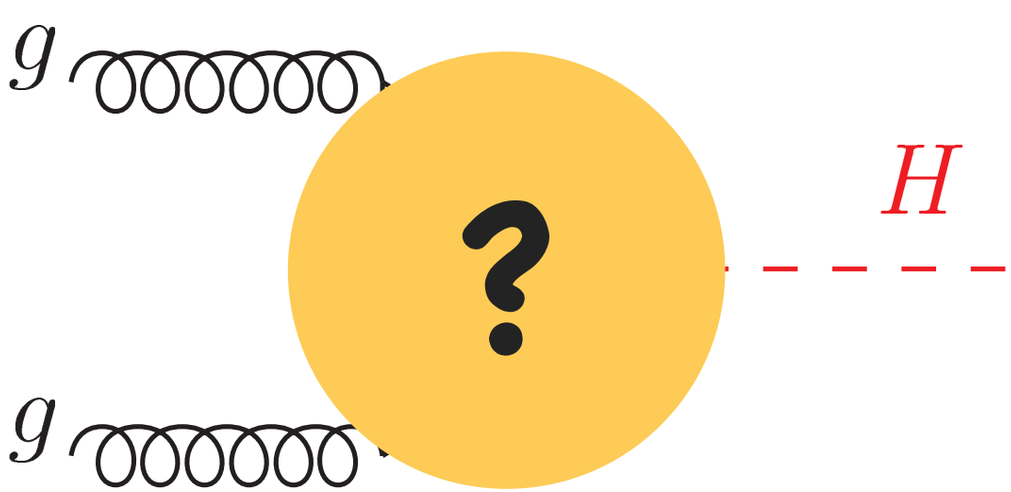


- Cluster the tracks and energy into a cone-shaped jet



HOW DO WE PRODUCE HIGGS BOSONS AT THE LHC?





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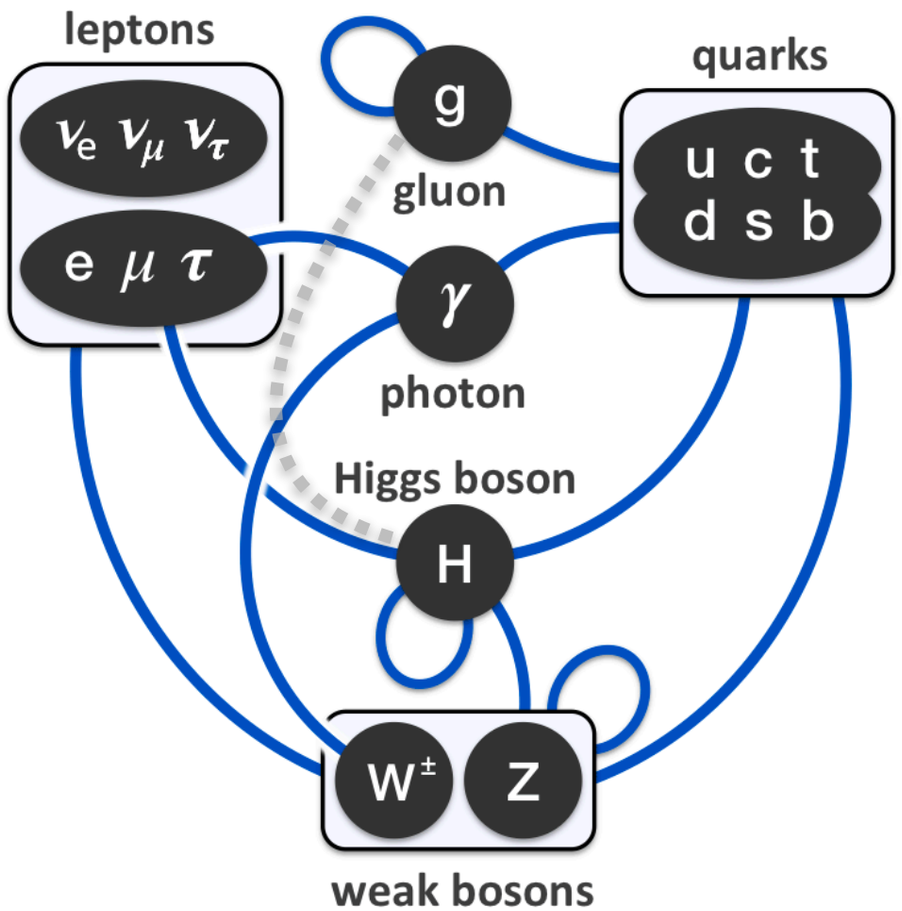

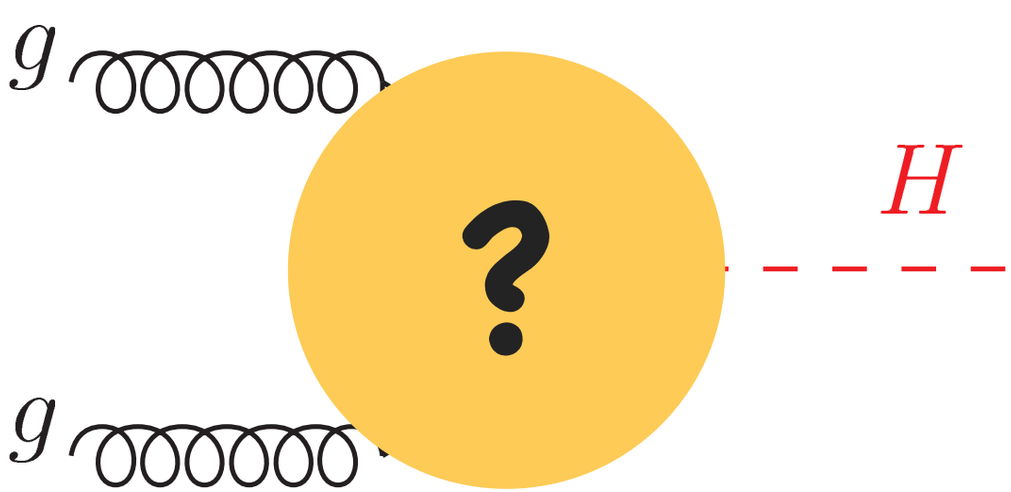

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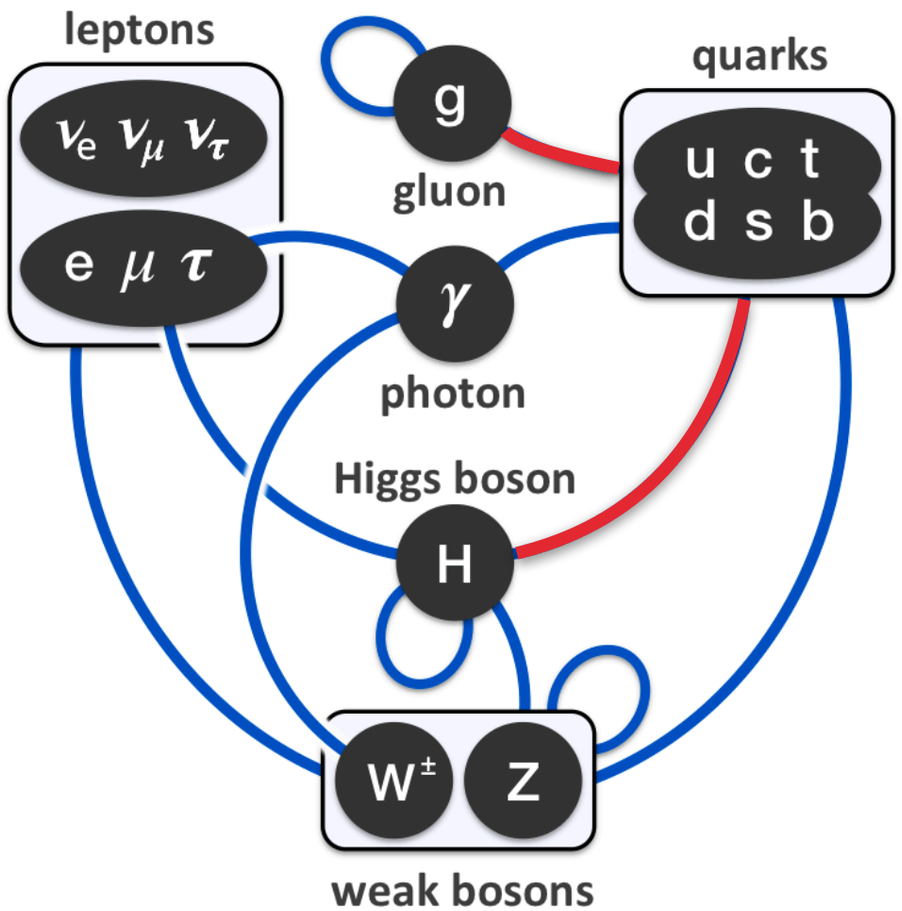

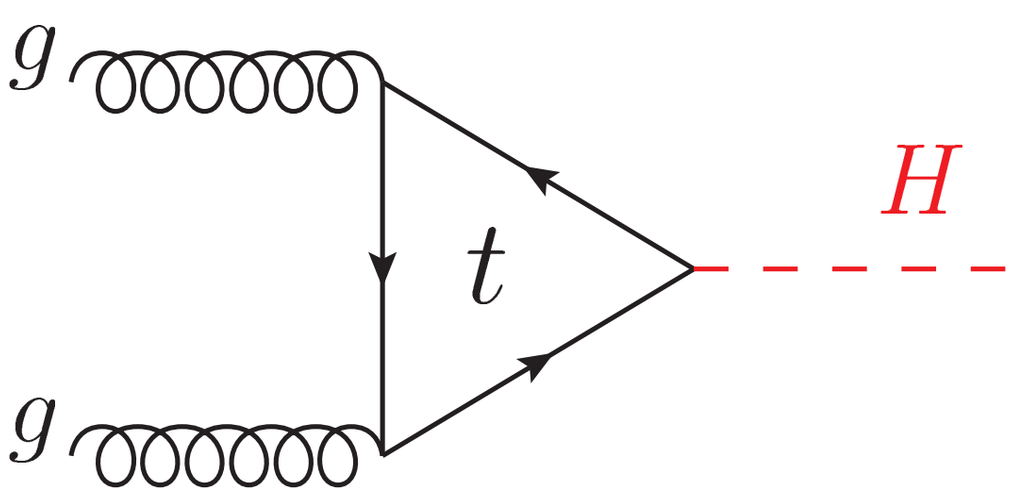

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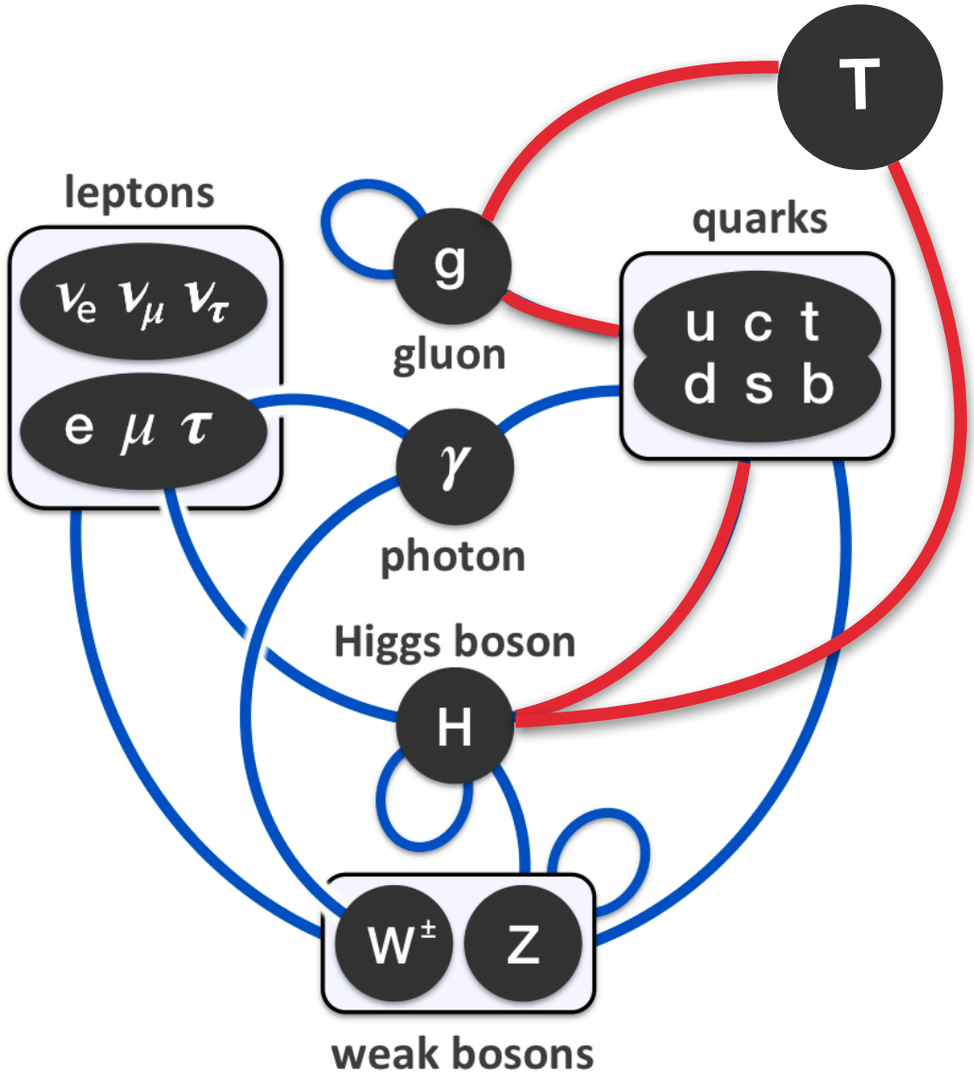

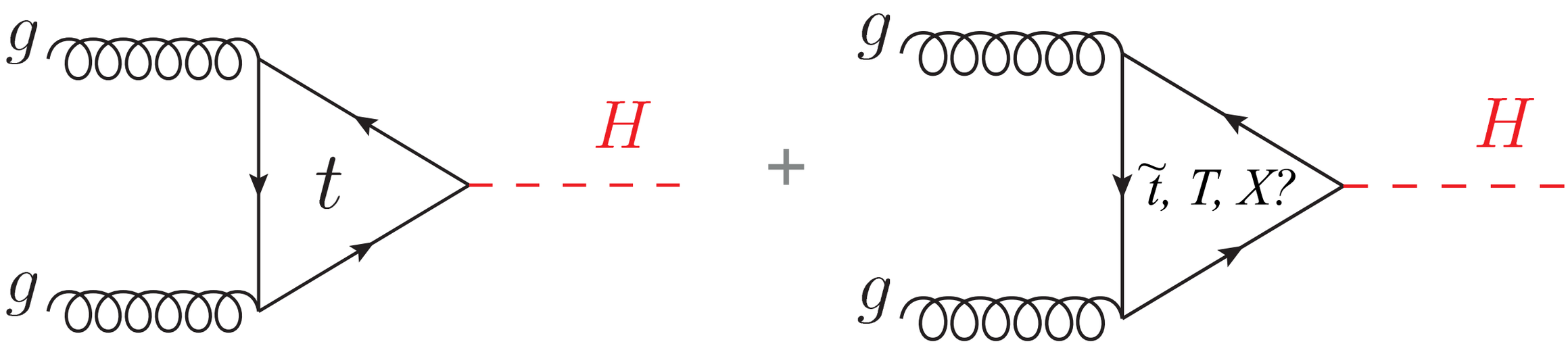

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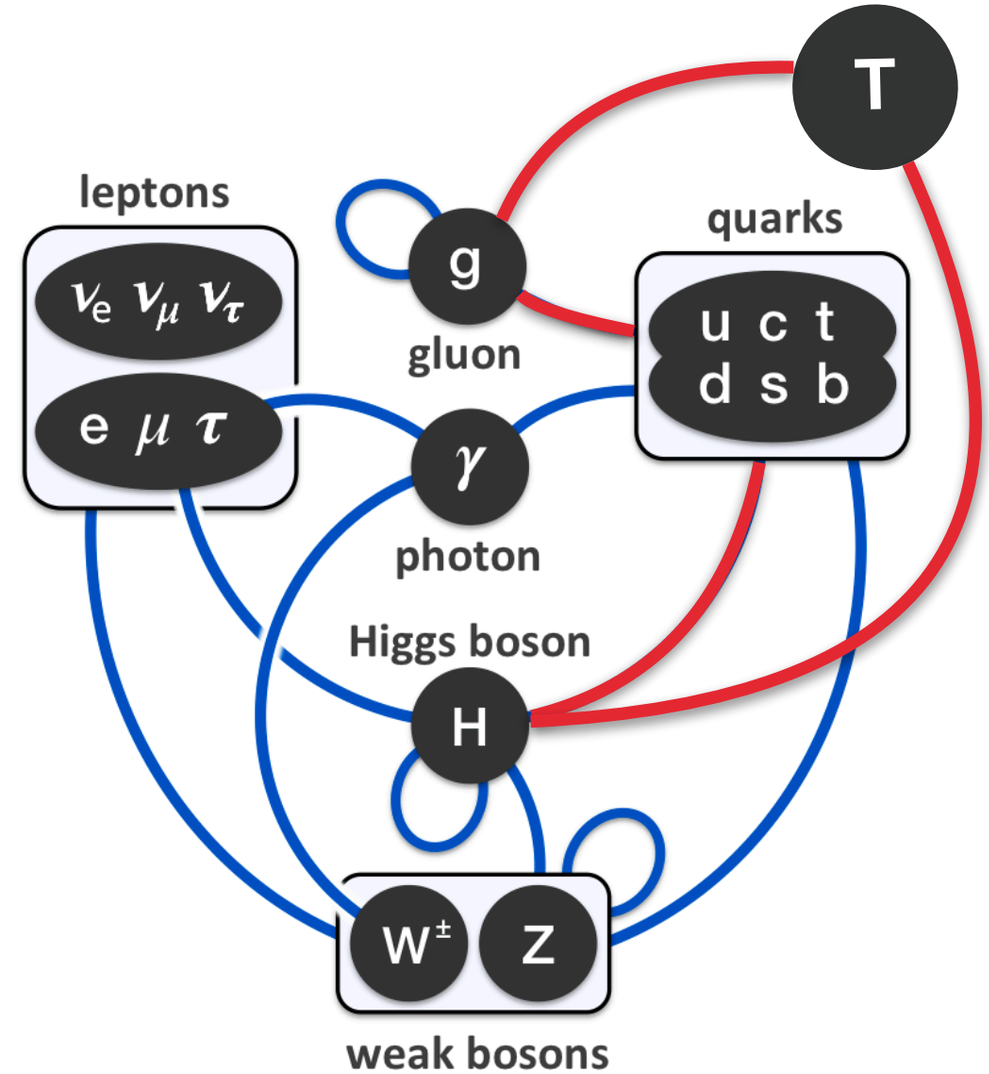
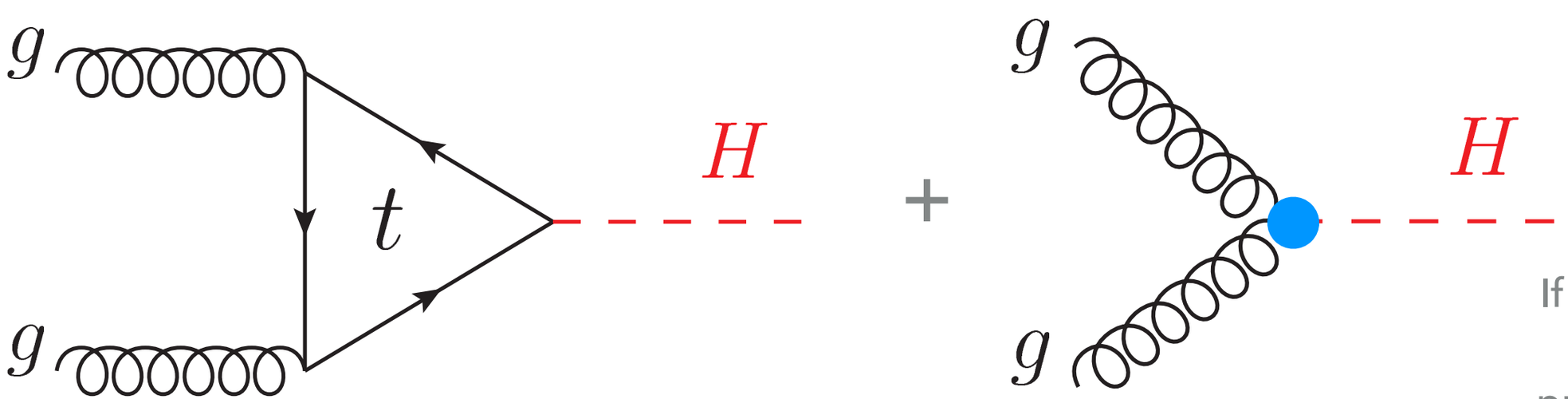




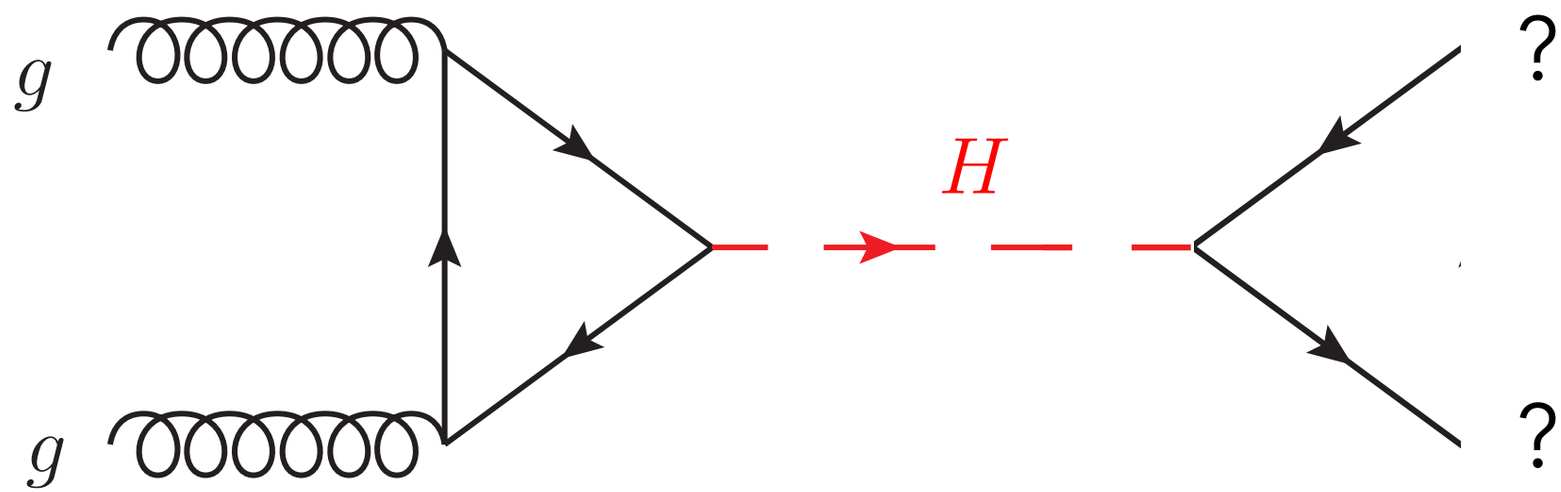
If the new particle is too heavy to be produced, this looks like a new interaction!

HOW DO WE DETECT HIGGS BOSONS?

produce

detect

(87%)



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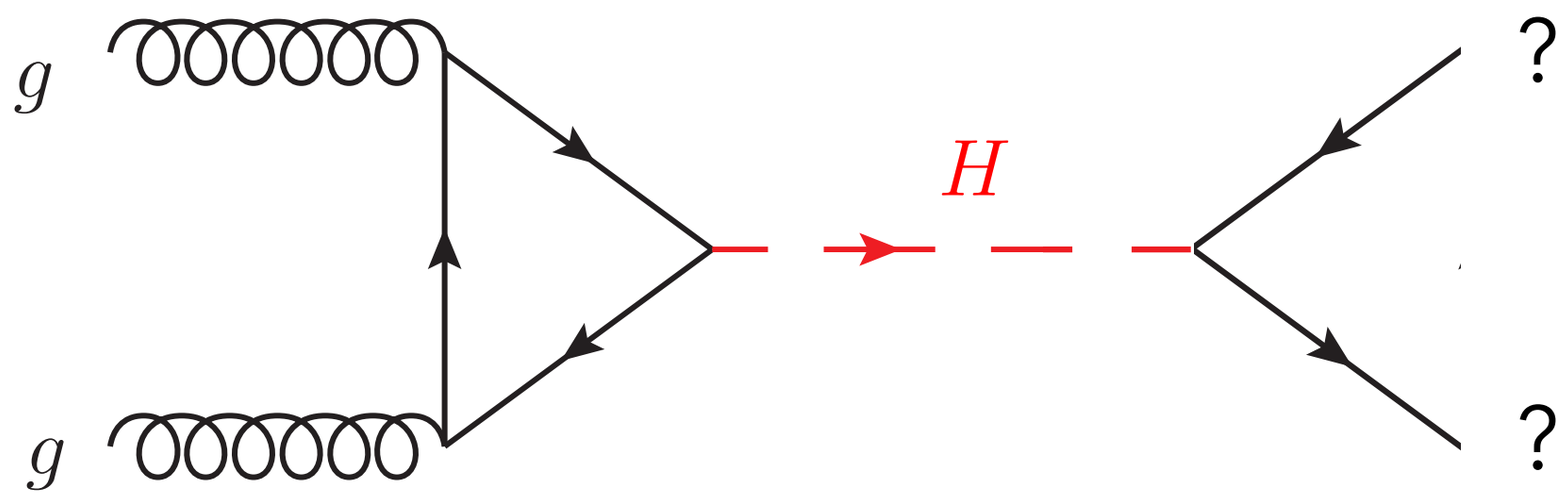

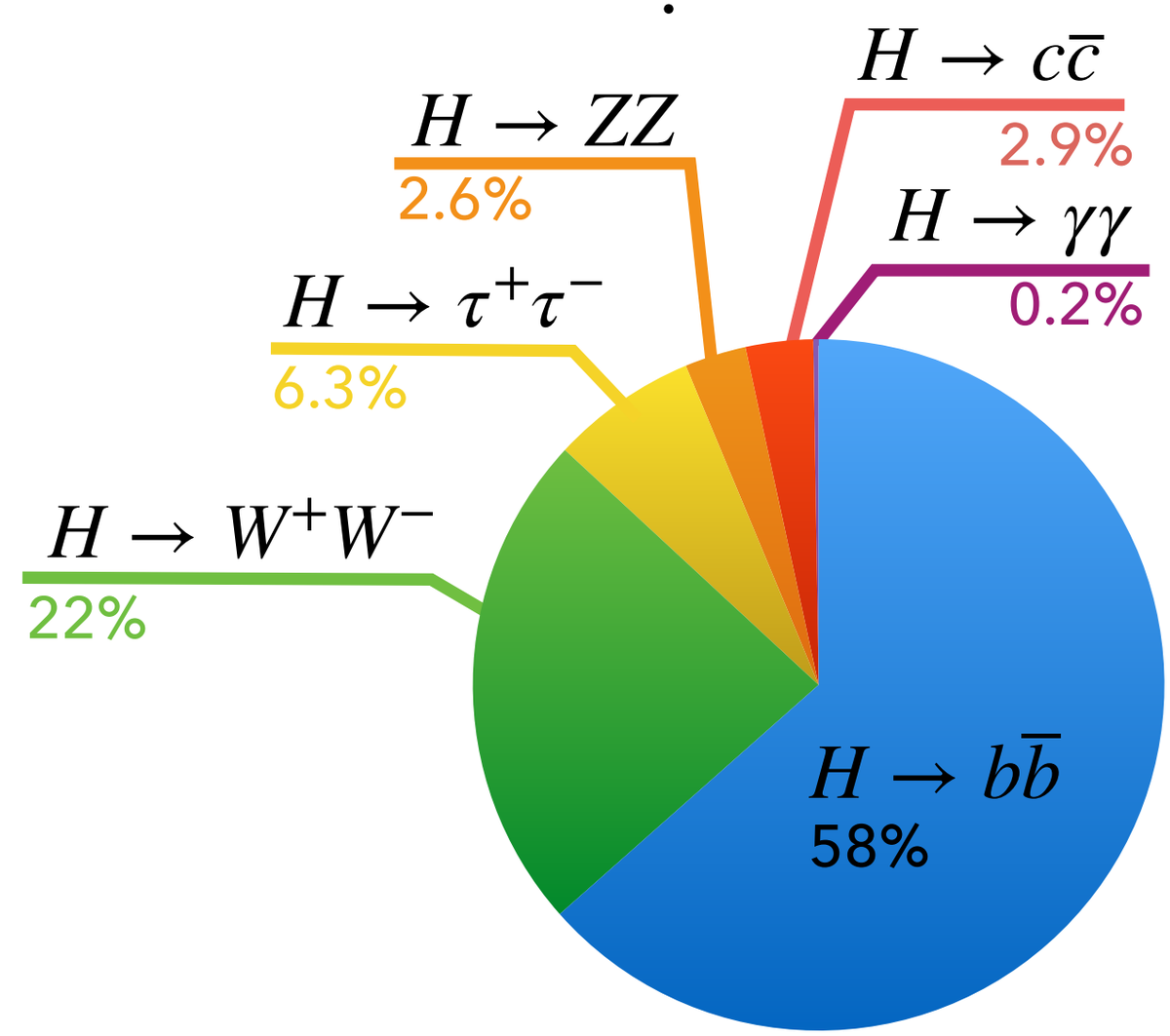

TODAY'S DATASET

- Luminosity (L) ~ number of collisions per unit time