Dark QCD
From Colliders to Cosmology

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DESY

Anticipating 13 TeV
GGI, Florence
16.10.15

Based on
Bai, PS, 1306.4676
PS, Stolarski, Weiler, 1502.05409
PS, 1504.07263
Dark QCD (aka Hidden Valley)

- $SU(N_d)$ dark sector
  - Confinement scale $\Lambda_d$
  - $n_f$ light dark quarks (no SM charges)

- Talks featuring dark $SU(N)$
  - Katz
  - Hochberg, Kuflik, Schmaltz
  - Graham, Harnik
  - Strassler

Baryogenesis

Dark Matter

Naturalness

Phenomenology
Dark QCD - DM

• New mechanisms for relic density, extend mass range:
  ‣ Asymmetric DM - GeV-TeV scale
  ‣ Strong Annihilation - 100 TeV scale
  ‣ SIMP - MeV scale

• Advantages of Composite
  ‣ DM mass scale and stability
  ‣ Fast annihilation for ADM
  ‣ Self-interactions for structure formation (?)
Today

- Emerging Jets from a GeV scale dark sector

- Gravitational Wave signals from hidden sector phase transitions
Dark QCD

- SU(N) dark sector with neutral "dark quarks"
- Confinement scale $\Lambda_{\text{darkQCD}}$
- DM is composite "dark proton"
- "Dark pions" unstable, long lived
Emerging Jets at the LHC

• Dark meson jets from dark parton shower

• Macroscopic lifetime for $m_{\pi_d} \sim \text{few GeV}$
Emerging Jets at the LHC

- Decay back to SM quarks
- Jets emerge at distance $C_T$
- Several displaced vertices inside a jet “cone”
Should we have seen this already?

- ATLAS (arXiv:1409.0746)
- CMS (arxiv:1411.6530)
- LHCb (arxiv:1412.3021)

Main differences:
- Lower mass
- Lower track multiplicities from individual vertices
- Multiple displaced vertices in same cone

(also: not trackless!)
Benchmark/Strategy

• Pair production of mediator:
  ‣ Two QCD jets
  ‣ Two Emerging Jets

• 4-jet trigger (calo!)

\[ p_T > 200 \text{ GeV} \quad H_T > 1 \text{ TeV} \]
Benchmark/Strategy

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\[ p_T > 200 \text{ GeV} \quad H_T > 1 \text{ TeV} \]
Reach ATLAS/CMS

- Optimistic scenario (no non-collisional BGs)
- More realistic studies under way at CMS (ATLAS soon?)
Other New Physics

- RPV SUSY
  \[ \mathcal{W}_{\text{RPV}} \supset \frac{1}{2} \lambda_{ijk} U_i D_j D_k \]

- One of the last “natural” MSSM scenarios

\[ q \rightarrow \tilde{q}^* \rightarrow q \bar{q} \tilde{\chi}_1 \]

QCD jet

Emerging jet

Emerging jet

QCD jet
RPV SUSY sensitivity

- Competitive with displaced vertex searches
- Less model dependent
- “Natural SUSY” scenario with top jets to be done

![Graph showing sensitivity of the emerging jets search for the RPV MSSM toy model, at the 14 TeV LHC. Contours are as in Fig. 10. A common mass $M_{\tilde{q}}$ is assumed for first and second generation right-handed up-squarks, while all other MSSM particles are assumed to be heavy. The squarks, of course, decay promptly via gauge or Yukawa interactions: $\tilde{q} \rightarrow q + 1$. In the following we generate events for a RPV toy model where only the right-handed up and charm squarks and the lightest neutralino are kinematically accessible. Signal events are generated using the MSSM implementation in Pythia. The squark masses $M_{\tilde{u}R} = M_{\tilde{c}R} = M_{\tilde{q}}$ and the neutralino lifetime $\tau$ are varied, and the neutralino mass is taken to be $m_{\tilde{\chi}} = 100$ GeV. Since the squark masses are of order TeV, the neutralino will have a significant boost, such that its decay products will be collimated. This is a challenging regime for searches which rely on reconstructing a common displaced vertex for a dijet pair. The emerging jets search has no problem picking up this signature, and we show our reach estimate in Fig. 16. There is sensitivity across four orders of magnitude in neutralino lifetime $\tau$ for squark masses as high as 1500 GeV. Compared with the dark QCD signature, the reach in $\tau$ is larger. The reason for this is that there is only one displaced decay per jet, while in the dark QCD model multiple displaced decays happen, which reduce the cut efficiency on the signal. Similar to the dark QCD case, going to 3000 fb$^{-1}$ can significantly improve the reach in the 100 mm channel, while the benefits in the 3 mm search are more moderate.

Before concluding, we would like to stress that the supersymmetric model used here was chosen purely for phenomenological reasons. From a naturalness perspective it would be more motivated to only have third generation squarks in the kinematic range. The resulting signature with prompt top-jets and displaced neutralino jets would be interesting to study in the future.

7 Conclusions

The LHC and its detectors are excellent machines for exploring the physics of the TeV scale. Yet, there are only a finite number of analyses that can be done on the data, so it is important to...
Other scenarios

- Dark pions prompt/stable - jets with MET
  - Cohen, Lisanti, Lou, 1503.00009

- Some prompt, some displaced dark pions
  - b-taggers
  - Simplified model (split Higgs portal) study underway with Kang, Mccullough, Scanlon

- Heavy mediator - search for individual dark pions
  - LHCb, SHiP
The Dark Phase Transition
QCD Phase Diagram

The QCD phase diagram at zero chemical potential is shown schematically. The dashed region represents our current lack of knowledge about the order of the PT in the limit of two massless flavours.

In the SM, the PT could be strong, but this is not a generic result for QCD and similar theories. The QCD phase diagram can be summarized in the so-called Columbia plot, reproduced in Fig. 1, based on [51]. The pure Yang-Mills limit $m_u, m_d, m_s \rightarrow 1$ is known to have a strong first order PT [52] from the restoration of a global $Z_3$ center symmetry at low temperatures. The opposite limit, i.e., theories with three exactly massless quarks, also feature a strong first order transition, related to the breakdown of the $SU(3) \rightarrow SU(3)$ chiral symmetry [53].
The aim of this work is to point out that gravitational waves could also be produced by a strong PT in a dark or hidden sector. The particular scenario we have in mind is a dark sector with a new SU($N_d$) gauge interaction which confines at some scale $\phi_d$. Such models have recently received renewed interest either as models of dark matter [27–42] or as part of the low energy sector of so-called Twin Higgs models [43–48]. Different from generic hidden sectors [49], these models provide a preferred mass range and some restrictions on the particle content, such that the frequency range of the potential GW signal can be predicted.

Given that the SM QCD transition is not first order, we will review the known results on the order of the PT in strongly coupled gauge theories in the next section, followed by a discussion of models that fall into this category. In Sec. 3 we calculate the GW spectra that can be produced in these models, and compare them to the sensitivity of current and planned GW detection experiments in Sec. 4. We discuss the complementarity of GW experiments with other searches for dark sectors in Sec. 5, before presenting our conclusions.
SU(N) - PT

- Consider $SU(N_d)$ with $n_f$ massless flavours.

- PT is first order for
  - $N_d \geq 3$, $n_f = 0$
  - $N_d \geq 3$, $3 \leq n_f < 4N_d$

- Not for:
  - $n_f = 1$ (no global symmetry, no PT)
  - $n_f = 2$ (not yet known)
GW Signal

First order PT $\rightarrow$ Bubbles nucleate, expand

Bubble collisions $\rightarrow$ Gravitational Waves
Peak Frequency

- **Redshift:**

\[
f = \frac{a_*}{a_0} \frac{H_0 H_* f_*}{H_*} = 1.59 \times 10^{-7} \text{ Hz} \times \left( \frac{g_*}{80} \right)^{\frac{1}{6}} \times \left( \frac{T_*}{1 \text{ GeV}} \right) \times \frac{f_*}{H_*}
\]

- **Peak regions:** \( k/\beta \approx (1 - 10) \)

\[
f_{\text{peak}}^{(B)} = 3.33 \times 10^{-8} \text{ Hz} \times \left( \frac{g_*}{80} \right)^{\frac{1}{6}} \left( \frac{T_*}{1 \text{ GeV}} \right) \left( \frac{\beta}{\mathcal{H}_*} \right)
\]
$T^* \sim \text{Few GeV}$

![Graph showing gravitational wave detection reach and comparison with different projects: EPTA, IPTA, ELISA, ALIA, LISA, DECIGO, BBO. The graph plots $h^2\Omega_{GW}$ against frequency $f$ in Herz (Hz).]
Summary

- **QCD like dark sectors** motivated in many models

- **Emerging jets** are “smoking gun”, good prospects for ATLAS/CMS

- **Gravitational waves** are independent probe of dark sector phase transition
Extra slides :)
Composition of QCD backgrounds

- QCD jets with $p_{T,j} > 200$ GeV

QCD Emerging Jets, n=0

QCD Trackless Emerging Jets, n=0

Track(s) appears at distance $r$

Flavour of long lived state

Purely trackless jets

identity of hardest particle
We have modified the Hidden Valley shower implementation in a number of dark mesons. This is the reason for the discrepancy in the energy between 500 GeV and 4 TeV, followed by a dark parton shower. We set the dark pions to be produced through the energy of dark quark pairs radiated and the number of mesons produced, such that the average particle multiplicity as a function of the energy of the process is calculable up to an unknown normalization factor. In the next to leading high energy approximation (MLLA), it was found that the dark QCD scale and dark meson spectrum corresponds to benchmark model of-mass energy

\[ e^+e^- \rightarrow Q_D \bar{Q}_D \]

\[ \langle N(\hat{s}) \rangle \propto \exp \left( \frac{1}{b_1} \sqrt{\frac{6}{\pi \alpha_s(\hat{s})}} + \left( \frac{1}{4} + \frac{5n_f}{54\pi b_1} \right) \log \alpha_s(\hat{s}) \right) \]
Factor 100-1000 improved S/B per jet, compared to ordinary 4-jet search.
LHCb, SHIP, low energy

- Z’ mediator is difficult to trigger at ATLAS/CMS
  Same if dominant production is off-shell

- Reconstruct individual dark pions, differentiate using lifetime, mass, decay products

- Depends on flavour structure → in progress
What is an Emerging Jet?

Tracking Volume

QCD hadrons

neutral, SM singlet states (dark pions)
Model

• Mediators:
  ‣ Bifundamental scalar \( \Phi \)
  ‣ or \( Z' \) (Hidden Valleys!)

\[ \mathcal{L} \supset \kappa \Phi \bar{Q}_D d_R \]

\[ \mathcal{L} \supset g' \bar{Q}_D \gamma^\mu Q_D Z'_\mu \]
  + couplings to SM

• Pair production of heavy bi-fundamental fields:

\[ q \overline{q} \xrightarrow{\Phi} \Phi^* \]

• Decay to quark - dark quark pairs: Two QCD jets, two Emerging Jets
Emerging Jets at the LHC

• Characteristic:
  ‣ few/no tracks in inner tracker

• New “emerging” jet signature

• Universal for large class of composite DM models!
Benchmark Signal/Strategy

- Pair production of 1 TeV bi-fundamental scalars
- Trigger on 4 HCAL jets \( p_T > 200 \text{ GeV} \)
- Require one or two “emerging jets:”
  Jets with at most 0/1/2 tracks originating from a distance \( r < r_{\text{cut}} \)
- Two scenarios:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda_d )</td>
<td>10 GeV</td>
<td>4 GeV</td>
</tr>
<tr>
<td>( m_V )</td>
<td>20 GeV</td>
<td>8 GeV</td>
</tr>
<tr>
<td>( m_{\pi_d} )</td>
<td>5 GeV</td>
<td>2 GeV</td>
</tr>
<tr>
<td>( c\tau_{\pi_d} )</td>
<td>150 mm</td>
<td>5 mm</td>
</tr>
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</table>
• Can still add paired di-jet cuts

• Will also catch some displaced vertex & SIMP signals, possibly photon jets

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th>Model B</th>
<th>QCD 4-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree level</td>
<td>14.6</td>
<td>14.6</td>
<td>410,000</td>
</tr>
<tr>
<td>≥ 4 jets,</td>
<td>η</td>
<td>&lt; 2.5</td>
<td></td>
</tr>
<tr>
<td>p_T(jet) &gt; 200 GeV</td>
<td>4.9</td>
<td>8.4</td>
<td>48,000</td>
</tr>
<tr>
<td>H_T &gt; 1000 GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E(1 GeV, 0, 3 mm) ≥ 1</td>
<td>4.1</td>
<td>4.1</td>
<td>45</td>
</tr>
<tr>
<td>E(1 GeV, 0, 3 mm) ≥ 2</td>
<td>1.8</td>
<td>0.8</td>
<td>~ 0.08</td>
</tr>
<tr>
<td>E(1 GeV, 0, 100 mm) ≥ 1</td>
<td>1.7</td>
<td>≤ 0.01</td>
<td>8.5</td>
</tr>
<tr>
<td>E(1 GeV, 0, 100 mm) ≥ 2</td>
<td>0.2</td>
<td>≤ 0.01</td>
<td>~ 0.02</td>
</tr>
</tbody>
</table>
Shapes & Substructure?
Jet Shape(s)

- **Girth**
  \[
  \frac{1}{p_T^{\text{jet}}} \sum_i p_T^i \Delta R_i
  \]

- **Model discrimination (?)**

- **Subtleties:** Might loose hardest dark meson, etc…
What if $c \tau \ll mm$?

- No displaced tracks. Can we still discriminate QCD and dark QCD jets?

- Sub-jets from individual dark pion decays

Probably discussed 8 years ago in context of Hidden Valleys

Much better tools now available!!!
Off-shell production

\[ \mathcal{O}_u = \frac{1}{\Lambda^2} (\bar{u}\gamma_\mu u) (\bar{Q}_D\gamma^\mu Q_D) \]

- Total rate: \[ \sigma(pp \rightarrow \bar{Q}_DQ_D) \approx 8.2 \text{ pb} \times \left( \frac{\text{TeV}}{\Lambda} \right)^4 \times N_d \times N_F \]
Forward region

- Fraction of all signal events with $N$ dark pions in $2 < \eta < 5$
- Momentum (not pT) distribution of dark pions in $2 < \eta < 5$
Decay characteristics

- Number of charged tracks from dark pion decays
- Also depend on flavour structure - some more work!

![Graph showing the number of charged tracks per \( \pi_D \) for models A and B.]

- Model A
- Model B

Figure 12: Multiplicity of charged tracks in \( \pi D \) decays, assuming 100% decay to down quarks, and with the fragmentation process simulated using PYTHIA.

When considering a specific model, a dedicated search will most likely deliver optimal results. For instance, if muons are likely to appear in the final state, those can be used for triggering purposes and to suppress backgrounds. On the other hand, given the variety of models on the market, it is also desirable to have searches which are more model independent, and thus will allow one to place bounds on multiple new physics scenarios.

In the following we will demonstrate that the emerging jet analysis can easily be used to obtain bounds on other new physics scenarios with displaced decays, even if their signature will appear different at first sight. As an example, we will use a supersymmetric scenario where the neutralino LSP decays through a UDD type RPV operator.

Add more details if we decide to keep this.

Conclusions

Awesome work :)
Very very (very) rough estimate

- 20 inverse fb

- Assume that events with 3 or more reconstructed dark pions are significantly different from QCD (i.e. no background)

- 10% reconstruction efficiency

→ Sensitivity to $\sigma = 8 \text{ fb}$, corresponds to $\Lambda \approx 5 \text{ TeV}$
Shape

- From Bubble collisions and turbulence

\[
\frac{d\Omega_{GW}^{\text{(B)}}}{d \log k} \approx \frac{2}{3\pi} h^2 \Omega_{r,0} \left( \frac{\mathcal{H}_*}{\beta} \right)^2 \Omega_{S_*} \epsilon^3 \frac{(k/\beta)^3}{1 + (k/\beta)^4},
\]

\[
\frac{d\Omega_{GW}^{\text{(MHD)}}}{d \log k} \approx \frac{8}{\pi^6} h^2 \Omega_{r,0} \left( \frac{\mathcal{H}_*}{\beta} \right) \Omega_{S_*} \epsilon^4 \frac{(k/\beta)^3}{(1 + 4k/\mathcal{H}_*)(1 + (\epsilon/\pi^2)(k/\beta))^{11/3}}.
\]

Caprini, Durrer, Siemens, 2010
Huber, Konstandin, Servant, ...

- \(k\) conformal wave number

\[\beta \sim (1 - 100)\mathcal{H}_*\]

Sound waves not included yet!
Hindmarsh, Huber, Rummukainen, Weir, 2013, 2015