TRIUMF

Opening the GeV Window at the LHC

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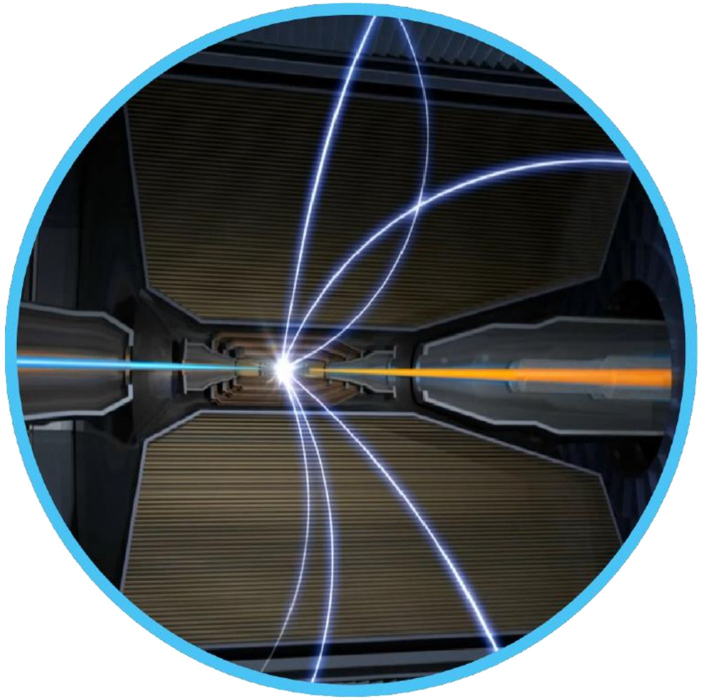
2026 Phenomenology Symposium



Based on: 2604.19864 | Collaborators: David McKeen and Maximilian Swiatlowski

GeV-Scale 1st Gen Quark Coupled BSM

- GeV-scale states that couple predominantly to first-generation quarks remains comparatively **unexplored** at high-energy colliders.

- They are **not difficult to produce** at the LHC!

$$\mathcal{L}_{\text{eff}} = \kappa_u \; S\bar{u}u \qquad \text{for} \quad J^{PC} = 0^{++}$$
$$\mathcal{L}_{\text{eff}} = \kappa_u \; A\bar{u}\gamma^5 u \qquad \text{for} \quad J^{PC} = 0^{-+}$$

- The challenge lies in identifying their signature!
  - It is often assumed that they are indistinguishable from the **overwhelming QCD background**.

maybe connected to Dark Matter 1712.10022, 1812.05103,2107.0805

maybe related do QCD axion 2601.02465

- The goal of this talk is to show that **this is not the case**, and **both** the **signal** and **background** determinations are **under control**.

QCD Resonances?

- GeV-Scale particles that decay hadronically **mimics** QCD resonances.
- Several resonances have the **same** characteristics:

$$0^{++}$$

$$f_0(980), f_0(1370), f_0(1500), f_0(1710), f_0(1770), f_0(2020), f_0(2100), f_0(2200), f_0(2320), f_0(2470)$$

$$0^{-+}$$

$$\eta(1285), \eta(1405), \eta(1475), \eta(1760), X(1835), \eta(2225), \eta(2370)$$

- Meson decays **cannot differentiate** a fundamental scalar that couples to quarks from resonances without a robust prediction for the background. can look for new resonances
- The LHC can: A fundamental particle that **couples directly** to quarks is **perturbatively produced!** after production, it decays to a quark pair which showers and hadronizes.

GeV-Scale Particles at the LHC

- Because the new scalar is a **color-singlet** with GeV-scale mass they decay to few hadrons.

- Their signature is **anomalous low multiplicity jet** at the LHC.

- For the signature we focus on $p\,p\ \rightarrow j +\ \gamma$ (QCD jet), where the **signal** is $p\,p\ \rightarrow \varphi +\ \gamma$.

Reconstructed inside the detector

Veto additional jets, leptons, or photons

Trigger requirements of $p_T > 150\text{GeV}$

- Focus on **three** jet properties:
  - Track Multiplicity, Track-Jet Mass and Jet Charge

robust against pileup

GeV-Scale Particles at the LHC

- Because the new scalar is a **color-singlet** with GeV-scale mass they decay to few hadrons.

- Their signature is **anomalous low**

How to reliably estimate the signal and background?

- For ... focus on $p\,p \rightarrow j + \gamma$ (QCD jet),
  where the **signal** is $p\,p \rightarrow \varphi + \gamma$.

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Signal Estimation

simulation with underlying events but no pileup

Signal Estimation

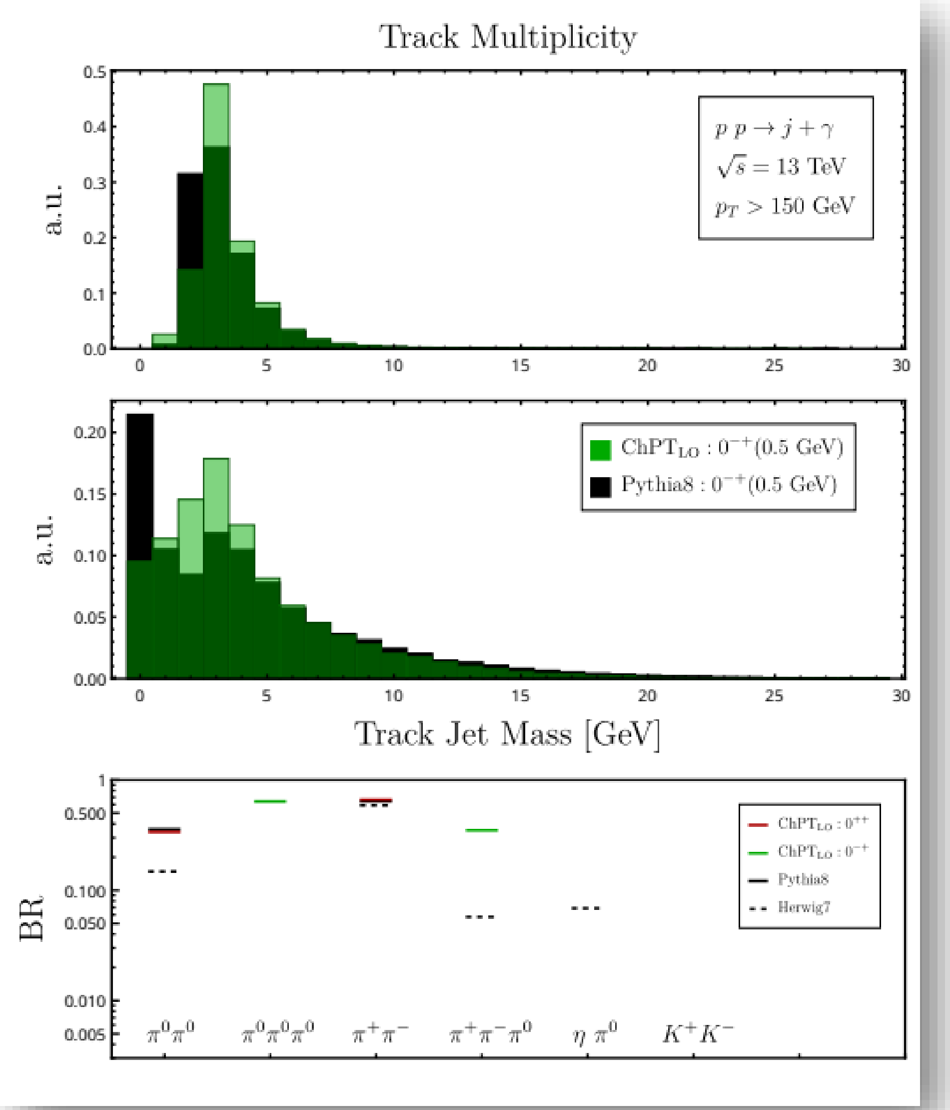
- **Dominant** theoretical uncertainty is the hadronic decay.

$m_\phi < 1.5$ GeV
Chiral Perturbation Theory

Basically, only Pions and fixed relations between neutral and charged decays

$1.5\text{ GeV} < m_\phi < 20\text{ GeV}$
Showering and Hadronization

Pythia and **Herwig** do not propagate the parity information



simulation with underlying events but no pileup

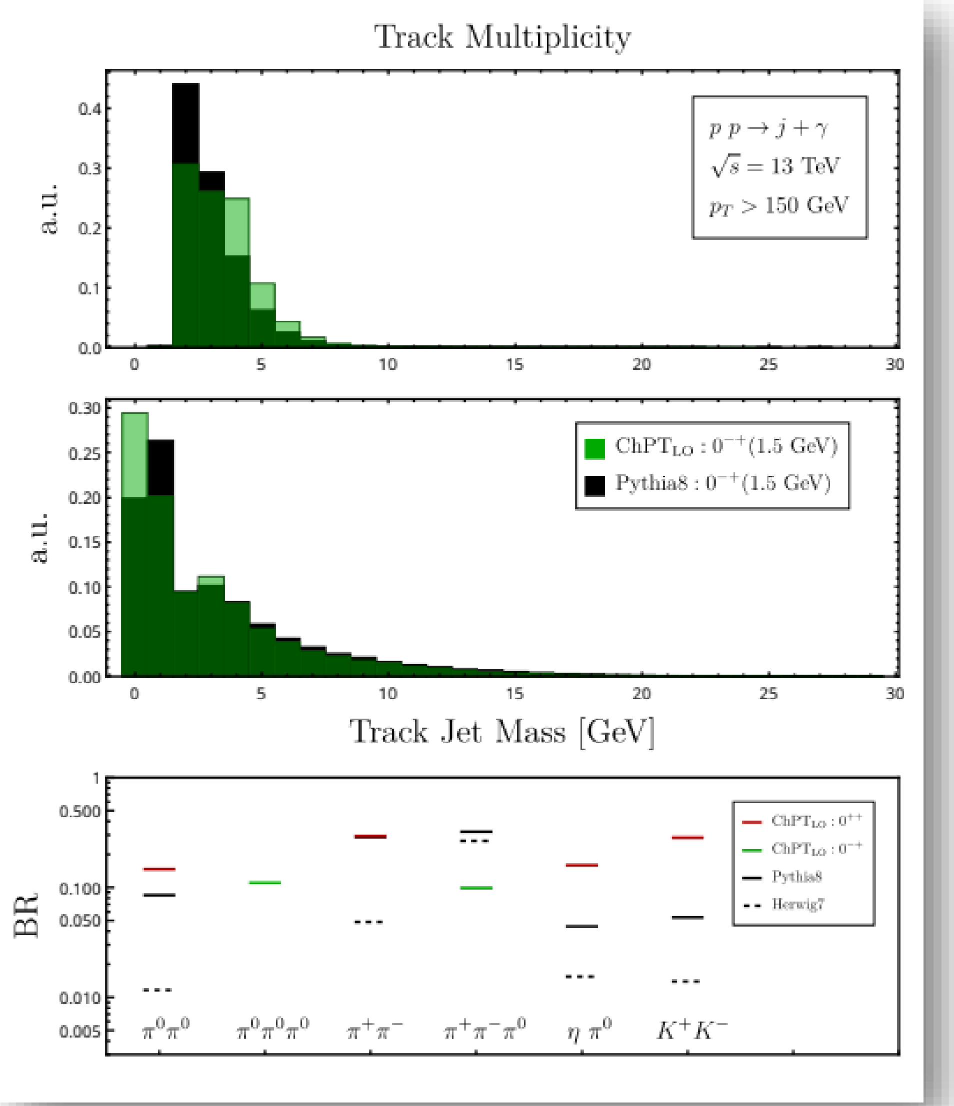
Signal Estimation

- Inclusive predictions are **robust**; they are mostly a consequence of the limited phase space.
- For our analysis we use the ChPT prediction below 1.5 GeV and use **Pythia8/Herwig7** above.
- For the basic cuts applied the cross-section is mostly independent of mass and is estimated to be:

$$\sigma_{sig} = \kappa_u^2 \, (2 \text{ pb})$$

Tree-level production makes the BSM cross-section huge!

- We expect many BSM events with low track multiplicity and mass, but **how many of those events exist in QCD?**



Background Estimation

Background Uncertainties

- The dominant background is

$$p\,p \;\rightarrow j + \gamma$$

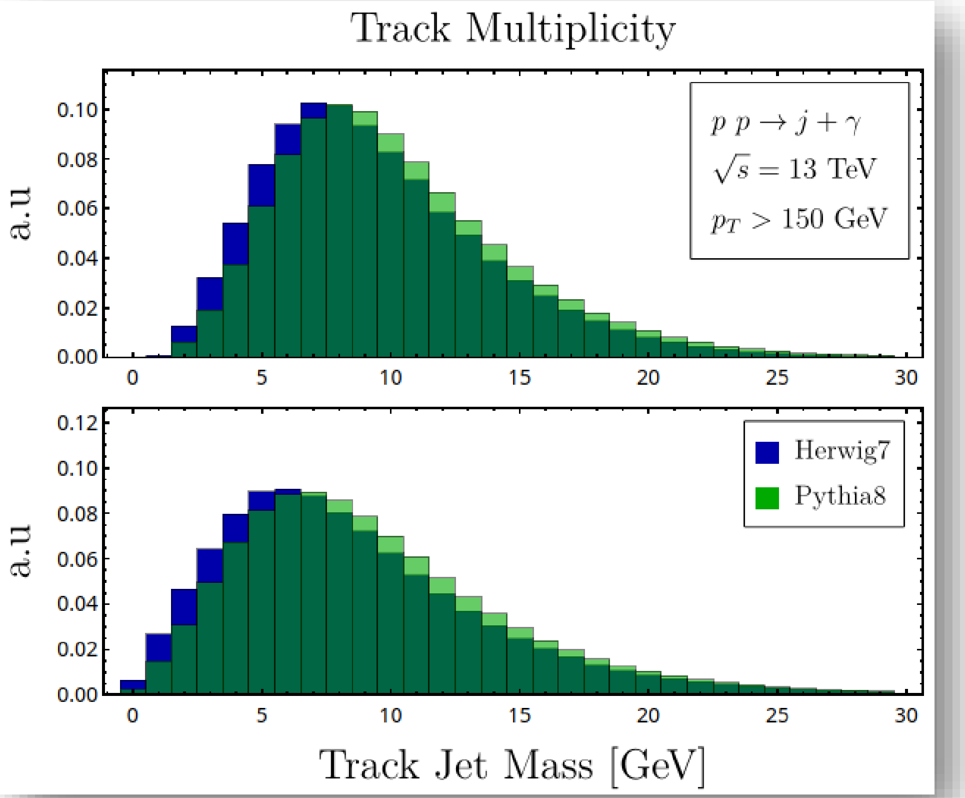
can be systematically improved at NLO

- The parton-level process is simulated at LO.

- The main uncertainties is the showering and hadronization. We use two different approaches **Pythia** and **Herwig**.

- The analysis is sensitive to how many anomalous low track jets and mass exist in QCD: **The lower tail of the QCD distributions**

tools are not optimized for this region.



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Can we do better than simulation for the background?

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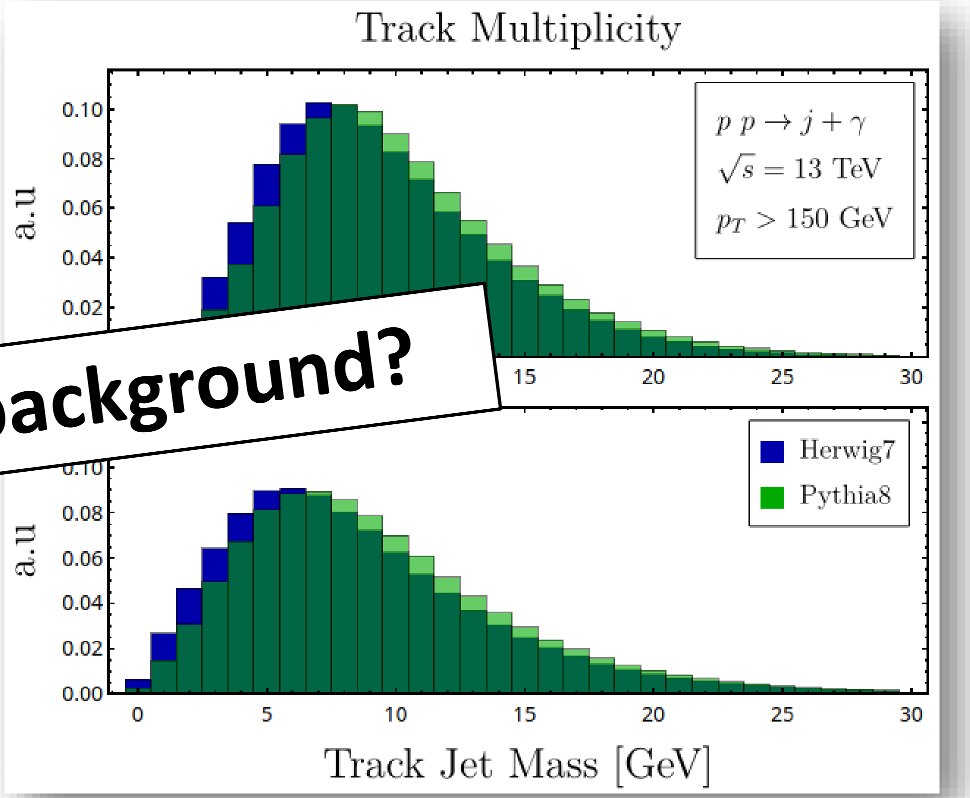


Data-driven Background Extraction

- While simulation of the background is **theoretically challenging**, it is possible to construct **data-driven** templates of jets from other QCD processes.

- This is not new and is used for **quark and gluon template extractions** in the LHC.

- In our case it is necessary to have a QCD process which has **no BSM signal contamination**.

Performance and calibration of quark/gluon-jet taggers using 140 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

The identification of jets originating from quarks and gluons, often referred to as quark/gluon tagging, plays an important role in various analyses performed at the Large Hadron Collider, as Standard Model measurements and searches for new particles decaying to quarks often rely on suppressing a large gluon-induced background. This paper describes the measurement of the efficiencies of quark/gluon taggers developed within the ATLAS Collaboration, using $\sqrt{s}$ = 13 TeV proton–proton collision data with an integrated luminosity of 140 fb^{-1} collected by the ATLAS experiment. Two taggers with high performances in rejecting jets from gluon over jets from quarks are studied: one tagger is based on requirements on the number of inner-detector tracks associated with the jet, and the other combines several jet substructure observables using a boosted decision tree. A method is established to determine the quark/gluon fraction in data, by using quark/gluon-enriched subsamples defined by the jet pseudorapidity. Differences in tagging efficiency between data and simulation are provided for jets with transverse momentum between 500 GeV and 2 TeV and for multiple tagger working points.

Data-driven Background Extraction

- A **signal free extraction** can be done using $p\,p \;\to j\,j$

- QCD background has high multiplicity of processes,
  while the signal ($p\,p \;\to j\,\phi$ and $p\,p \;\to \phi\phi$) not so much

- If we split the data between two central jets and two forward jets, they have different parton contents but also **no signal contamination**:

$$\sigma_{QCD}^{central} = 8228 \text{ pb} \qquad \sigma_{QCD}^{forward} = 1651 \text{ pb}$$

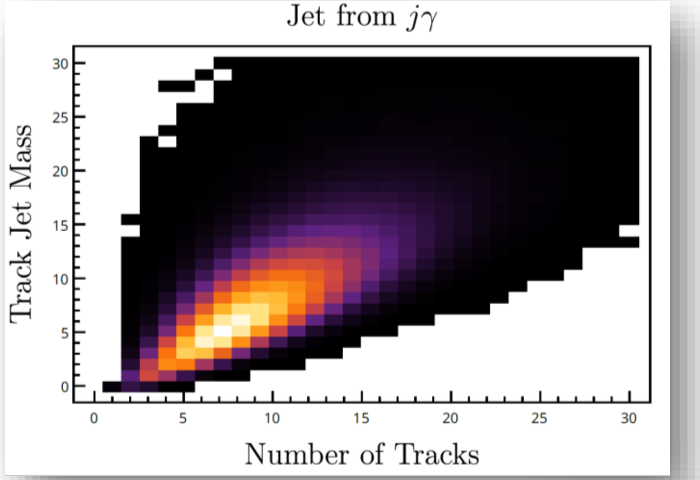
$$\sigma_{\phi(\kappa_u=1)}^{central} = 7 \text{ fb} \qquad \sigma_{\phi(\kappa_u=1)}^{forward} = 2 \text{ fb}$$

Data-driven Background Extraction

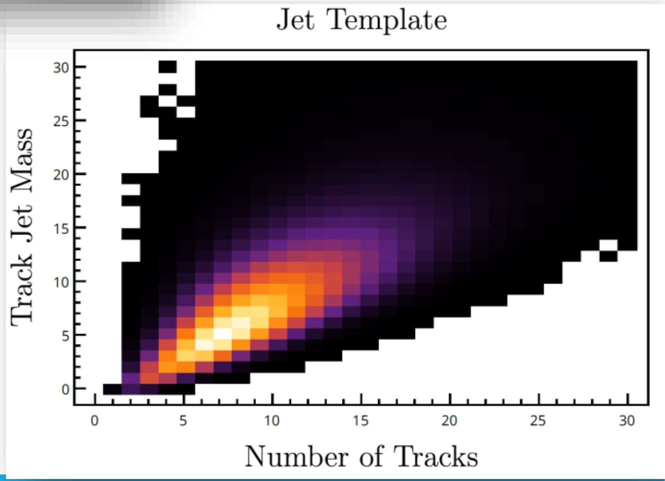
- In a real search the **theoretical background uncertainties can be bypassed**.

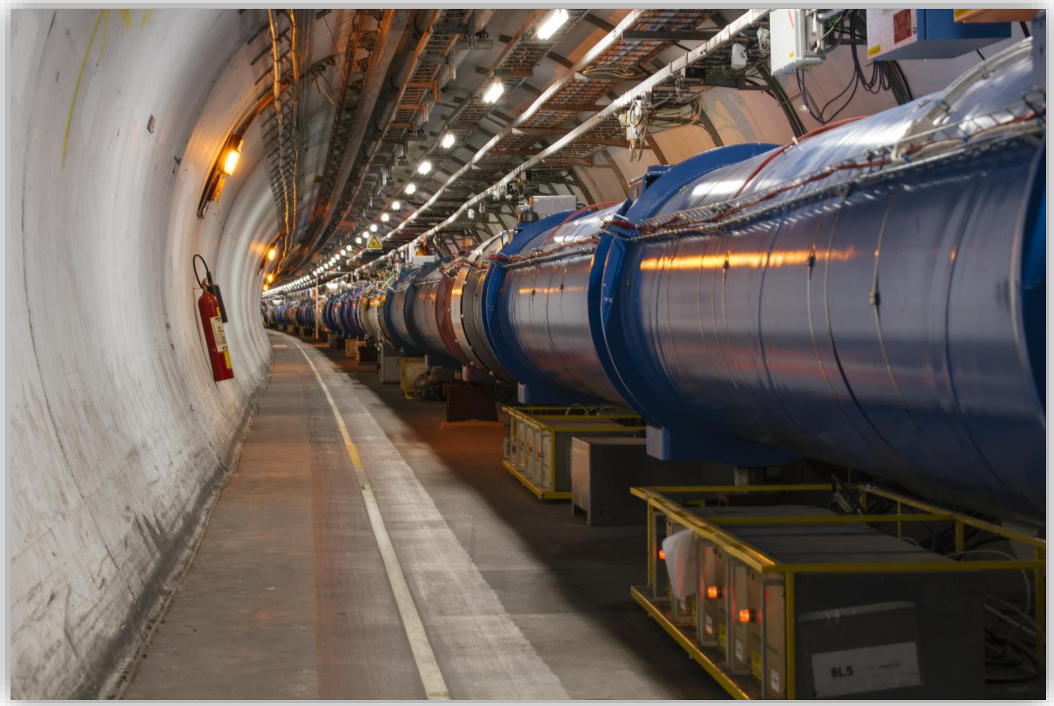
- In our estimation, we include an **overall 50% background uncertainty** to account for possible deviations from simulation.

- Differences between **Pythia** and **Herwig** are smaller than this uncertainty and both simulations provide **similar** experimental reaches.



Verified in simulation-to-simulation extraction





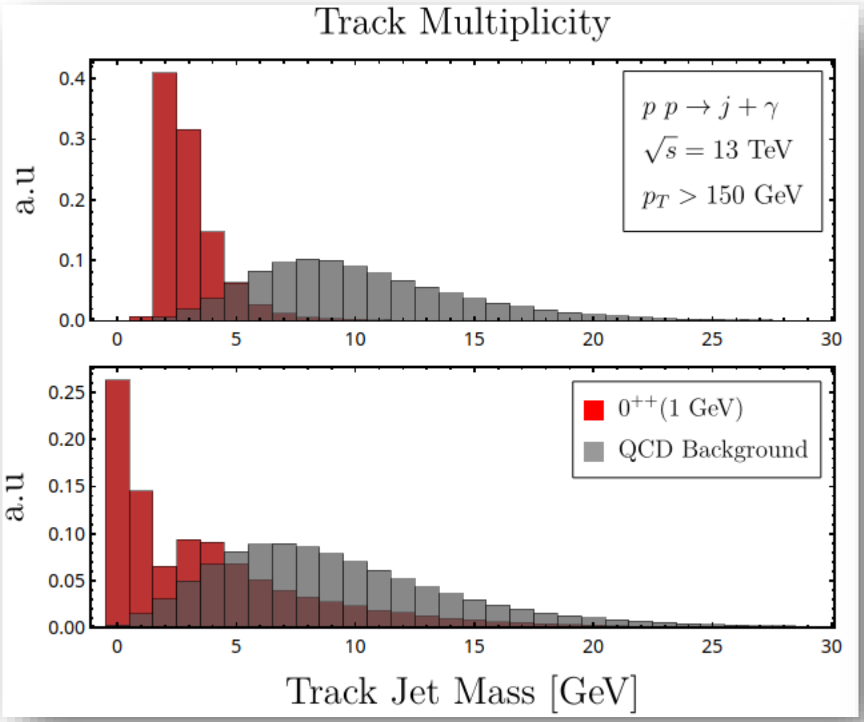
LHC Search

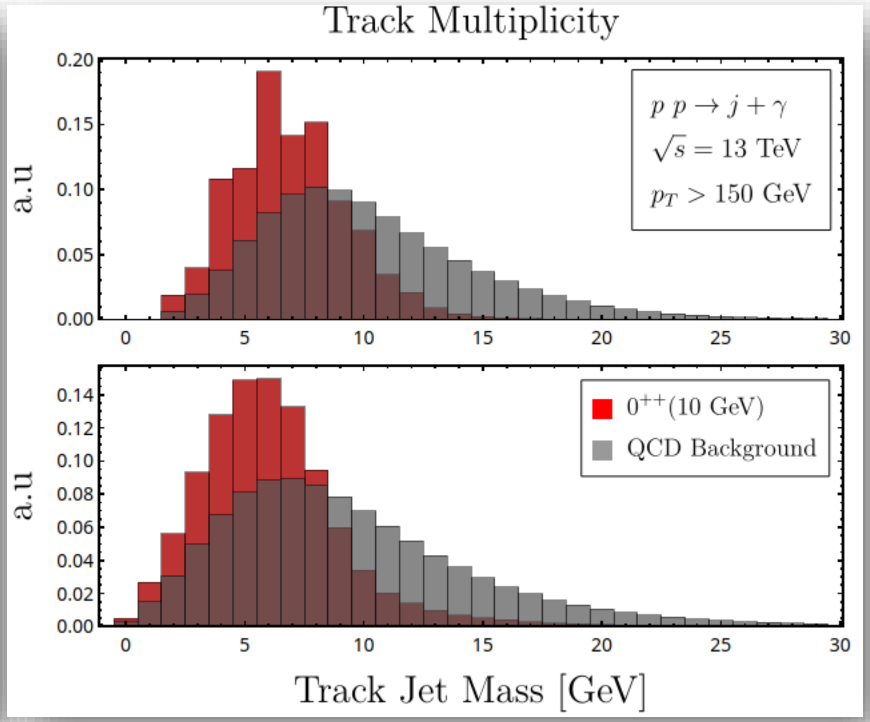
LHC search

We stop the search at 20 GeV scalar mass. Above it is necessary to include other backgrounds (top and EW)

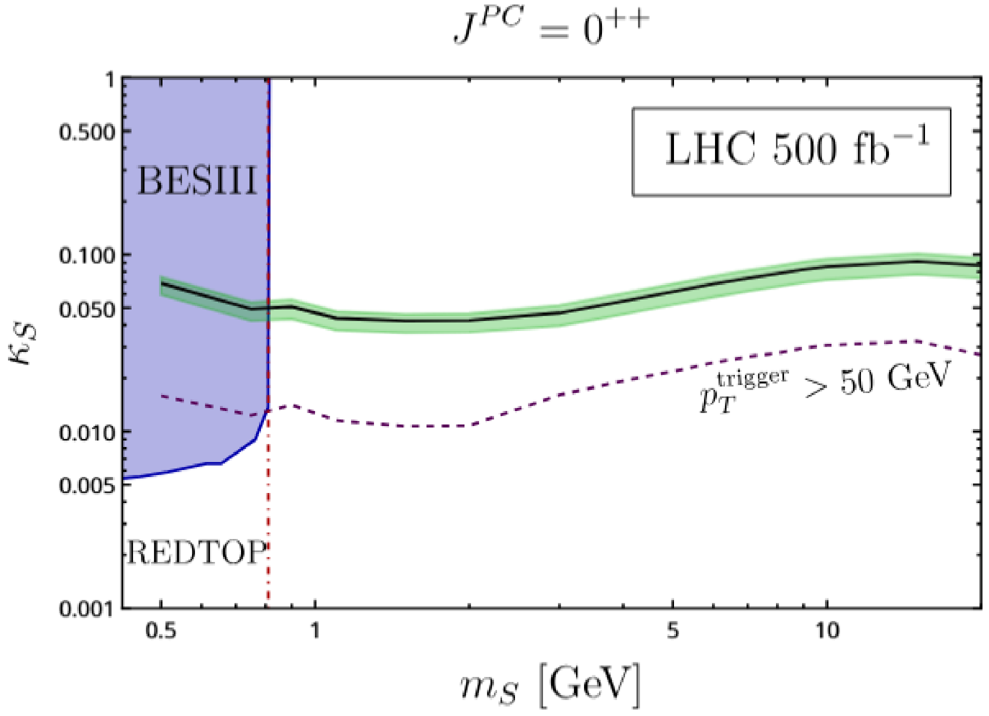
- The expectation is the presence of **more** events at **lower track multiplicity, low mass** and with **zero jet charge**.

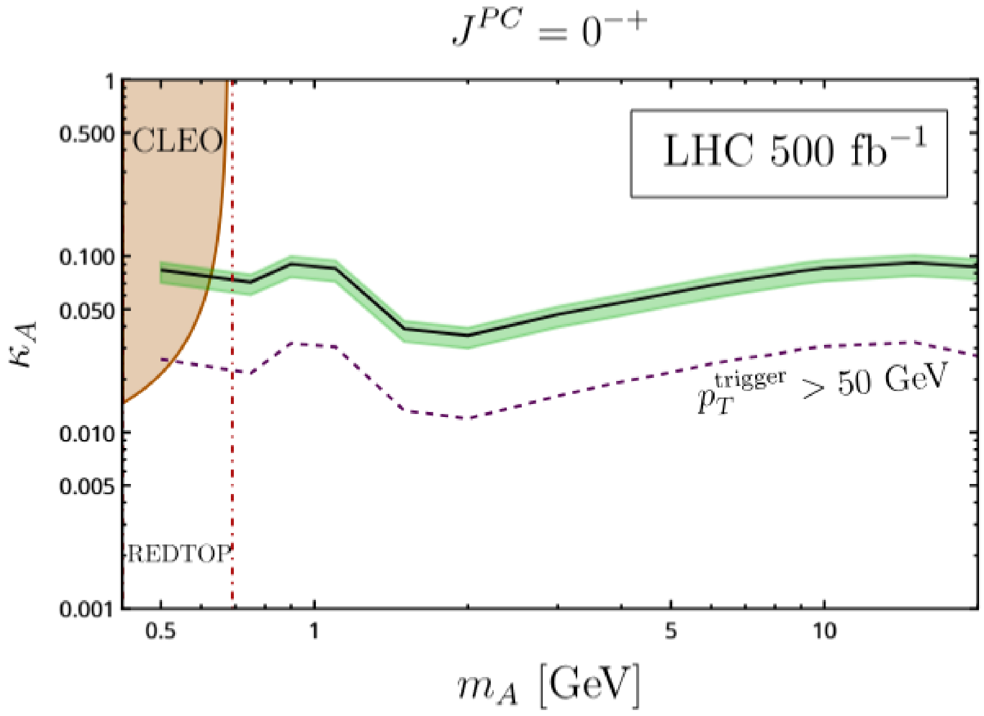
- Besides the basic cuts, we enforce zero jet charge and make a profile likelihood ratio constructed from **2d Poisson log-likelihood** floating the background by 50%



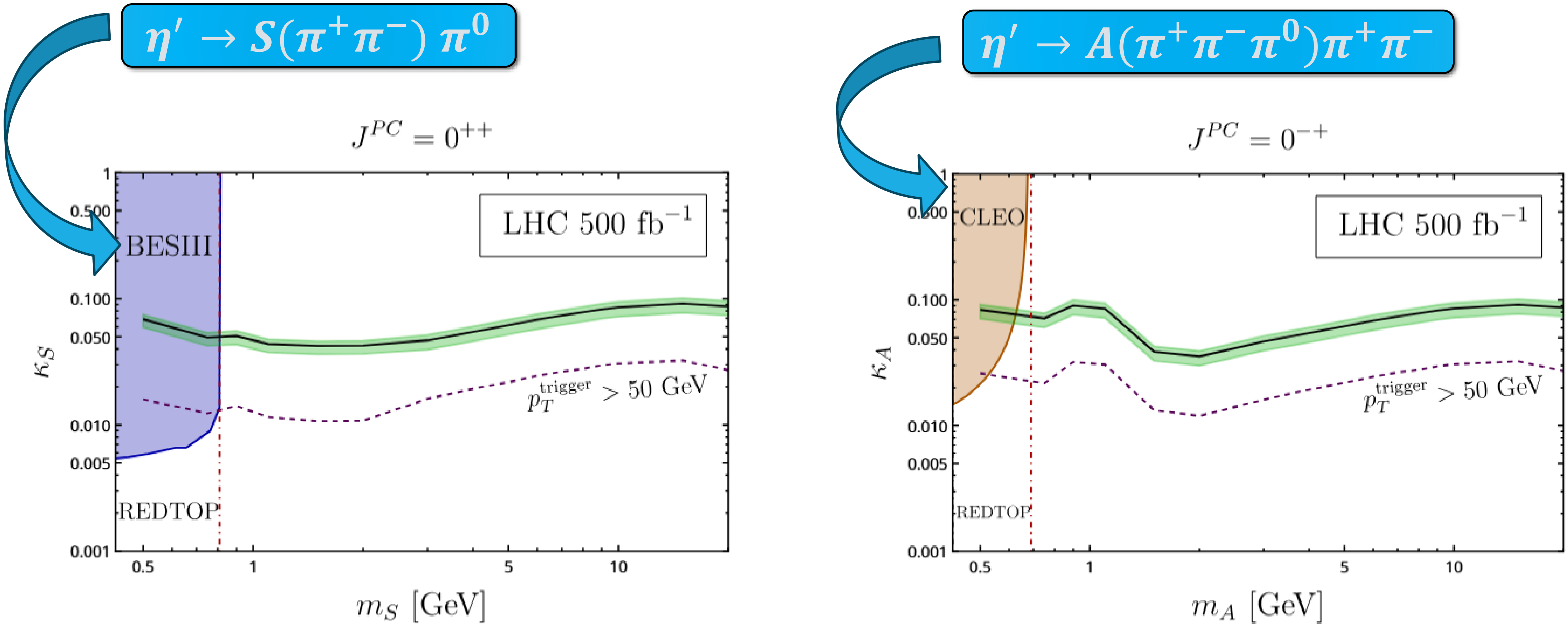


Experimental Reach



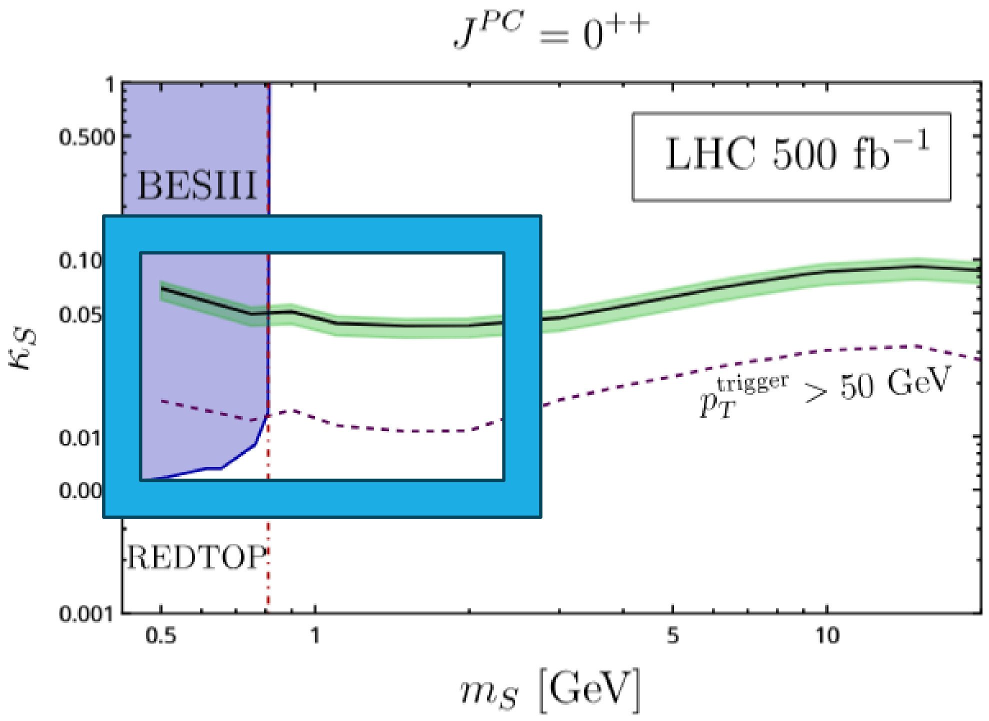


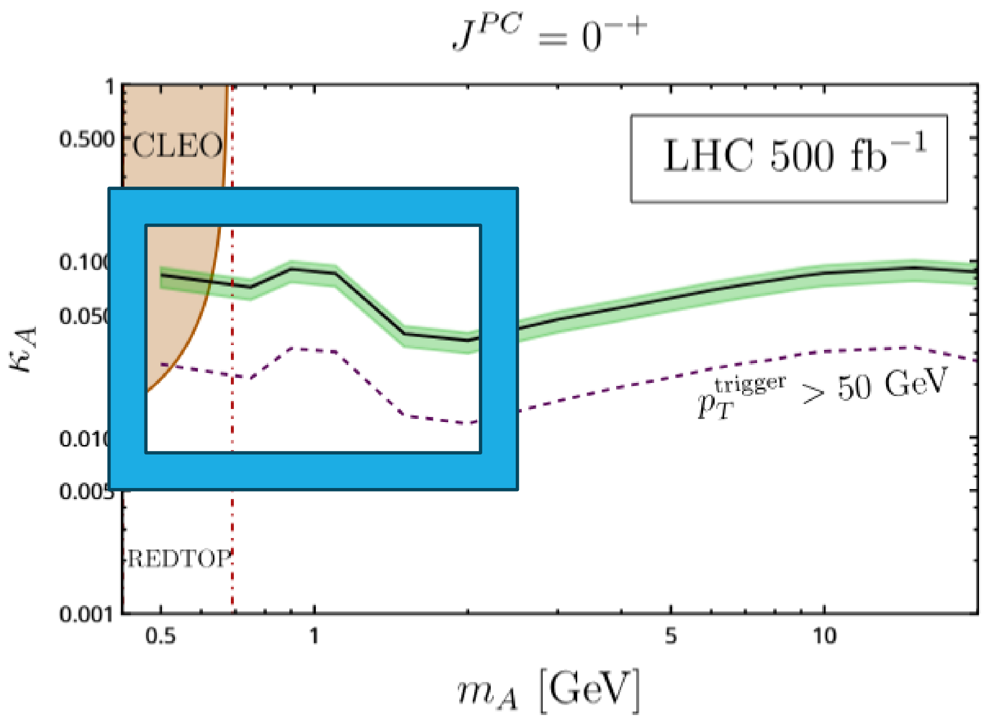
Experimental Reach



Experimental Reach

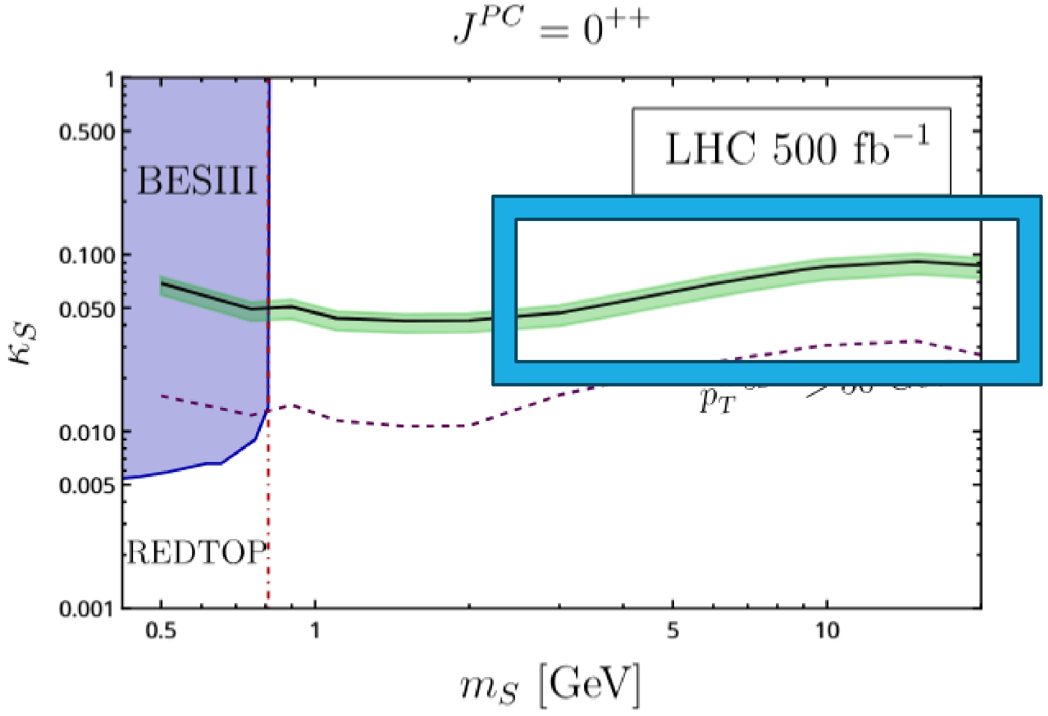
Only difference is the branching ratio to 2 vs 0 tracks from ChPT

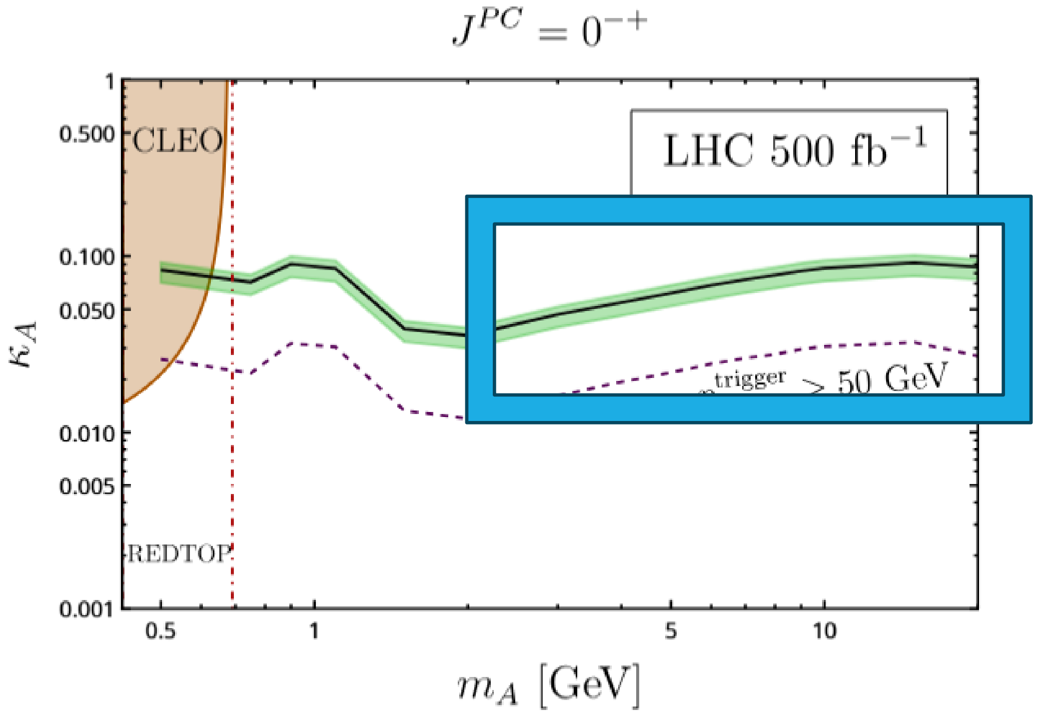




Experimental Reach

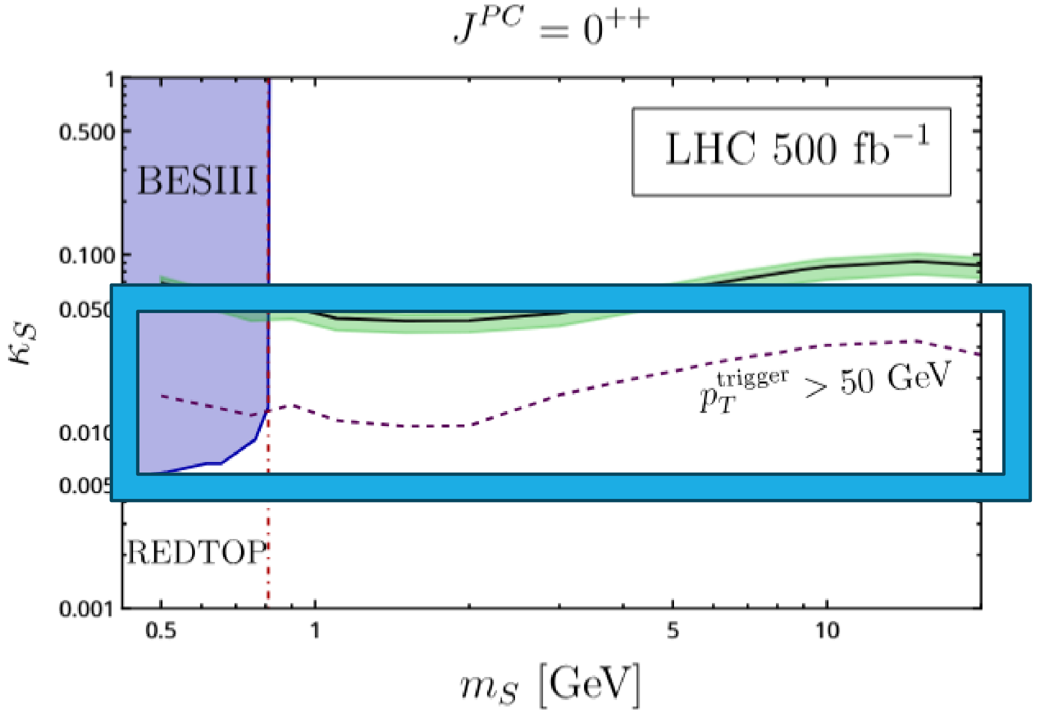
Universal and insensitive to parity

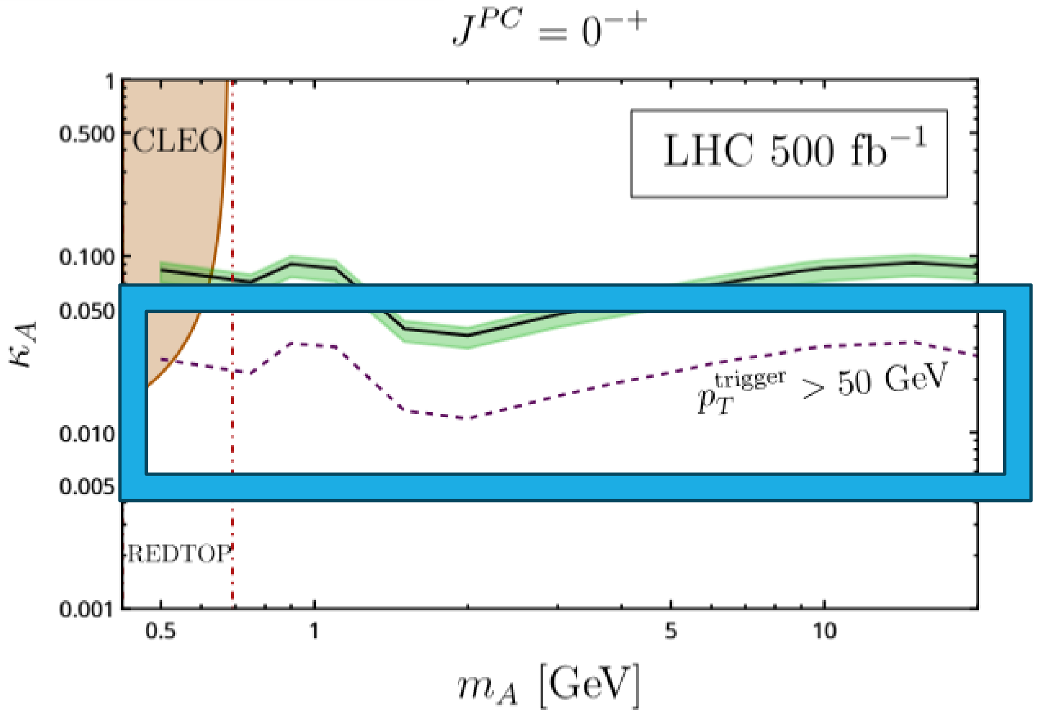




Experimental Reach

Significant improvement potential for HL–LHC with Trigger Level Analysis.





Conclusion

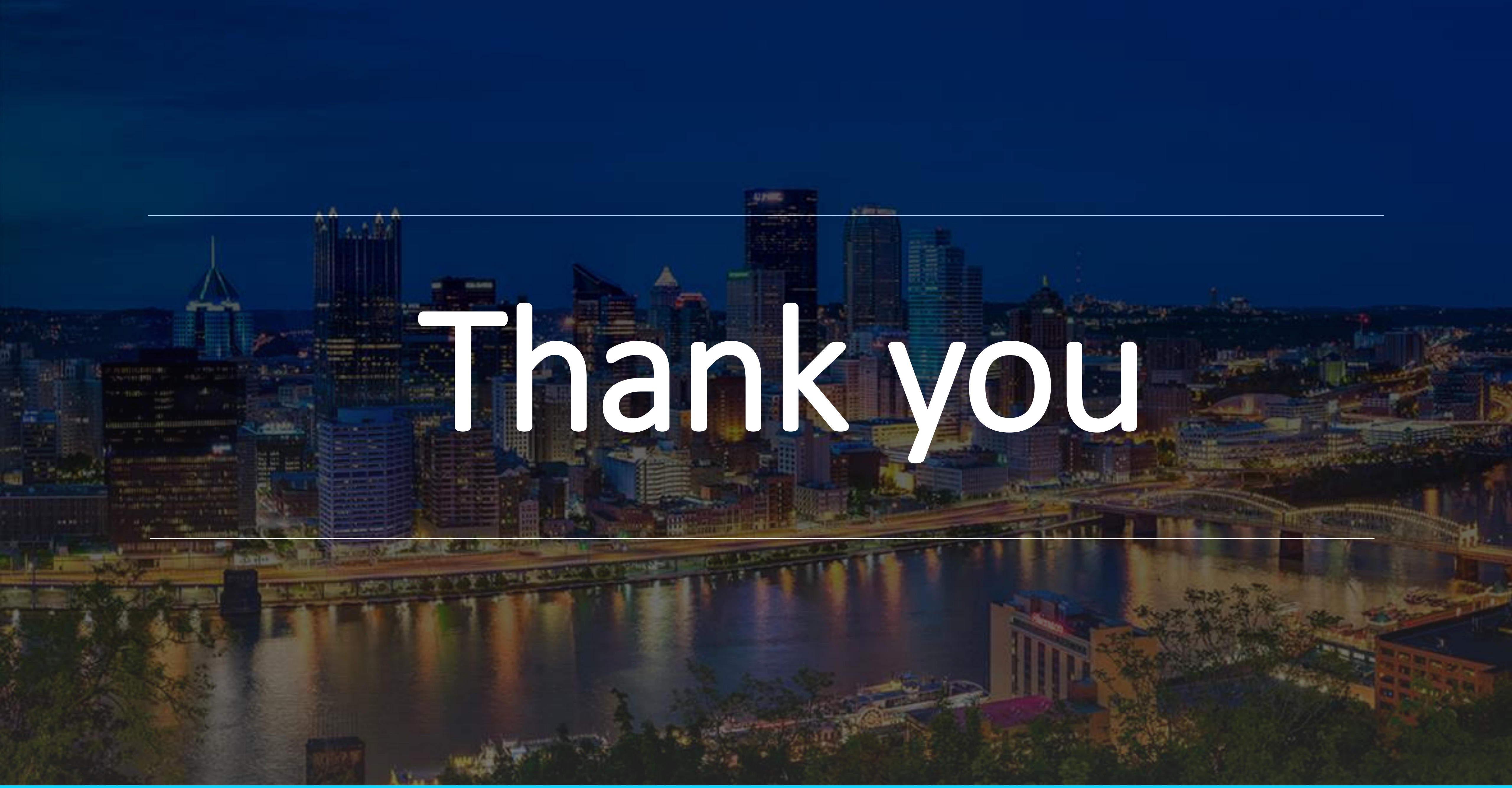
- We have proposed a new search strategy for GeV-scale particles coupling to light quarks at the LHC.

- GeV-scale particles that coupled to light quarks produce **distinctive jet features** at fixed transverse momentum:
    - Low charged-track multiplicity
    - Small jet mass
    - Zero Jet Charge

- Strong sensitivity in 0.5–20 GeV range **and can be done with the current data**!

- **Significantly increased sensitivity** (60x) if the triggers get lowered!

    Trigger Level Analysis for HL-LHC?!



Thank you